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Historical Rewiev

This year University of Ljubljana marks its 90th anniversary. Technical fields were joint in the School of Engineering that included the Geologic and Mining Division while the Metallurgy Division was established in 1939 only. Today the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before War II the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical Rudarski zbornik (Mining Proceedings). Three volumes of Rudarski zbornik (1937, 1938 and 1939) were published. The War interrupted the publication and not untill 1952 the first number of the new journal Rudarsko-metalurški zbornik - RMZ (Mining and Metallurgy Quarterly) has been published by the Division of Mining and Metallurgy, University of Ljubljana. Later the journal has been regularly published quarterly by the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy, and the Institute for Mining, Geotechnology and Environment.

On the meeting of the Advisory and the Editorial Board on May 22nd 1998 Rudarsko-metalurški zbornik has been renamed into "RMZ - Materials and Geoenvironment (RMZ -Materiali in Geookolje)" or shortly RMZ - M&G.

RMZ - M&G is managed by an international advisory and editorial board and is exchanged with other world-known periodicals. All the papers are reviewed by the corresponding professionals and experts.

RMZ - M&G is the only scientific and professional periodical in Slovenia, which is published in the same form nearly 60 years. It incorporates the scientific and professional topics in geology, mining, and geotechnology, in materials and in metallurgy.

The wide range of topics inside the geosciences are wellcome to be published in the RMZ -Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and antropogenic pollution of environment, biogeochemistry are proposed fields of work which the journal will handle. RMZ - M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, and the Institute for Mining, Geotechnology and Environment Ljubljana. In addition it is financially supported also by the Slovenian Research Agency, Science and Technology of Republic of Slovenia.

Editor in chief

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Original Scientific Papers – Izvirni znanstveni članki

Determination of the strain-rate sensitivity and the activation energy of deformation in the superplastic aluminium alloy Al-Mg-Mn-Sc

Določevanje indeksa občutljivosti na preoblikovalno hitrost in aktivacijske energije za deformacijo superplastične aluminijeve zlitine Al-Mg-Mn-Sc

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Abstract: This paper deals with determining the strain-rate sensitivity *m* and the activation energy for the superplastic deformation *Q* of a cold rolled aluminium Al-Mg-Mn-Sc alloy. The experiments were carried out under uniaxial tension over the temperature range 390 °C to 550 °C and at a constant strain rate or constant cross-head speed between $1 \cdot 10^{-4}$ s^{-1} and $2 \cdot 10^{-2}$ s^{-1}. The *m*-values were determined on the basis of the true stress, true strain curves and also using the jump-test method. The *m*-values varied from 0.35 to 0.70, which depended upon the forming conditions. The activation energy for the deformation was determined by the flow curves at various temperatures and at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}.

Izvleček: Članek obravnava določanje indeksa občutljivosti na preoblikovalno hitrost *m* in aktivacijsko energijo za superplastično preoblikovanje aluminijeve zlitine Al-Mg-Mn-Sc. Preizkusi so bili narejeni z nateznim preizkusom pri temperaturah od 390 °C do 550 °C pri konstantnih preoblikovalnih hitrostih med $1 \cdot 10^{-4}$ s^{-1} in $2 \cdot 10^{-2}$ s^{-1} in konstantnih hitrostih raztezanja. Vrednosti *m* so bile določene na osnovi krivulj dejanska napetost – dejanska deformacija in tudi s skokovitim spreminjanjem preoblikovalne hitrosti. Vrednosti *m* so bile v mejah 0,35 do 0,70, kar je bilo odvisno od preoblikovalnih

Original scientific paper

razmer. Aktivacijska energija za deformacijo je bila določena s krivuljami tečenja pri različnih temperaturah in konstantni začetni preoblikovalni hitrosti 7,5 · 10^{-4} s^{-1}.

Key words: strain-rate sensitivity, activation energy, superplasticity, Al-Mg-Mn-Sc alloy
Ključne besede: indeks občutljivosti na preoblikovalno hitrost, aktivacijska energija, superplastičnost, zlitina Al-Mg-Mn-Sc

INTRODUCTION

Superplasticity is the ability of certain polycrystalline materials to achieve large elongations in a tensile test without necking prior to failure. These elongations are up to 1000 %, and in some cases even more. The superplastic forming (SPF) of aluminium-alloy sheets has been commercially established for more than 30 years, and the mechanisms of SPF and the requirements for achieving the superplasticity of materials are now well known.[1, 2] In general, three important conditions are needed to attain the SPF of the material: (i) the grain size should be very fine and stabile, typically less than 10 µm; (ii) the flow stresses must be low compared with those of conventional materials; and, (iii) the strain-rate sensitivity values *m* must lie in the range of 0.4 to 0.8.[3]

The strain-rate sensitivity index *m* is considered to be the most important parameter that characterises superplastic deformation.[2] The characteristic equation that describes superplastic behaviour is usually written as $\sigma = K.\dot{\varepsilon}^m$, [1–6] where σ is the flow stress**,** *K* is a material constant, $\dot{\varepsilon}$ is the strain rate and *m* is the strain-rate sensitivity index of the flow stress. The *m*-value is a function of the forming parameters, such as the strain rate and the temperature, and is also connected with the microstructural characteristics.[7]

There are a number of reports where the various experimental methods for determining the value of *m* are described.[2–6] The most convenient method is a uniaxial tensile test at a particular constant temperature and at different strain rates. The simplest method is reflected in the relation ship between the flow stress (σ) and the strain rate ($\dot{\varepsilon}$). The *m*-value is then defined as the slope of the curve lg σ vs. lg $\dot{\varepsilon}$. The jump test is also quite often used.[2] Different variations of this method are distinguished by the way the results are handled.

A knowledge of the activation energy enables the evolution of the deformation mechanism of SPF.[8] For aluminium SPF alloys this energy is usually within the range anticipated for grain-boundary diffusion in pure aluminium and interdiffusion in Al-Mg alloys.[9] The activation energy is usually obtained from an Arrhenius plot of ln $\dot{\varepsilon}$ vs. the reciprocal absolute temperature $1/T$ at a constant stress or from a plot of $\ln\sigma$ vs. $1/T$ at a constant strain rate.[2, 3]

The purpose of this paper is an experimental survey of two methods to determine the strain-rate sensitivity index and to determine the activation energy of the superplastic forming. The examined material was a slightly modified AA5083 (Al-Mg-Mn) alloy with the addition of scandium.

Experimental procedure

The strain-rate sensitivity index m and the activation energy Q of the SPF were determined for a Al-4.5Mg-0.46Mn-0.44Sc alloy. The alloy was produced by ingot casting and conventionally processed to a sheet with a thickness of 1.9 mm. The superplastic parameters m and Q were determined using a uniaxial tensile test. The samples for this test are shown in Figure 1.

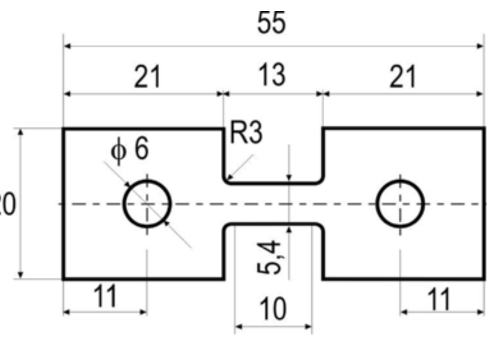

Figure 1. Sample for the tensile test

The tensile tests were carried out using a Zwick Z250 universal testing machine with 0.5 kN load cell. The machine was equipped with a three-zone electrical resistance furnace. A photograph of the tested equipment is shown in Figure 2. The testing procedure and the evolutions of the results were controlled by the TestXpert II software system.

The measurements included a determination of the flow stresses as a function of the true strain and of the strain rate at various strain rates and forming temperatures, which ranged from $1 \cdot 10^{-4}\ s^{-1}$ to $2 \cdot 10^{-2}\ s^{-1}$ and from 390 °C to 550 °C, respectively. The data from these experiments were used for a calculation of the strain-rate sensitivity indexes and the activation energy. The strain-rate sensitivity index m as a function of the strain rate was estimated from the stress-strain plots and from the multi-

Figure 2. The test equipment

strain-rate jump test. The tensile tests were conducted at a constant strain rate with a continuous change of cross-head speed and with a constant cross-head speed, where the initial strain rate decreased with the increased strain.

RESULTS AND DISSCUSION

Strain-rate sensitivity index *m*

The *m*-values are usually calculated from the logarithmic plot of the flow stress vs strain rate (method I). Figure 3 shows stress-strain rate plots at 550 °C covering the true strains from 0.7 to 1.4. The constant strain rates were in the range from $5 \cdot 10^{-4}$ s^{-1} to $1 \cdot 10^{-2}$ s^{-1}. The curves exhibit the sigmoid shapes. The *m*-values at several strain rates and strains were calculated from the slopes of the plots; these values are presented in Figure 4. The highest *m*-values for all the strains were in the range of strain rates from $5 \cdot 10^{-4}$ s^{-1} to $1 \cdot 10^{-3}$ s^{-1}.

The other method (method II) for determining the *m*-value is the multi-strain-rate jump test. The jump test was conducted by increasing and decreasing the strain rate by 20 % at every 100 % increment of elongation. The strain rate was constant during the single jumps, which was controlled by software for a continuously changing cross-head speed. The change of cross-head speed is shown in Figure 5 as an example of increasing the strain rate from $\dot{\varepsilon} = 2.5 \cdot 10^{-3}$ s^{-1} (downward strain rate) to $\dot{\varepsilon} = 3 \cdot 10^{-3}$ s^{-1} (upward strain rate) for a progressive elongation, and the corresponding simultaneous change of the

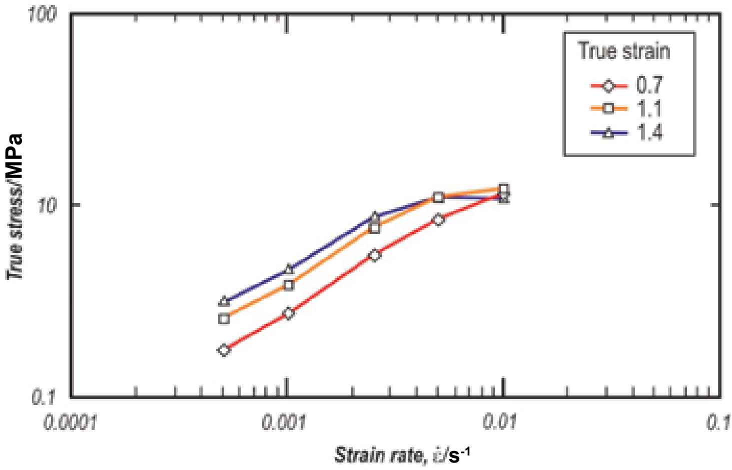

Figure 3. Stress-strain rate plots for various strains at a temperature of 550 °C

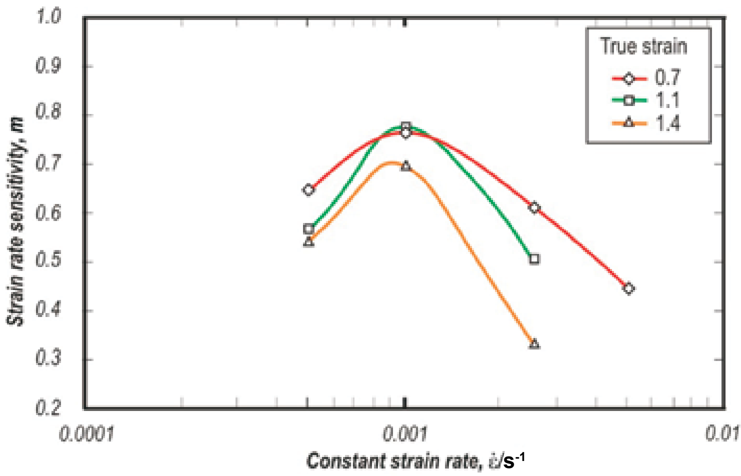

Figure 4. Strain-rate sensitivity index *m* as a function of constant strain rate for various strains at a temperature of 550 °C calculated from the stress-strain rate curves in Figure 3

force. The m-values for various strains or elongations, respectively, were calculated according to the equation:

$$m = \frac{\lg \frac{\sigma_2}{\sigma_1}}{\lg \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}} = \frac{\lg \frac{F_2(1+e)S_0}{F_1(1+e)S_0}}{\lg \frac{\upsilon_2(1+e)L_0}{\upsilon_1(1+e)L_0}} = \frac{\lg \frac{F_2}{F_1}}{\lg \frac{\upsilon_2}{\upsilon_1}} \qquad (1)$$

where σ_1 and σ_2 are the flow stresses, $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ are the corresponding instantaneous strain rates, F_1, F_2 are the forces and v_1, v_2 are the cross-head speeds before and after the jump. By convention, the m-value is attributed to the downward strain rate $\dot{\varepsilon}_1$.[2]

The multi-strain jump test makes possible to examine the m values at various progressing strains or elongations

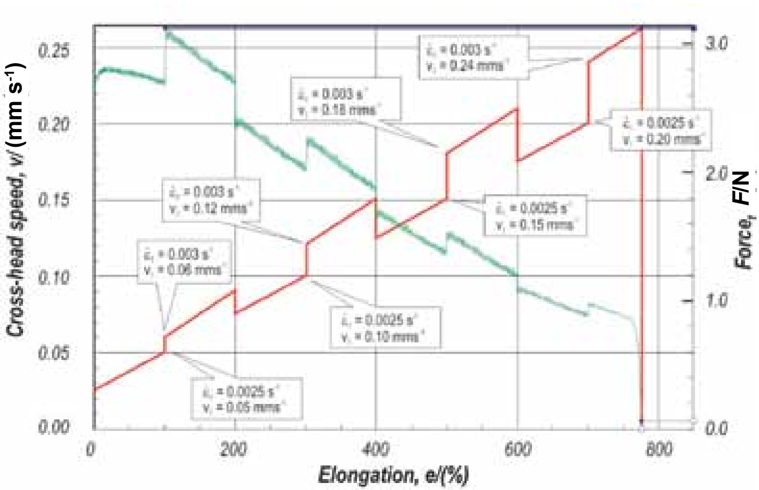

Figure 5. The change of cross-head speed (red line) and force (green line) during the multi-strain-rate jump test

Table 1. Cross-head speeds, forces and m-values for the investigated alloy during the jump test at a downward strain rate $\dot{\varepsilon} = 2.5 \cdot 10^{-3}$ s^{-1} and at 550 °C

ε	e/%	v_1/(mm s^{-1})	v_2/(mm s^{-1})	F_1/N	F_2/N	m
0.69	100	0.0501	0.0602	2.722	3.082	0.68
1.10	200	0.0752	0.0901	2.411	2.711	0.65
1.38	300	0.1000	0.1203	2.031	2.259	0.58
1.61	400	0.1248	0.1498	1.654	1.838	0.58
1.79	500	0.1502	0.1803	1.356	1.491	0.52
1.95	600	0.1755	0.2096	1.072	1.179	0.53
2.08	700	0.1990	0.2403	0.877	0.959	0.47

at a fixed strain rate during a single test. The experimental data of the cross-head speeds v_1 and v_2 with the corresponding forces F_1 and F_2 and the calculated m-values at a single strains during the jump test from Figure 5 are given in Table 1.

Indexes m, calculated from the jump test, are plotted as a function of strain rate for strains over the range from 0.7 (100 %) to 2.6 (1300 %) at temperature of 550 ºC in Figure 6. The index m is changed at all the strains with the strain rates; the data demonstrate the bell-shape curvature that is typical of superplastic materials. The m-values also change with the increased strain.

The highest m-values were achieved in the range of constant strain rates $3.5 \cdot 10^{-4}$ s^{-1} to $1 \cdot 10^{-3}$ s^{-1} (Figure 6). The maximum m-value was in accordance with the largest elongation of about 2000 % (Figure 7).

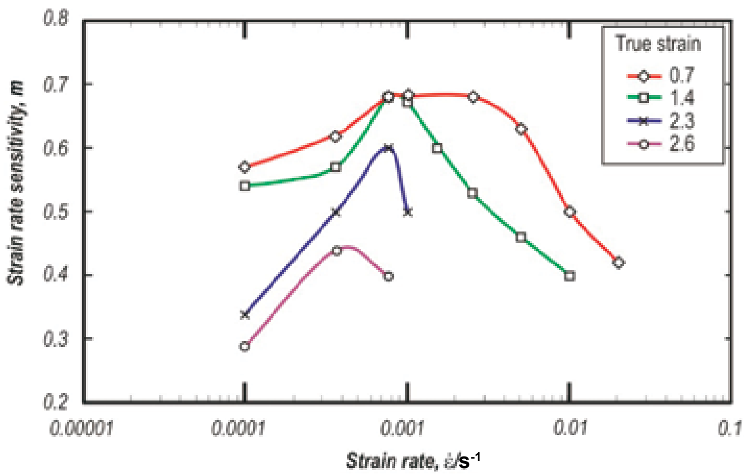

Figure 6. Strain-rate sensitivity index m as a function of the constant strain rate for various strains at 550 °C (jump test with a 20 % increase of the strain rate)

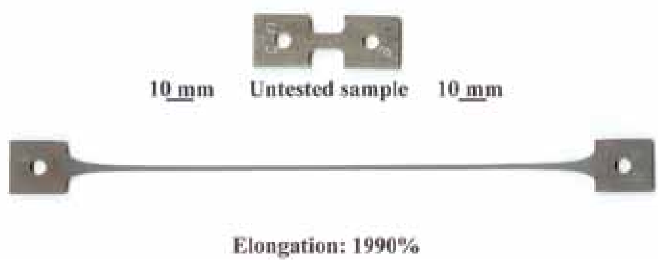

Figure 7. Untested and tested sample of Al-4.5%Mg-046%Mn-0.44Sc alloy at 550 °C and an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}

Table 2. Indexes m of the investigated alloy at a true strain of 0.7, various strain rates and a forming temperature of 550°C for methods I and II

Strain rate, $\dot{\varepsilon}$	Method I	Method II
$1 \cdot 10^{-3}$ s^{-1}	$m = 0.77$	$m = 0.62$
$2.5 \cdot 10^{-3}$ s^{-1}	$m = 0.68$	$m = 0.68$

The m-values of the tested alloy are comparable to the reported data for alloys with a similar composition and forming conditions.[10, 11, 12] The m values that were obtained with method I varied somewhat from those of method II. However, these differences originated from a fault in the measurements of extreme low forces and cross-head speeds during the tensile tests.

Activation energy of superplastic deformation

An activation energy for the superplastic deformation Q was determined by assuming that the strain rate follows an Arrhenius type of dependence for the absolute temperature:[2, 3, 13, 14]

$$\dot{\varepsilon} \cdot \exp\frac{Q}{R \cdot T} = A \cdot \sigma^n \tag{2}$$

where A is the material constant, R is the gas constant and $n = 1/m$ is the stress exponent. The activation energy Q under a constant strain rate $\dot{\varepsilon}$, can be calculated with an equation deduced from (2):

$$\ln\sigma = \frac{\ln\dot{\varepsilon} - \ln A}{n} + \frac{1}{T} \cdot \frac{Q}{R \cdot n} \tag{3}$$

The slope of the line obtained with a linear regression method in the plot *ln* σ *vs.* $1/T$ is $Q/(R \cdot n)$.

An example of a determination of the activation energy for the investigated alloy is shown for the case of SPF at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1} and at a true strain of $\varepsilon = 0.5$. Figure 8 shows the flow curves at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1} for forming temperatures in the range from 390 °C to 550 °C.

The flow stresses during true strain of 0.5 and at various temperatures from Figure 8 were used for the plot ln σ *vs.* $1/T$ in Figure 9.

The slope of the line in Figure 9 is: $k = Q/(n \cdot R) = Q \cdot m/R = 8419.069$. Taking the average strain-rate sensitivity index $m = 0.46$ over 390–550 °C, the average activation energy for a given test condition is: $Q = k \cdot R/m = 8419.069 \cdot 8.3144/0.46 \approx 152$ kJ/mol. The obtained average activation energy for high-temperature superplastic forming of the investigated Al-Mg-Mn-Sc alloy is about 152 kJ/mol, which is close to the reported values of similar alloys.[7, 11, 15] The value of 152 kJ/mol is also close to the activation energies for Al lattice diffusion (142 kJ/mol)[8] and for magnesium diffusion in aluminium (136 kJ/mol) [8, 11, 16]. The value of 152 kJ/mol is much higher than the activation energies for the grain-boundary diffusion of these alloy types.[14] This suggests that a dislocation pile-up model and a dislocation glide model control the superplastic deformation mechanism.[11]

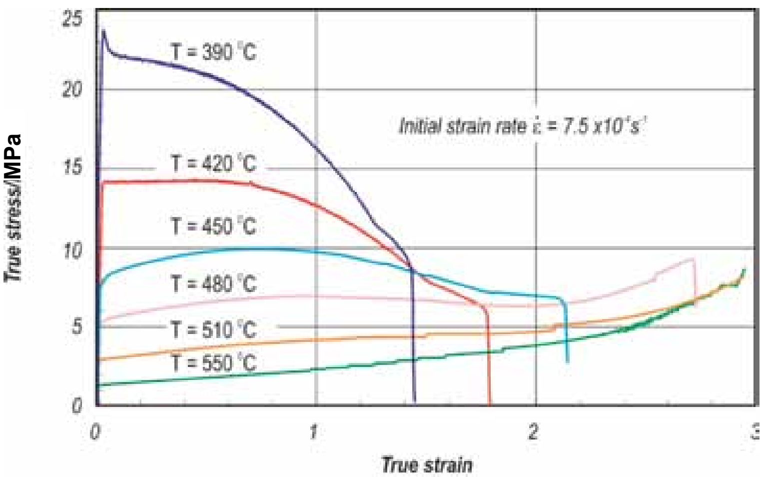

Figure 8. Flow curves for various tested temperatures at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}

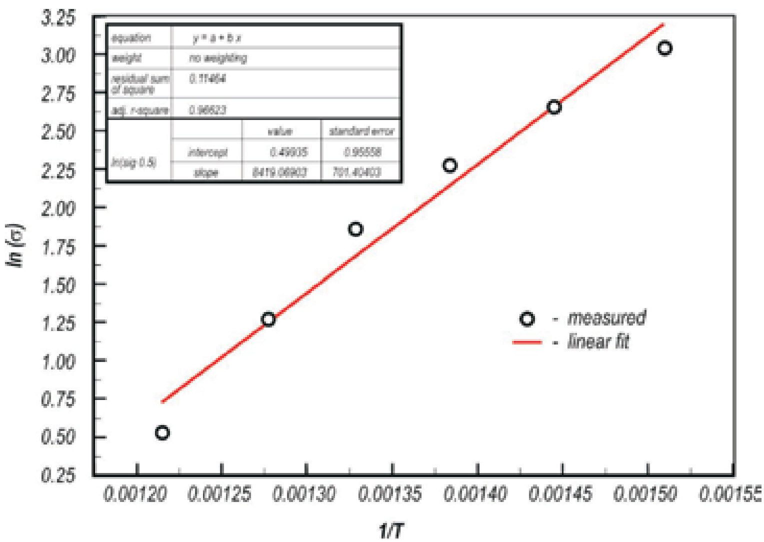

Figure 9. Measured and linear fitted values between lnσ and $1/T$

CONCLUSIONS

The strain-rate sensitivity *m* of cold-rolled Al-4.5Mg-0.46Mn-044Sc was determined on the basis of the true stress, true strain curves and by the method of the multi-strain-rate jump test. The *m*-values measured using these two different methods differed somewhat. The differences originated from the fault during the measurement of extremely low forces and cross-head speeds during the tensile tests. The *m* values varied from 0.35 to 0.70, which depended upon the forming conditions. The strain-rate jump test enables an examination of the *m*-values at various progressing strains or elongations at a fixed strain rate during a single test. The calculated activation energy for the superplastic forming was 152 kJ/mol, which is comparable to earlier reports for Al-Mg-Mn-Sc alloys with a similar composition.

Acknowledgement

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Effect of the chill wheel cooling during continuous free jet melt-spinning

Vpliv hlajenja valja med kontinuirnim litjem na napravi za hitro strjevanje

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Abstract: New method for determining contact resistance through variable heat transfer coefficient is introduced which takes into account physical properties of the casting material, process parameters and contact time/length between metal melt or metal ribbon and substrate and enables cooling and solidifying rate prediction before the experiment execution. The calculations show that contact resistance between metal melt and chilling wheel has a great influence on melt cooling and wheel heating rate, and must not be neglected in numerical calculations, even if its value is very low.

Influence of process parameters on cooling and solidifying rate and consequently on microstructure development over ribbon thickness are outlined. It can be concluded from the results, that process parameters which determine the thickness of the melt puddle in the downstream have major influence on cooling and solidifying rate of the ribbon. Among thermal properties, the thermal diffusivity of the metallic melt, solidified ribbon and wheel material has major influence on cooling and solidifying rate of the melt and solidified ribbon respectively.

In the case of continuous casting, heat balance of the wheel is calculated and influence of the chill wheel cooling mode on cooling rate of metallic ribbon is analyzed.

Original scientific paper

Izvleček: V delu je uporabljen numerični model izračunavanja kontaktne upornosti z uporabo variabilnega koeficienta toplotne prestopnosti, ki vključuje fizikalne lastnosti litega materiala, procesne parametre in kontaktni čas/dolžino med kovinsko talino oziroma trakom in hladilno podlago ter omogoča predvidevanje hitrosti ohlajanja in strjevanja pred izvedbo poskusa. Izračuni nakazujejo, da ima kontaktna upornosti med kovinsko talino in hladilnim valjem zelo velik vpliv na hitrost ohlajanja in strjevanja taline in se je v numeričnih izračunih ne sme zanemariti, tudi v primeru, ko je njena vrednost zelo majhna.

Analiziran je vpliv procesnih parametrov na hitrost ohlajanja ter strjevanja taline in posledično razvoj mikrostrukture po debelini traku. Iz izračunov lahko sklenemo, da imajo procesni parametri, ki določajo debelino talinske pete v spodnjem toku, največji vpliv na hitrost ohlajanja in strjevanja traku. Med toplotnimi lastnostmi imajo največji vpliv na hitrost ohlajanja in strjevanja temperaturna prevodnost kovinske taline, strjenega traku in materiala valja.

Izračunana je toplotna bilanca v primeru kontinuirnega litja in analiziran vpliv različnih načinov hlajenja valja na hitrost ohlajanja taline oziroma traku.

Key words: rapid solidification, metallic materials, heat transfer balance, heat transfer coefficient, numerical modeling

Ključne besede: hitro strjevanje, kovinski materiali, toplotna bilanca, koeficienta toplotne prestopnosti, numerično modeliranje

INTRODUCTION

Single roll melt spinning is the most commonly used process for the production of rapidly solidified thin metal foils or ribbons with amorphous, microcrystalline or even combined microstructure. In this type of a process, a molten material is introduced onto a surface of the spinning wheel, where melt puddle is formed (Figure 1). Material is then dragged out from the puddle by relative motion of the wheel. Usually thin ribbons are produced which can leave the wheel surface in solidified, semi-solidified or fully liquid form, depending on the contact resistance between the melt and substrate, heat transfer in the melt and wheel respectively, process parameters, and nucleation and crystal growth characteristics of the particular casting material.[1] The most important advantages of rapid solidification, which can be made with this process are extended solubility, refined microstructure, thermal stability at elevated temperatures, and improved magnetic and electrical properties.[1, 2, 3]

Heat transfer calculation

Primary objective of our work was to calculate the temperature field inside the chilling wheel and to ascertain the influence of the chill wheel cooling on metal ribbon cooling and solidification velocity. Because melt puddle is thin compare to its width and length we can make an assumption of two-dimensional (2D) transient heat transfer. Assuming 2D transient heat transfer with variable thermal properties and internal heat generation (latent heat of crystallization), general partial differential equation for the melt is reduced to:

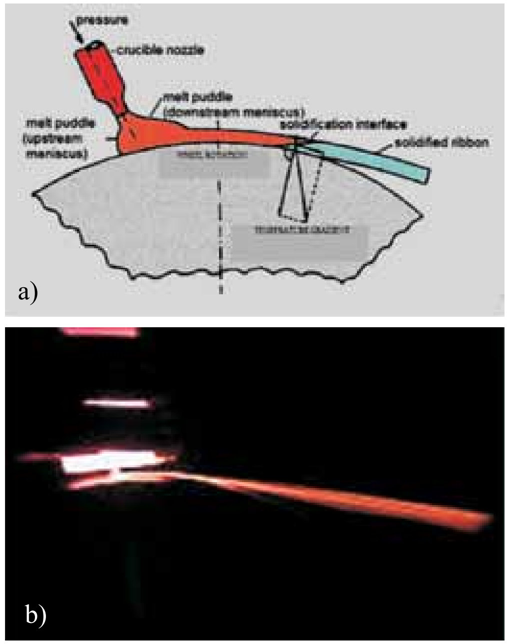

Figure 1. Melt puddle development on the surface of the wheel at free jet melt-spinning process Sheme (a), Snap shot[4] (b)

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{1}{r^2}\cdot\frac{\partial}{\partial\varphi}\cdot(\lambda\cdot\frac{\partial T}{\partial\varphi})+q^{'''}=\rho\cdot c\cdot\frac{\partial T}{\partial t} \tag{1}$$

And for chill wheel, where no heat is released by wheel material:

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{1}{r^2}\cdot\frac{\partial}{\partial\varphi}\cdot(\lambda\cdot\frac{\partial T}{\partial\varphi})=\rho\cdot c\cdot\frac{\partial T}{\partial t} \tag{2}$$

Where:

r, φ, z	cylindrical coordinate system [m; rad; m]
T	temperature [K]
$\rho = \rho(T)$	density [kg/m^3]
$\lambda = \lambda(T)$	thermal conductivity [W/(m · K)]
$c = c(T)$	specific heat [J/(kg · K)]
$q^{'''}$	volumetric heat generation rate [W/m^3]

For calculation of temperature distribution inside the melt puddle and chill wheel, we used explicit finite difference method (FDM) with cylindrical coordinate system. Thermal properties of the melt and wheel material ($\lambda(T)$, $c(T)$) are temperature dependant and are calculated for each iteration step with linear interpolation from tabulated values. Density in solidification interval of the casting material is changing linearly or parabolic, depending of the alloy solidification type (eutectic, dendritic),[5] whereas density of the wheel material is approximated as constant.

In situations where a detailed description of thermal physics is very complicated, such as in melt-spinning process, where heat transfer between melt and substrate (wheel) is coupled with fluid flow which is further complicated by the presence of solidified region, combined modes of heat exchange are usually taken in to account with the overall heat transfer coefficient.[5, 6] This coefficient (α) includes conduction and radiation of heat, as well as any convective effects and is defined as the ratio of the heat flux (q) from the liquid metal and solid ribbon across the interface with the wheel, to the temperature difference between molten metal or ribbon and wheel.

Because the temperatures of the casting material and chill wheel are changing along contact length, numerical modeling of the heat transfer with constant heat transfer coefficient and nominal chill wheel temperature is not realistic. Actually, heat transfer coefficient is dependant by many factors which include physical and thermal properties of the melt and chill substrate, fluid velocity, state and geometry of the chill surface and its temperature. Moreover, molten material solidifies and shrinks, which changes the physical contact from liquid/solid to solid/solid or (solid + gas)/solid.[5] Consequently, value of heat transfer coefficient over entire contact length can vary in wide range.

Furthermore, values of the heat transfer coefficient are difficult to measure with confidence. In literature you can find different techniques. From those based on pyrometric, photocalorimetric or wheel surface temperature measurements with embedded thermocouples, to those based on dendrite arm or interlamellar spacing, but none of them can predict the value of the local heat transfer coefficient particularly accurate.[6]

To simplify the mathematical model, we considered number of assumptions. The local heat transfer coefficient $\alpha(x)$ is calculated with the integral method for liquid metals flow over flat plate. The approximation of the flat plate is reasonable, because of the large aspect ratio between puddle length and radius of the wheel. Another assumption in our model is to consider that there is no velocity gradient in the puddle. This is not completely true in the actual case, but when metallic materials are cast, we believe that velocity gradient can be neglected for thermal field calculation inside the chill wheel and melt puddle. Namely, metal melts have very low Prandtl number and consequently thermal boundary layer much thicker than velocity boundary layer.[7] Ribbon thickness is also found to be proportional to circumferential velocity of the chill wheel (u_w^{-1}) and the pressure in the crucible ($p^{0,5}$), as predicted by continuity and Bernoulli equations.[1] Next assumption is that temperature of the melt in the puddle direct under the impinging jet stays equal to casting temperature, because strong turbulences in that region.

The equation for local heat transfer coefficient $\alpha(x)$ calculation, included in the numerical scheme is:

Results and discussion

Figure 2 represents calculated cooling curves in Al ribbon and heating curves for Cu wheel surface, considering different modes of contact resistance: ideal contact, variable contact resistance (*α(x) = integral method*) and constant contact resistance through entire contact time/length ($\alpha(x) = 10^6 \mathrm{W/(m^2 \cdot K)}$). Value for constant average heat transfer coefficient for aluminum was obtained with subsequent microstructure analyses and reported by other authors.[8]

By applying different modes of contact resistance, calculations revealed that cooling and heating rates of the ribbon and the wheel diverse considerably. Calculated cooling and heating rate is relatively much slower when some contact resistance is considered. Although the contact resistance value is very low ($\approx 10^{-6} \mathrm{(m^2 \cdot K)/W}$), it should not be neglected.

$$\alpha(x) = \alpha(R, \varphi_j) = \lambda \frac{\partial \theta}{\partial y}\Big|_{y=0} = \frac{3 \cdot \lambda}{2\delta_t} = \frac{3 \cdot \lambda}{2 \cdot \sqrt{8}} \cdot \sqrt{\frac{u_w}{a \cdot x}} \tag{3}$$

u_w	circumferential velocity of the wheel [m/s]
λ	thermal conductivity of the casting material (temperature dependant) [W/(m · K)]
δ	thermal boundary layer thickness [m]
a	thermal diffusivity [m²/s]
x	distance from the initial contact point to the actual calculation point [m]

Integral method calculation of the heat transfer coefficient gives the most logical results for entire duration of the contact. Calculated solidification time is practically the same to those obtained by overall (constant) heat transfer coefficient, but final temperature of the ribbon at the detachment point is much greater, especially for longer contact time. Constant contact resistance approximation (10^{-6}($m^2 \cdot K$)/W) for longer contact time predicts even lower ribbon temperature then ideal contact calculation, which is physical unlikely. Irrespective of contact resistance approximation, the wheel surface temperature after reaching its maximum decrease, although it is in contact with hotter ribbon. By considering the wheel as a whole, its enthalpy is constantly rising, since temperature more than 0.3 mm under the surface, is increasing the entire contact time (Figure 4 a). Namely, conduction heat transfer rate in the wheel is faster than the heat transfer rate across ribbon/wheel interface and through solidified ribbon.

When thicker ribbons are cast or materials with lower thermal conductivity, thermal resistance in already solidified region of the ribbon becomes the limiting factor of the heat transfer. High cooling and solidifying rates, through entire cross section of the ribbon, especially on its free surface, can be achieved only when very thin (<30 μm) ribbons are cast (Figure 3).

We also analyzed influence of the wheel material on the solidification characteristics. Figure 4 shows calculated temperature profiles in steel or copper wheel, when aluminum melt is cast. As we can see, surface temperature will increase significantly, especially for a wheel of low thermal diffusivity. Because short duration of the contact (<1 ms) and limited thermal diffusion in the wheel, the energy can penetrate only a short distance in the wheel, which results in a higher temperature at the wheel surface. The magnitude of temperature increase depends on the wheel material. For steel wheel, which has much lower thermal diffusivity than copper, an increase of surface temperature is over 400 °C, and heat penetration depth about 0.5 mm. On contrary, copper wheel surface temperature increase is about 200 °C and penetration depth twice as much. When materials with higher melting point are cast, surface temperature will increase much higher. Obviously, such a large deviation in surface temperature should not be neglected in calculation of cooling and solidification rate of the melt. Importance of wheel material selection is evident. Pure deoxidized copper has the highest thermal diffusivity between all commercially useful materials and therefore is the best choice for the wheel material.

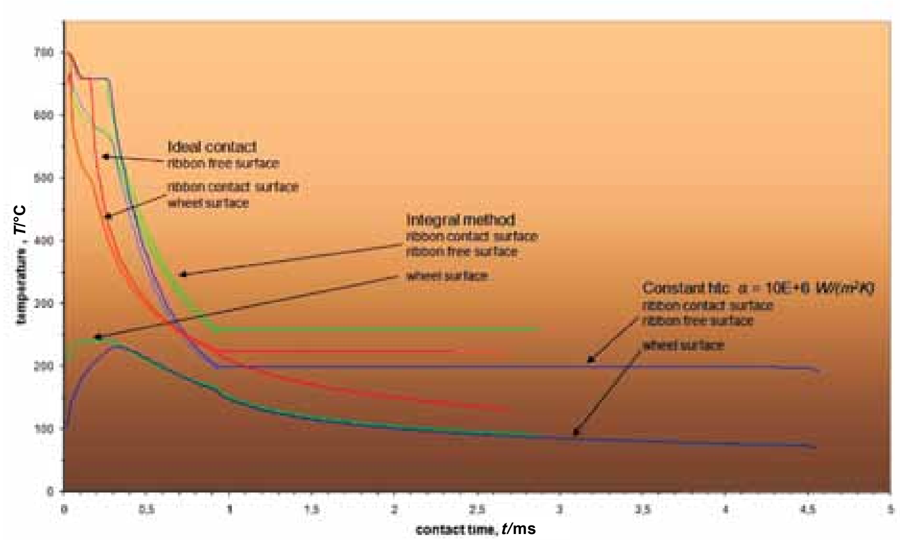

Figure 2. Cooling curves of free and contact surface of Al ribbon and contact surface of the Cu wheel as a function of different contact resistance. (u_w = 18.9 m/s, ribbon thickness 66 μm, contact time 0.923 ms)

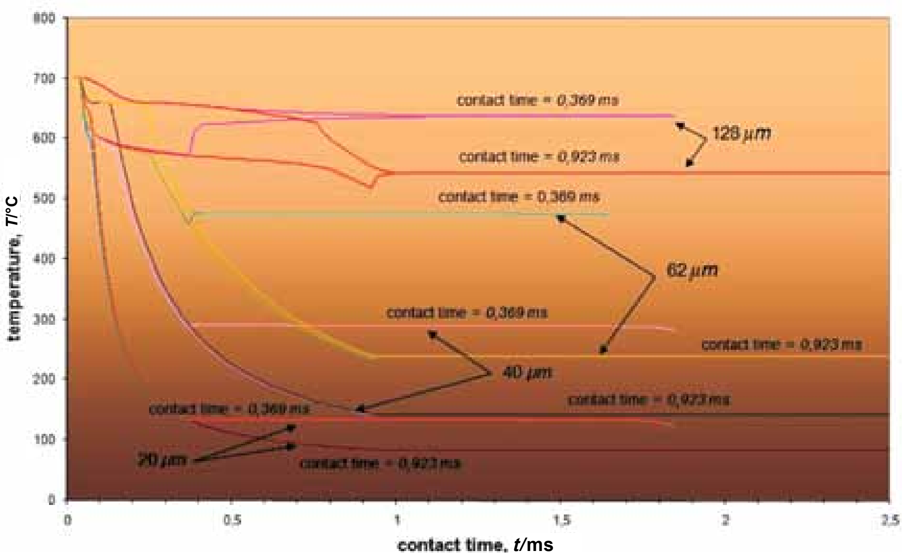

Figure 3. Cooling curves of contact and free surface of the Al ribbon as a function of its thickness and contact time (u_w = 18.9 m/s, $\alpha(x)$ = integral method)

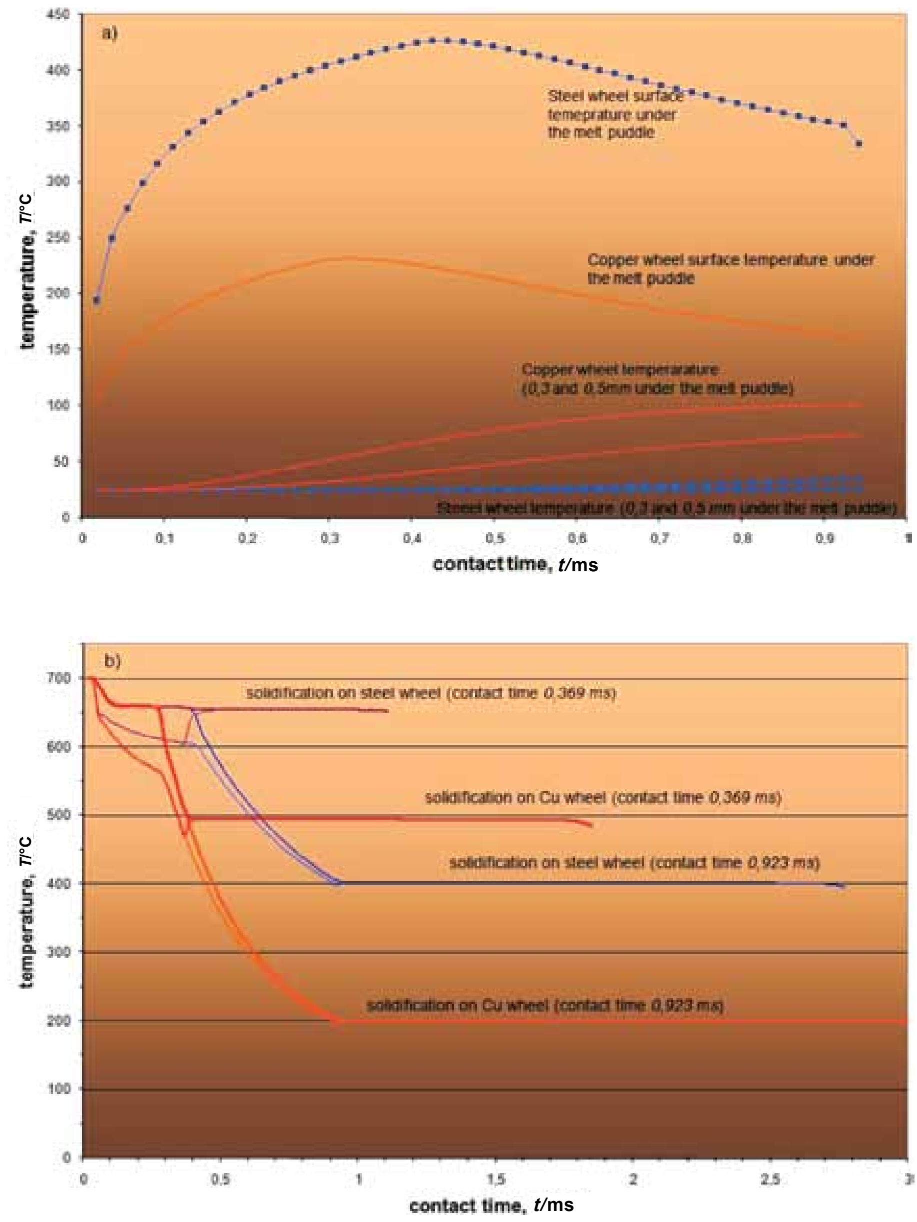

Figure 4. a) Steel and copper wheel temperature increase as a function of contact time
b) Cooling curves of Al ribbon as a function of wheel material and contact time (u_w = 18.9 m/s, ribbon thickness 66 μm, contact time 0.923 ms, $\alpha = 10^6$ W/(m$^2 \cdot$ K))

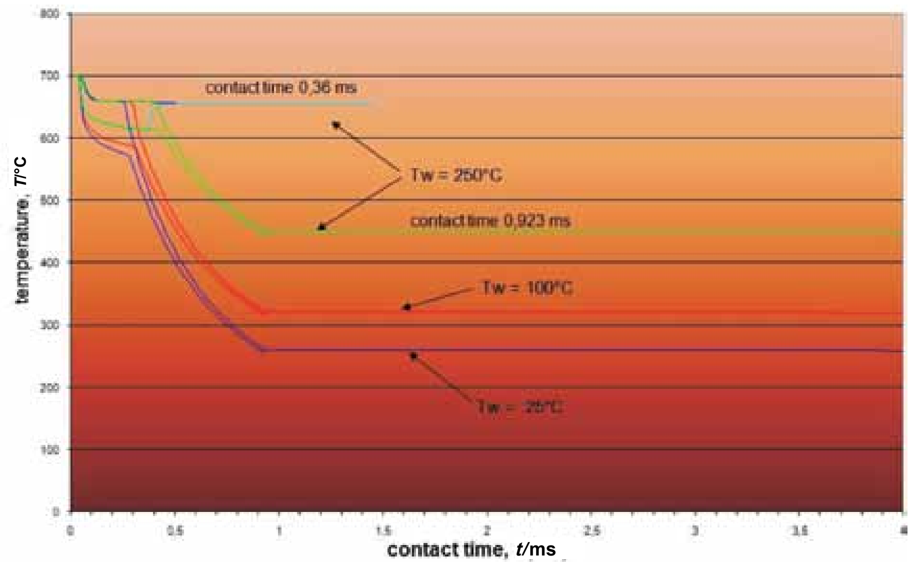

Figure 5. Cooling curves for 66 μm thick Al ribbon as a function of initial wheel temperature and contact time (u_w = 18.9 m/s, $\alpha(x)$ = integral method)

During continuous casting process, the wheel is not subjected only to heat transfer from the solidifying material, but also to radiation and convection heat transfer from the crucible. In that case, significant "long term" surface temperature increase may take place, if the wheel in not externally or internally cooled. In calculations discussed above, we have assumed that the wheel surface is at room temperature at the beginning of the contact. For first ten to hundred revolutions surface temperature increase may indeed not be insignificant, but when continuous casting is performed, especially when materials with high melting point are cast, surface temperature of the wheel can increase in such an extent, that formation of the ribbon will be disturbed, because of decreased cooling and solidifying rate in the melt puddle. Figure 5 shows the effect of the initial wheel temperature on calculated temperature profiles in the Al ribbon. . As we can see, initial wheel temperature has substantial influence on ribbon cooling rate especially if the contact time is short (high wheel speed).

For the purpose of the continuous casting, we calculated temperature profiles in inner water cooled wheel (R_w = 0.2 m) as a function of casing thickness. From the outside, wheel is convectively cooled with surrounding atmosphere, because its rotation, and from the inside with water stream. For simplicity of the mathematical model, convective heat transfer coefficients are taken as constants (α_{water} = 5000 W/(m^2 · K) and α_{air} = 50 W/(m^2 · K)) and represent average values, calculated from forced convection correlation equations. No radiation from the crucible is taking into account. To ascertain influence of external cooling, we also make an assumption of exaggerated value for convective heat transfer coefficient (α_{air} = 1000 W/(m^2 · K)). The calculated surface temperatures for 10 mm thick wheel casing are shown in Figure 6. Each saw tooth spike corresponds to the temperature of the wheel surface being underneath the puddle. As we can see, internally water cooled wheel will reach the periodic steady state after few revolutions. But still, surface temperature can increase significantly when iron is cast (>200 °C), although we assume exaggerated value (α_{air} = 1000 W/(m^2 · K)) for convective heat transfer coefficient. Namely, duration of one revolution of the wheel is so short that external gas convective cooling would have no significant influence on the wheel surface temperature. Conducting of heat into the wheel and cooling of the inner casing surface with water stream is much faster than external convective cooling with surrounding atmosphere.

If we reduce wheel casing thickness up to 2 mm, internal water cooling will be more effective, and wheel surface temperature that melt will effectively "see" at the beginning of the next pass of the wheel under the puddle, will be practically the same as at the first revolution, even if high melting temperature materials are cast (Figure 7).

But if we reduce wheel casing even further, beneath the heat penetration depth under the melt puddle, convective heat resistance on the inner side (wheel – water interface) becomes significant. Even if we assume heat transfer coefficient value on inner side of a casing as high as 100 000 W/(m^2 · K), which can be reached with high pressure impingement water jets,[9] heat removal from the melt will be slower as in the case of full or internally water cooled wheel with 10 mm thick casing (Figure 8). Reducing the thickness of the wheel casing is unsuitable, from rapid solidification and from steadiness point of view.[10]

CONCLUSIONS

An improved FDM method with variable heat transfer coefficient was used to calculate the heat balance of free jet melt-spinning process.

The mathematical model developed, includes the effect of the conduction heat transfer within the chilling wheel and allows us to investigate the influence of heat contact resistance between the melt and the chill wheel, wheel material, and inner wheel cooling. The fact that the wheel surface temperature is increasing significantly under the solidification melt puddle, selection of the wheel material is important. Because copper has the highest thermal diffusivity between all commercially

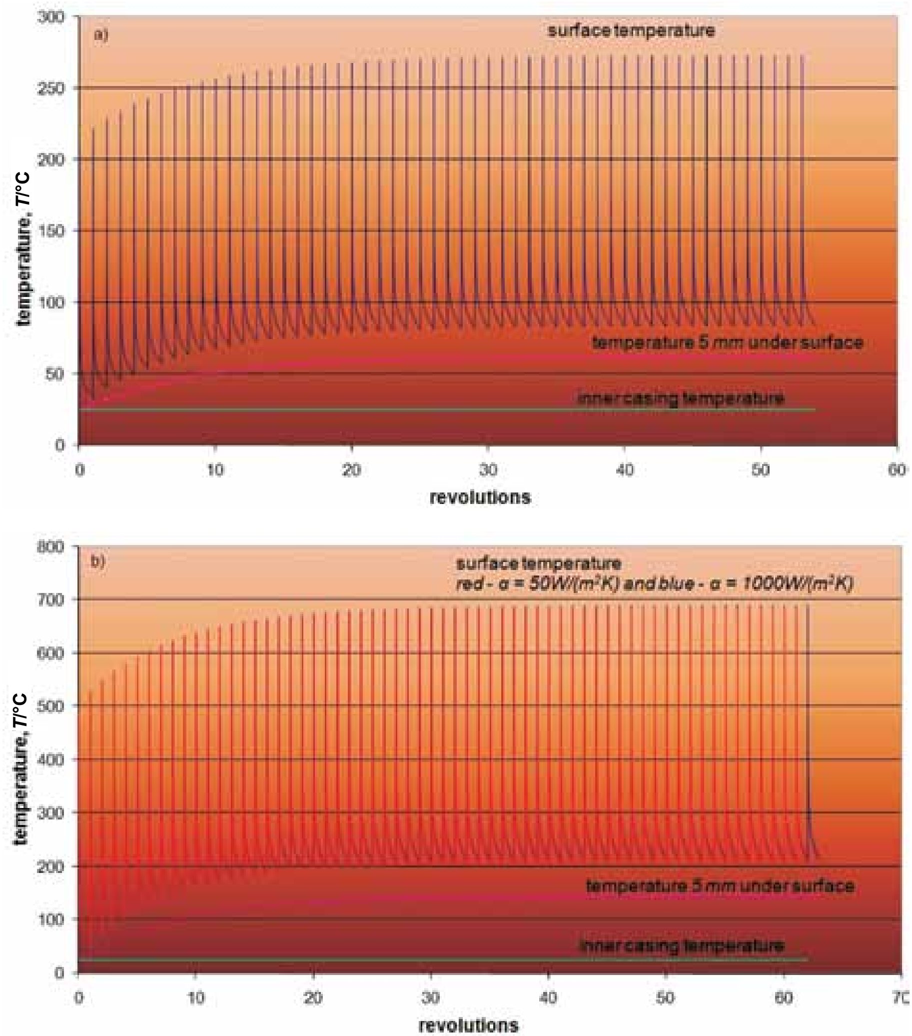

Figure 6. Surface temperature of the internally water cooled wheel with casing thickness 10 mm and wheel radius 0.2 m a) aluminum casting; b) iron casting (u_w = 18.9 m/s, α_{water} = 5000 W/(m^2 · K) and α_{air} = 50W/(m^2 · K) and (α_{air} = 1000 W/(m^2 · K))

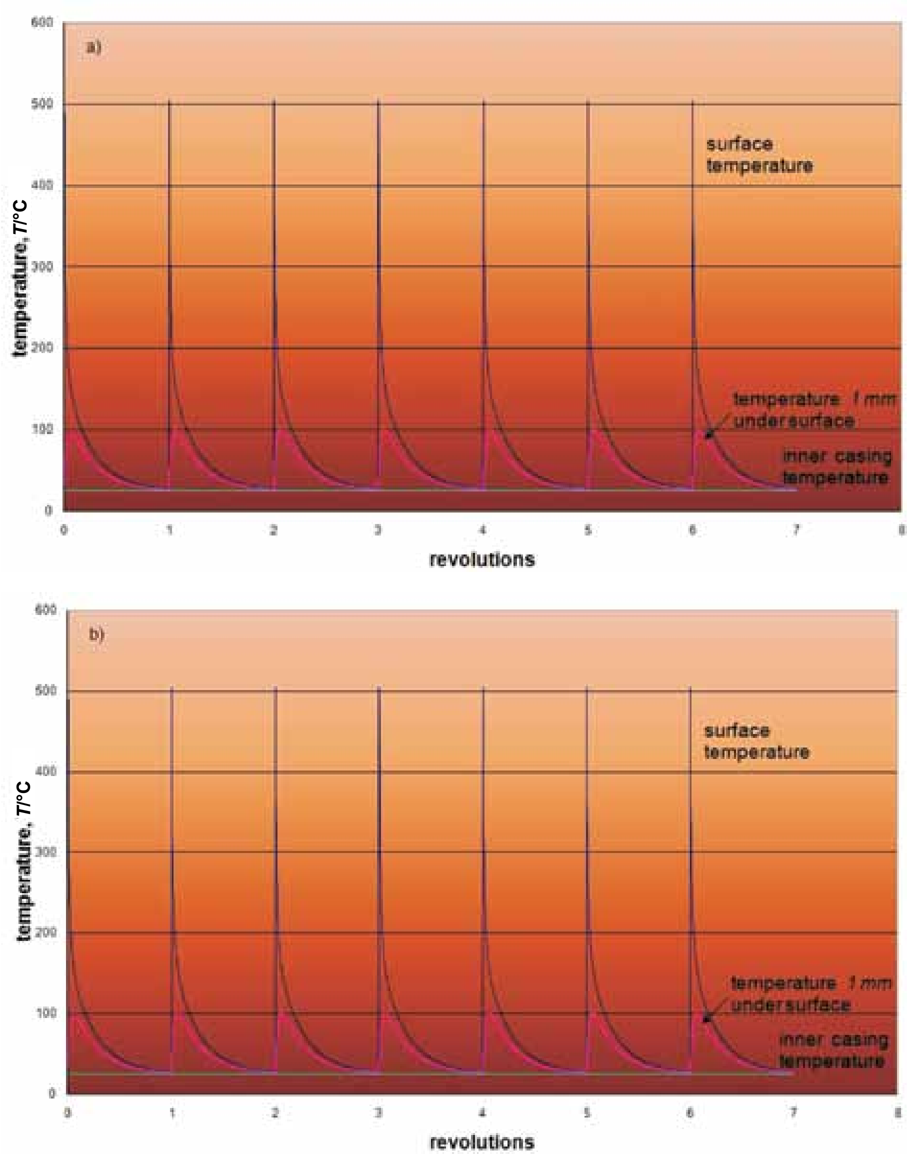

Figure 7. Surface temperature of the internally water cooled wheel with casing thickness 2 mm and wheel radius 0.2 m a) aluminum casting b) iron casting (u_w = 18.9 m/s, α_{water} = 5000W/($m^2 \cdot K$) and α_{air} = 50 W/($m^2 \cdot K$))

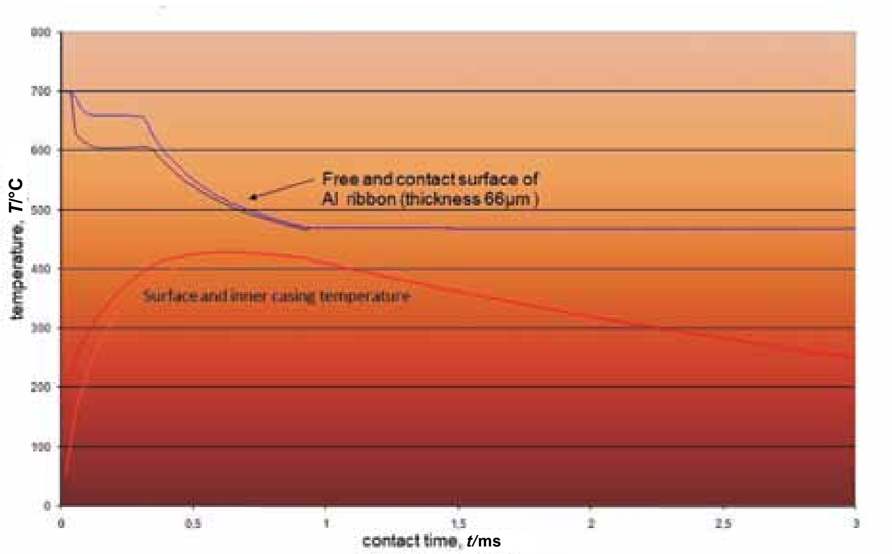

Figure 8. Internally cooled copper wheel surface temperature increase as a function of contact time and thickness of wheel casing for aluminum casting. (R_w = 0.2 m, u_w = 18.9 m/s, ribbon thickness 66 µm, contact time 0.923 ms, htc on wheel-water side 100 000 W/(m^2 · K))

useful materials, we propose deoxidized copper for a wheel material.

For continuous casting internally cooled wheel is preferable, but only in the case when wheel casing thickness is correctly selected. When too thick casing is applied, water cooling will not have adequate influence on wheel surface temperature increase. When the casing of the wheel is too thin, thermal resistance on the cooling side (wheel-water interface) becomes the limiting factor, which reduces the heat transfer from the melt and consequently its cooling and solidifying rate.

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Mapping of sub-surface fracture systems using integrated electrical resistivity profiling and VLF-EM methods: a case study of suspected gold mineralization

Kartiranje podpovršinskih sistemov razpok z integriracijo električnega upornostnega profiliranja ter VLF-EM-metode: primer domnevnega orudenja z zlatom

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Abstract: This study highlights the application of horizontal electrical resistivity profiling (HRP) and Very Low Frequency Electromagnetic (VLF-EM) methods as mapping tools for detection of subsurface structural features in respect of gold mineralization prospects located at the outskirt of New-Bussa, Niger State. Nigeria. The overall intent is to map and delineate the possible structural controls on gold mineralization in the study area. In total seven (7) EM-profile lines and three (3) HRP-profile lines were established, while data processing of the VLF-EM results involved Fraser and Karous-Hjelt filtering followed by 2D inversion.

Interpretation HRP data and quantitative evaluation of VLF-EM data revealed a number of subsurface zones with high real component current density which define the potential subsurface structural features (as fracture zones) with possible gold mineralization. In addition, correlation and extrapolation of the anomalous low resistivity zones with high current density zones revealed fracture systems trending roughly N–S at a strike range of 350° to 005°. These zones are interpreted as the potential or inferred structurally controlled fracture zones with possible gold mineralization worthy of follow-up geochemical exploration studies.

Original scientific paper

Izvleček: Raziskali smo možnost uporabe horizontalnega električnega upornostnega profiliranja (HRP) in zelo nizkofrekvenčne elektromagntne metode (VLF-EM) kot orodja za kartiranje podpovršinskih struktur za odkrivanje mineralizacije z zlatom na obrobju New-Bussa, Niger, Nigerija. Namen naloge je na raziskovanem območju kartirati in izdvojiti možne strukture, orudene z zlatom. Meritve smo opravili v sedmih (7) EM in treh (3) HRP-profilih ter VLF-EM podatke obdelali z Fraserjevim ter Karous-Hjeltovim filtriranjem, ki mu je sledila 2D-inverzija.

Interpretacija HRP podatkov in kvantitativno vrednotenje VLF-EM podatkov sta pokazala številne podpovršinske cone z visoko realno komponento gostote toka, s katerimi definiramo potencialne podpovršinske strukturne oblike (npr. razpoklinske cone) z možno mineralizacijo z zlatom. Korelacija in ekstrapolacija anomalnih nizkoupornostnih con s conami z visoko gostoto toka kaže na sistem razpok, usmerjenih približno S–J, z razponom smeri od 350° do 005°. Ta območja smo interpretirali kot strukturno kontrolirane cone razpok z možnim orudenjem z zlatom, ki bi jih bilo smiselno raziskati tudi geokemično.

Key words: VLF-EM-method, electrical resistivity profiling method, 2-D VLF inversion, apparent resistivity, current density, fracture mapping

Ključne besede: metoda VLF-EM, metoda električnega upornostnega profiliranja; 2D VLF-inverzija; navidezna upornost, gostota toka, kartiranje razpok

INTRODUCTION

In the recent past, integrated geophysical investigations have found useful and increasing applications in many geological studies ranging from shallow engineering studies, groundwater and mineral deposits explorations as well as in a variety of geo-environmental studies like investigations of contaminated sites or waste disposal areas (OLORUNFEMI & MESIDA, 1987; SHARMA, 1997; FROHLICH & PARKE,1989; STEEPLES, 2001). High urbanization rate and urgent need for natural resources on one hand and non-invasive character of the geophysical methods such as geoelectrics, electromagnetic methods, very low frequency (VLF), and induced polarization (IP), which can provide information over larger areas, are said to expedite this trend (FROHLICH et al., 1994; Dahlin, 1996; Aristodemu & Thomas-Betts, 2000; Draskovits & Vero, 2005; Gokturkler, et al., 2008). Especially geoelectric and electromagnetic methods are widely and jointly employed in many geological investigations to solve various problems (Bernstone et al. 2000; Karlik & Kaya 2001; Oskooi & Pedersen, 2005).

The electrical resistivity, a commonly used method, is based on the apparent resistivity measurements along the earth surface (Frohlich & Parke, 1989; Sporry, 2004). The measured apparent resistivity represents some kind of averaging of the true resistivities existing between the ground surface and the depth reach of the electrodes configuration (Telford et. al., 1990). For this study, resistivity profiling (Wenner array) was employed which entails apparent resistivity measurements using a fixed electrode array at different locations (stations) along a survey line. The interval between stations is preferably kept constant while the variation of earth resistivity along the profile line is measured with a more or less constant investigation depth. The concept is based on the fact that the variation of resistivity for an inhomogeneous earth is caused by the distortion of current flow lines and with that, of the electric potential field around the potential electrodes. Hence, for a stratified earth, the distortion is systematic, with the consequence that through processing and interpretation the stratification of the earth can be derived from a systematic collection of resistivity data at one location (Milsom, 1989; Sporry, 2004).

The VLF-EM is a well known method for quick mapping of near surface geologic structures most especially in respect of mineral exploration and related geological structures (Saydam, 1981; Ligas & Palmoba, 2006; Babu et al., 2007). In addition, it has been used to high level of success to map weathered basement layer and detection of water – filled fractures or shallow faults. The VLF-EM method is considered as one of the most used among electromagnetic methods and is adequately described by several authors (e.g. Wright, 1988; McNeill & Labson, 1991). The VLF-EM uses radio signals from worldwide network transmitter stations and operates in frequency ranges between 5 kHz and 30 kHz.

The principle of VLF-EM survey is based on the fact that the ratio of the secondary vertical magnetic component to the horizontal primary magnetic field is a measure of conductivity/resistivity contrast since this tipper component is of internal origin of the anomalous body (Chouteau et al., 1996; Gharibi & Pedersen, 1999). To this end an integrated geophysical investigation (Very Low Frequency electromagnetic and electrical resistivity survey) techniques have been employed in this study as mapping tools with the overall objective of geophysical mapping for possible detection of buried subsurface structural features (such as fractures, quartz or pegmatitic veins) in respect of gold mineralization prospects located at the outskirt of New-Bussa, Niger State. Nigeria. The present evidence of gold mineralization is a quatz-pegmetitic vein which is exposed within a farmland grown with groundnuts at a coordinate of about 9° 50’ 32” N & Longitude ≈ 4° 32’ 10” E. Hence, further specific objectives are:

a) to isolate zones within the study area with gold mineralization / enrichment
b) to highlight possible structural features and control (fractures and mineralized veins).

The study is also partly intended to possible structural features (fractures and mineralized veins). The combined geophysical techniques are expected to provide information on the subsurface structural features in respect of gold mineralization potential in the study area and possible further localized geochemical investigation.

STUDY AREA

Location and Accessibility

The study area is located at the outskirt of New Bussa near Kainji with main access via the major road from Mokwa to Wawa, off the Ilorin-Jebba-Mokwa Federal Highway. The study site at the outskirt of New Bussa is linked by an unpaved rural road/foot path about 4 km south of New Bussa Township. Figure 1 is a generalized geological map of Nigeria showing the location of the study area. The study area has a tropical savannah climate with temperature averaging ≈32 °C and up to 40 °C during the peak of the dry season. The climate is characterized by two distinct seasons; hot dry season (mid-October to April) and rainy season (May to mid-October) with average precipitation of about 600–800 mm. The local physiography comprises of relatively flat but undulating topography with valley as low-lying areas. This generally flat relief is characteristic of savannah forest dominated by grasses and shrubs as undergrowths with scattered tress such as shear-butter and locus beans tress.

Geological Setting

Regionally, the study area lies within the Precambrian Basement Complex and located at the northern edge of the

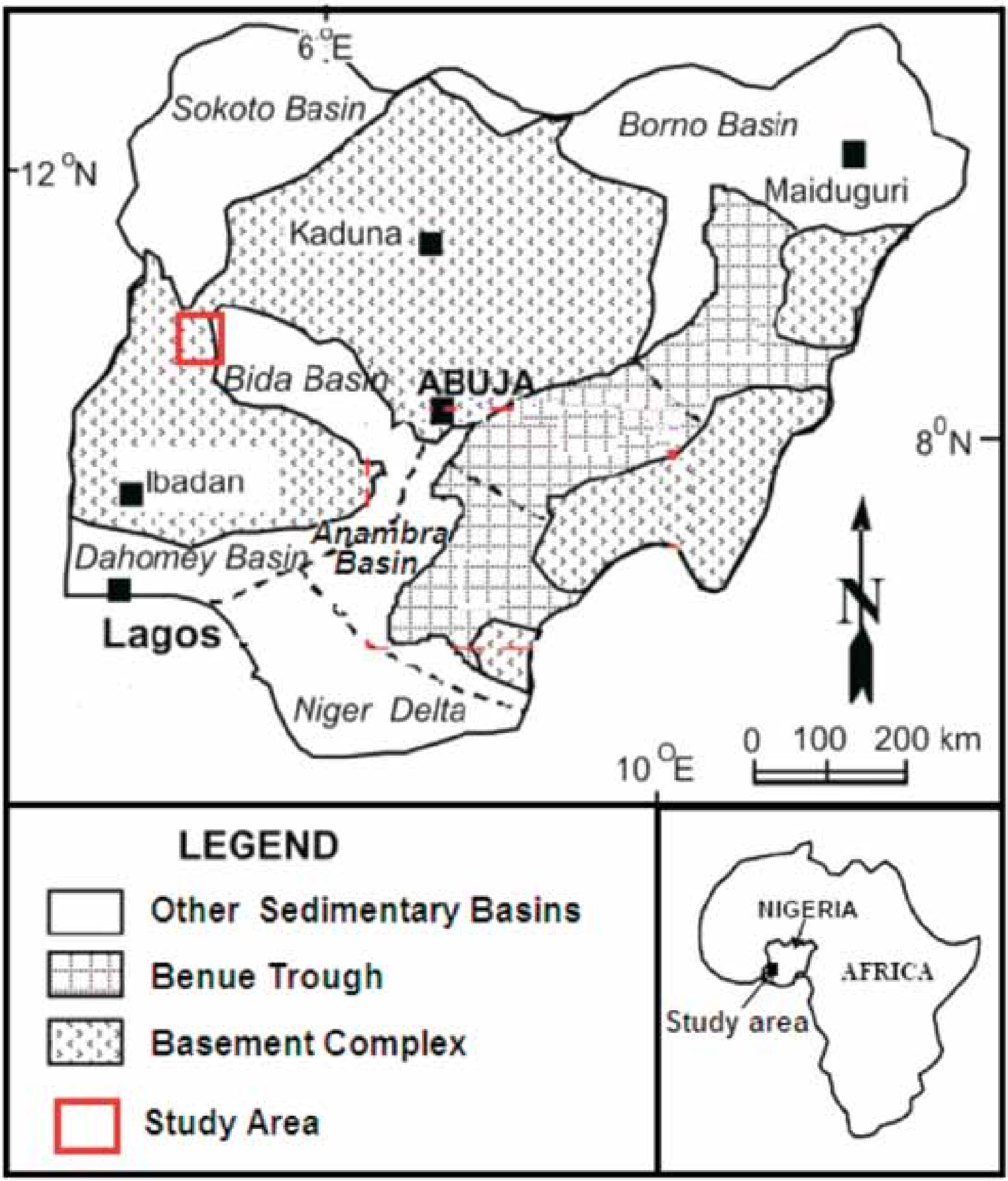

Figure 1. Generalized geological map of Nigeria showing the location of the study area

Basement Complex of South-Western Nigeria. The study area and environs are underlain by crystalline igneous and metamorphic basement rocks, mostly undifferentiated migmatized granite-gneiss, quartzite and quartz-schist complex as well as localized pegmatite and quartz veins intrusions. Various studies have described the geology and characterized the rock units of the Basement Complex setting in South-Western Nigeria (JONES & HOCKEY, 1964; OYAWOYE, 1970; RAHAMAN, 1976; ODEYEMI, 1976 and ODEYEMI, 1981).

Locally, the study area is characterized by Precambrian Basement Complex rocks, mostly the migmatite-gneiss, schist-quartzite complex. Figure 2 highlights the local geological of the study area and environs. In the immediate vicinity of the study area, there are limited outcrops mainly of granite gneisses, schist and amphibolite complex with evidence of shearing and brecciated (cataclastic) zones in places.

Within the study site, gold mineralization veins are exposed in farmland areas at an approximate coordinate of 9° 50' 32" N & ≈ 4° 32' 10" E located about 500–800 m from the main Mokwa-New Bussa-Wawa highway. The geology around the veins consists of mainly gneiss and schist with amphibolite unit as well as pegmatitic intrusion as found within the central part of the study area. The intrusion apparently created an alteration aureole in the pre-existing metamorphosed mafic rock units. The observed main alteration is the growth of porphyroblastic texture in gneisses especially in the western section of the study area.

The general strike of rock foliation and main structural trends is between 350° and 005° azimuth, while the veins trends between 305–315°. This implies that the veins are injected into joints systems that are not conformable to the joints system of the host rock. Veins exposures show a dextral displacement of less than 1 m, while further detailed study may help to expose larger fault/fracture systems in the study area. Furthermore, field observations revealed a couple of shear zones to the south-west portion of the study site and a number of the observed veins composed of highly ferruginized quartz, while the gold occurrence seems to correlate with the degree of ferruginization. The implication of this in terms of exploration is that secondary enrichment may be found in weathered regolith.

Field methods and data collection

Geophysical measurements were carried out during a field camping exercise at Kanji – New Bussa area by late 2008. The field investigation involved application of both Very Low Frequency electromagnetic (VLF-EM) measurements and horizontal resistivity profiling (HRP) for mapping of subsurface conductive zones.

VLF-EM Measurements

Very Low Frequency electromagnetic (VLF-EM) geophysical prospecting method is a passive geophysical method which uses radiation from military navigation radio transmitters operating in the VLF band (15–30 kHz) as the primary EM field to generate signals for various applications (Babu et al., 2007). In this study, VLF-EM method was employed to map the study area with the object of isolating fractured zones which are likely to be enriched with gold mineralization. ABEM Wadi VLF electromagnetic equipment with in-built digital display unit and powered by battery was used. For the VLF-EM measurements, radio signal from stations GBR and GBZ in Rugby UK (52N22, 001W11) were the main signal stations tuned / selected. These correspond to frequency values of 22.6 kHz and 19.6 kHz and are employed to generate the primary electromagnetic field around the buried conductors in order to induce the detected secondary field and measured as a fraction of the primary field by the VLF-meter.

In total 7 E–W trending profiles were occupied with measurement station intervals of 20 m. Each profile is about 1 km long and runs perpendicular to the general N–S geologic strike in the study area. The position of profiles is shown in Figure 3. Central profile-1 runs across the existing/identified gold mineralized fracture zone at the central part of the study area. Other profiles (2–7) run parallel and symmetrical to the central profile-1 with spacing of about 50–100 m. Generally, due to the rural nature of the study area there are no sources of noise such as power lines that might have affected the data quality.

Electrical Resistivity Profiling Measurements

For the electrical resistivity profiling investigation, resistivity of rocks is usually determined in the field using an array of four electrodes where electrodes A and B are used to run the electrical current, I into the ground (current electrodes), while electrode M and N measure the difference ΔV between the potentials at the positions of these elec-

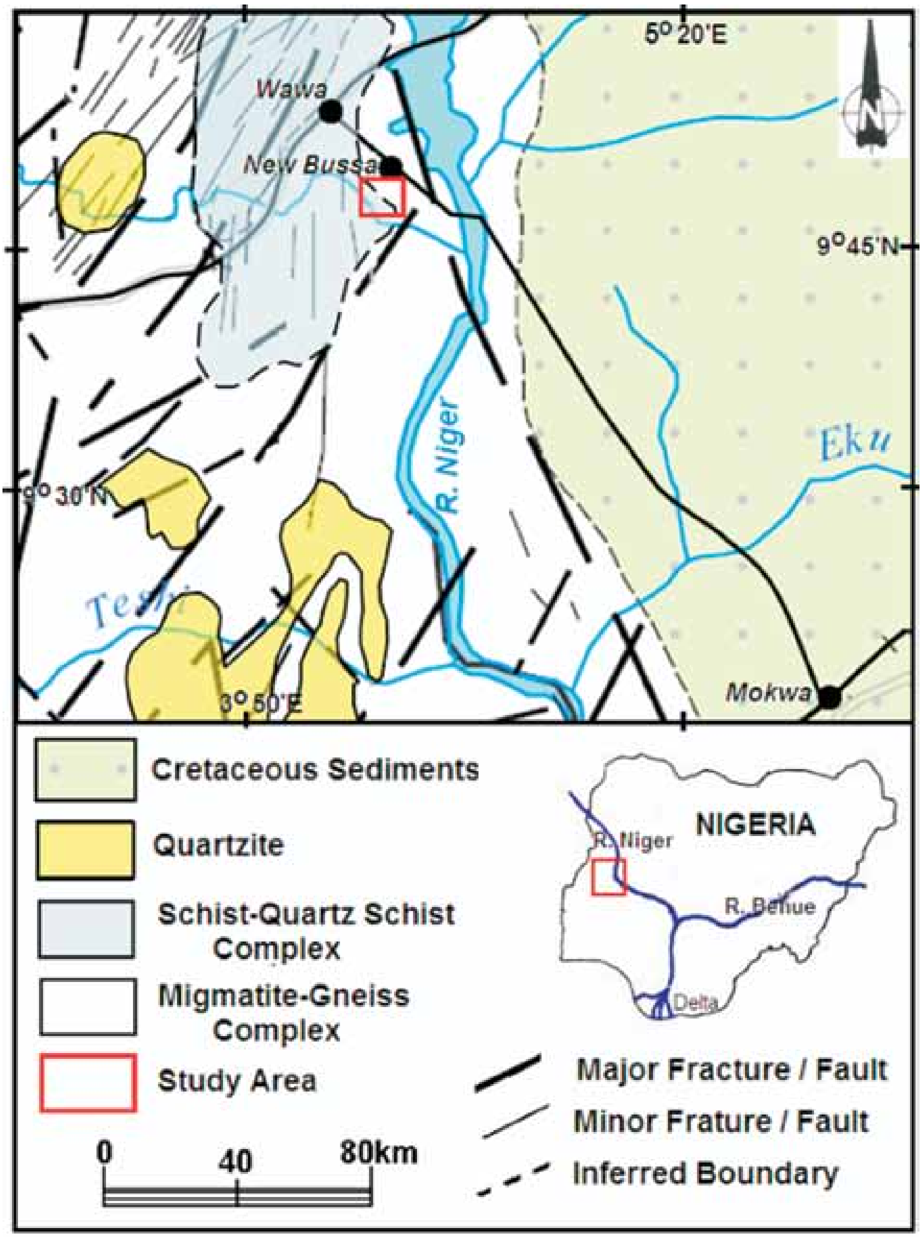

Figure 2. Geological map of the study surrounding neighborhoods of the study Area (Compiled from NGSA Lineament and Geological Map of Nigeria, 2006)

trodes (potential electrodes) (Milsom, 1989). In this study Wenner array was applied using AGI Terrameter model Sting R1 with in-built digital display unit connected to a 12 V battery for adequate energization of subsurface. A constant separation of 15 m was employed with station interval of 15 m, while the profile/traverse lines are about 600–850 m long. In total three (3) HRP-profile lines were established as also indicated in Figure 3, while measurements were taken in approximately E–W profile direction which is more or less perpendicular to the general N–S geologic trend in the study area. Profile 1 coincides with VLF–EM profile 1, i.e. at the center of the field while profiles 2 and 3 are 100 m to the north and south of profile 1 respectively.

Data Processing / Evaluation

Subsequent to field survey measurements, VLF-EM data as well as those of the HRP measurements were subjected to data processing and evaluation as the basis for interpretation.

For the VLF-EM, the acquired field data were processed to simplify the obtained complex information into a profile in which the displayed function is directly related to a physical property of the underlying rock. Thus measured raw real and imaginary components were subjected to Fraser (Fraser, 1969) and Karous-Hjelt (Karous & Hjelt, 1983) filtering operations to suppress noise and enhance signal. The Fraser filter (Fraser, 1969) converts crossover points into peak responses by 90° phase shifting. This process removes direct current bias that reduces the random noise between consecutive stations resulting from very low frequency component of sharp irregular responses (Al-Tarazi et al., 2008).

The filtered profile data were then subjected to 2D inversion operation. The 2D inversion involved joint inversion of the real and imaginary components of the tipper based on a forward solution using the finite-element method. Pilot resistivity survey and geologic field investigation of the area of study supplied the priori information for the subsurface model with RMS misfit of 0.7 obtained after 16 iterations. Subsequently, the obtained current density information was used to isolate regions having contrasting conductivity value when compared to the host rock that could be interpreted in terms of fractures within the basement rocks. The Karous-Hjelt filter (Karous & Hjelt, 1983) uses the linear fit theory to solve the integral equation for the current density. This forms the basis of the overall interpretation and delineation of potential fracture zone and or mineralized zones.

For the HRP, the resistivity is calculated from the relationship below where K is termed the Geometrical Factor, dependent on the type of electrode array:

$$\rho_a = K \cdot \Delta V/I \quad (1)$$

Because the earth is not homogeneous and isotropic, the measured resistivity is generally addressed as apparent resistivity ρ_a (ROY & APPARAO, 1971; KELLER & FRISCHKNECHT, 1966). Hence, direct interpretation of the apparent resistivity values with respect to the inter-electrode spacing (a) was employed for quantitative interpretation of the HRP results.

RESULTS AND INTERPRETATION

VLF-EM Surveys

As highlighted earlier, the acquired field data were processed to simplify the obtained complex information. The representative results of the Fraser model filtered data plots as well as Karous-Hjelt filter 2-D inversion current density plots for Profiles 1, 5 and 6 are presented in Figures 4 to 6. The 2-D inversion shows the variation of apparent current density, and change in conductivity with depth. With such apparent current density cross-section plots, it is possible to qualitatively discriminate between conductive and resistive structures where a high positive value corresponds to conductive subsurface structure and low negative values are related to resistive one (BENSON et al., 1997; SHARMA & BARANWAL, 2005).

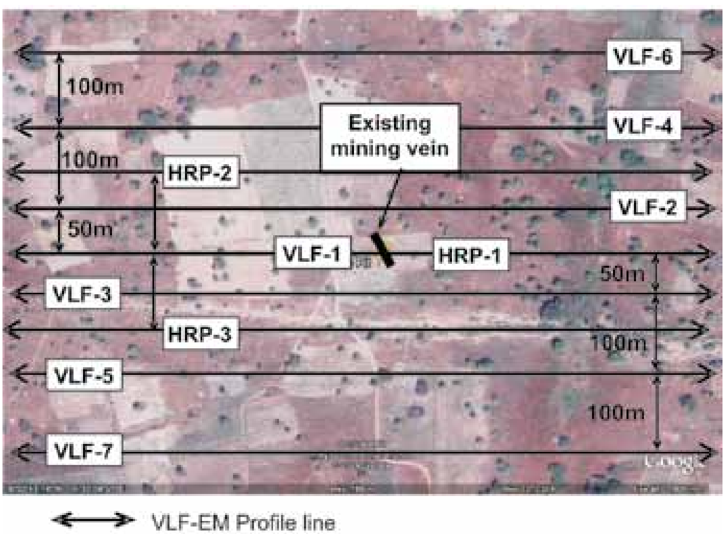

Figure 3. Lay-out of the field measurements for VLF-EM and HRP operation

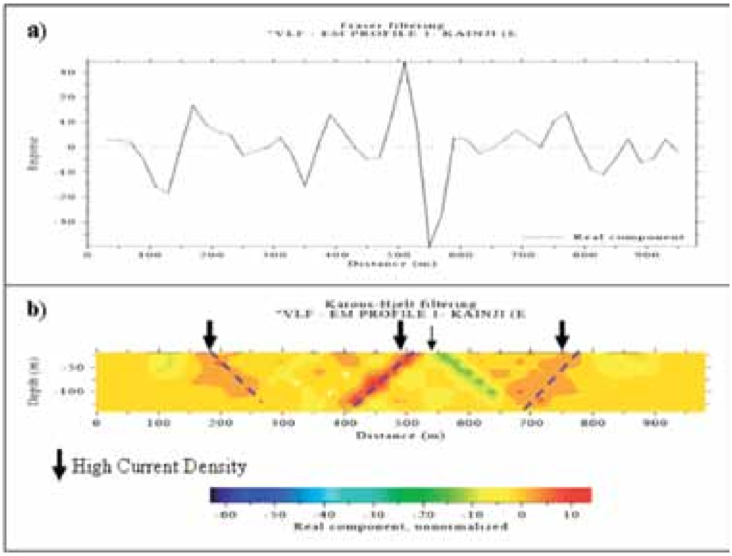

Figure 4. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM Profile – 1

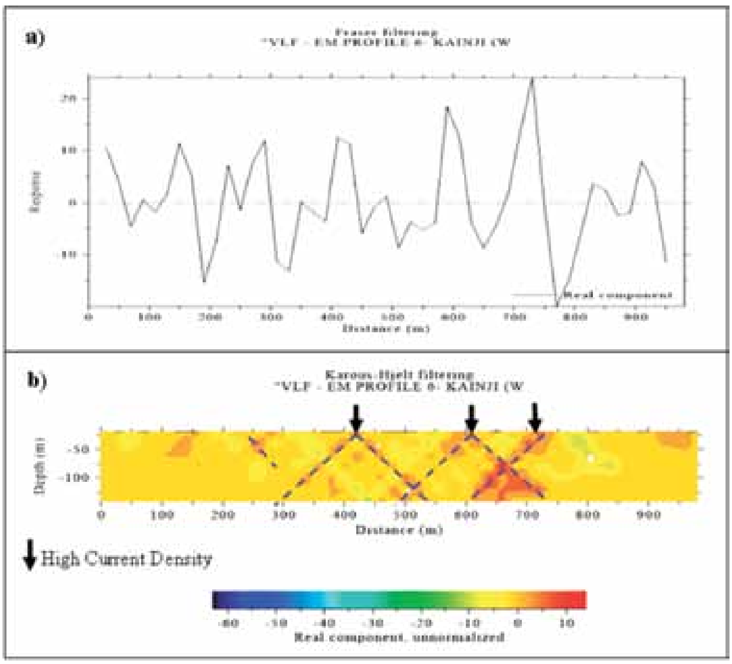

Figure 5. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM Profile – 6

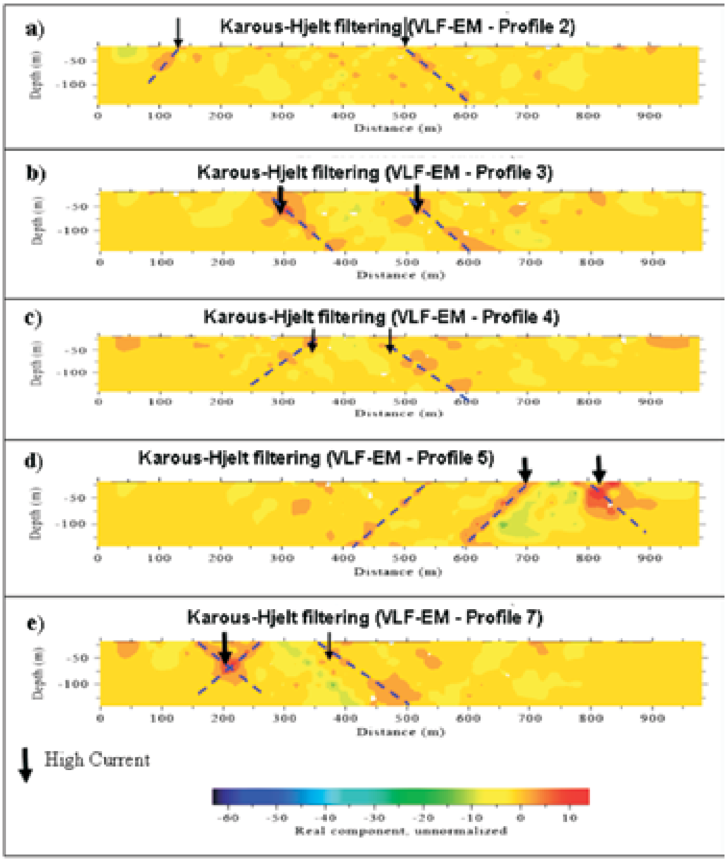

Figure 6. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM profiles 2, 3, 4, 5 and 7.

The apparent current density cross-section of profile 1 (Figure 4) reveals the presence of a major anomaly at the central section of the profile (at about 500 m). Qualitatively it is hard sometimes to discriminate between deep and shallow sources, partly due to possible influence of water saturation (NOBES, 1996; SHARMA & BARANWAL, 2005). However, this anomaly coincided with the existing mineralized vein in the study area. Furthermore, two high current density zones at about 200 m and 750 m along the profile (Figure 4) can also be inferred as indications of the potential subsurface fracture systems and/or mineralized zones. In addition, the Fraser filtered data plots and the Karous-Hjelt current density plot for profile 6 as presented in Figure 5 revealed a number of anomalies which reflect conductive subsurface structural trends of inferred fractures and/or mineralized zones. These together with other high current density zones as outline in Figure 6 represent apparently fractured and jointed quartz fillings associated with gold mineralization. However, an incline vein, dipping to the right at 540 m of VLF profile 1, having negative real component value of about –10 to –20 (zone marked X) represents fracture/vein apparently filled with unsaturated materials such as massive non-fractured quartz veins. This type of zone as also evident along profiles 2, 5 and 6 are, unlike the mineralized zones, usually associated with massive barren quartz veins with no gold mineralization. Similarly, 2D current density cross-section plots of VLF-EM profiles 2, 3, 4, 5 and 7 showing inferred fracture and / potential mineralized zones are presented in Figures 6 a, b, c, d and e respectively.

These apparent current density cross-sections disclose a number of anomalies with structural disposition at depths that can be attributed to subsurface structural features which may be mineralized. Although the exploration depth in the study area is expected to be about 50 m, the representative apparent current cross-sections of profiles 3, 4, 5 and 7 (Figure 6) exhibited conductive anomalies at much greater depths. This can be attributed to a combination effect of fracture systems with or without mineralization but saturated with groundwater systems at depths. In other words, the development of conductive zones of high apparent current with positive values reflects inferred subsurface structural fractures and/or mineralized zones.

Horizontal Resistivity Profiling (HRP) Surveys

As pointed out earlier, Wenner electrode configuration with constant electrode separation of a = 15 m and interstation distance of 15 m was adopted for effective lateral coverage of the subsurface in the study area. HRP profile 1 coincides with VLF–EM profile 1, i.e. at the center of the survey area while HRP profiles 2 and 3 are 100 m to the north and south of profile 1 respectively. The field data for the HRP surveys were presented in form of profile plots as presented in Figures 7, 8 and 9 below, indicating the apparent ground resistivity trends against distance along W–E direction.

As shown in HRP profile 1 (Figure 7), the two closely spaced existing mineralized veins exhibited apparent resistivity low of about 110 Ω m. The additional two low resistivity zones around 200 m and 700 m are consistent with the high current density zones at about 200 m and 750 m along the VLF-EM profile 1 (see Figure 4). These can also be inferred as indications of the potential subsurface fracture systems and/or mineralized zones.

Therefore, baring minor discrepancies in the data which could be due to irregularity in surface topography as well as non-linearity of the profile lines, resistivity values of less than 110 Ω m may be inferred as threshold value indicative of areas with similar electrical resistivity properties as the known mineralized vein. Hence such identified low resistivity zones as also highlighted in Figures 8 and 9 for HRP 2 and 3 respectively could be taken as potential zones for further ground-truthing in form of reconnaissance pitting and geochemical survey / sampling.

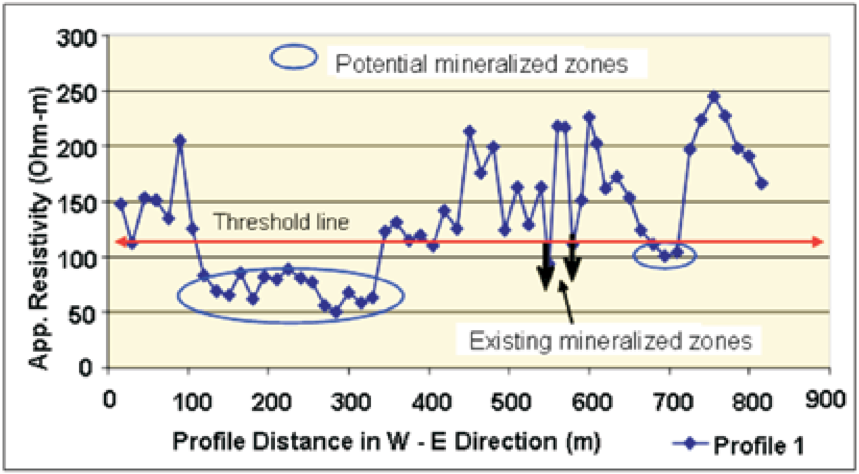

Figure 7. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 1

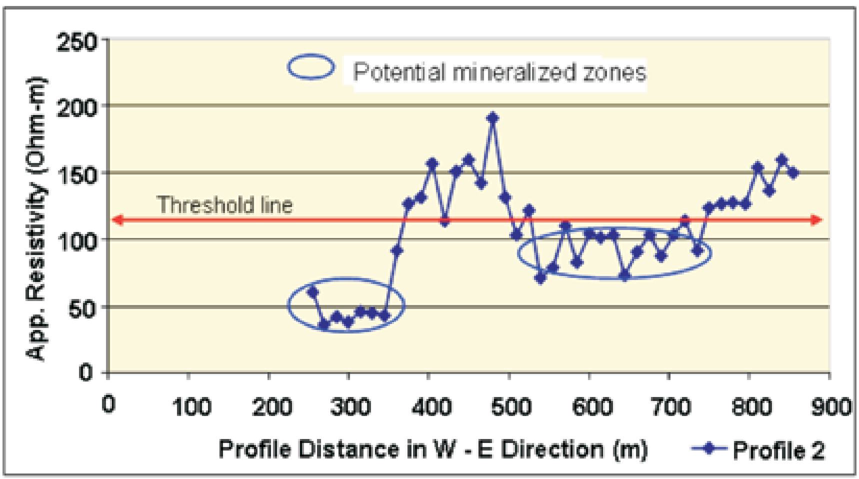

Figure 8. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 2

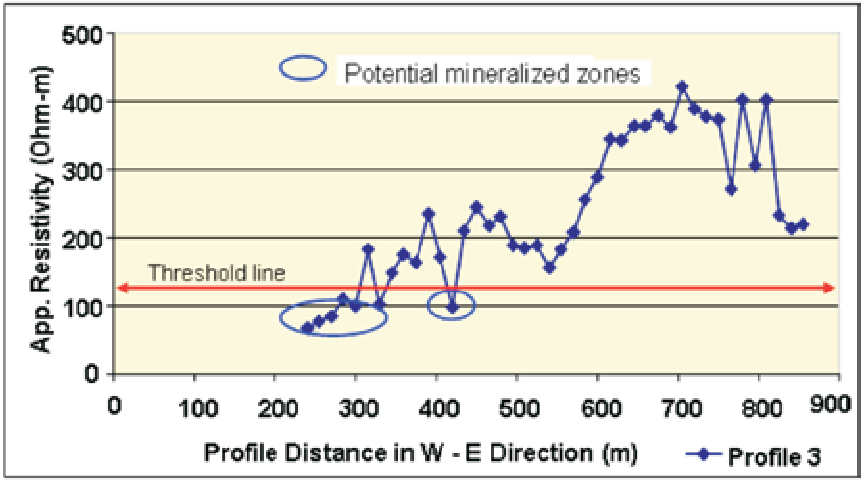

Figure 9. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 3

Synthesis and conclusion

This study presents the results of the combined application of VLF-EM and electrical resistivity profiling HRP methods in highlighting the distribution of subsurface structural lineaments. Based on the VLF-EM data plots, Profile 1 filtered result as shown in Figure 4 shows major fracture patterns at the center of the profile about 500 m midway along the profile. As indicated the two identified fractured zones coincide with the known mineralized zones where there are active illegal mining activities as at the time of this study. The fracture on the left (about 500 m) was determined from the plot to be about 18 m in diameter, about 120 m in length and dipping at about 35°. Therefore, the results of EM profile-1 are in good agreement with field observation.

Similarly, EM-VLF profile 6 as presented in Figure 5 as well as profiles 2, 3, 4, 5 and 7 presented in Figure 6 display areas with isolated and high current density values; similar to region with gold mineralization enrichment in profile-1. For example, EM-profile 6 in particular displays structural controlled zones of high conductivity at about 400 m, 600 m and 700 m along the profile. Likewise, profiles 3, 5 and 7 (see Figure 6) display similar zones with high conductivity. The values of current density in all these cases are in excess of 8 which could have been due to the high conductivity of infill material within the fracture zones, suspected to be similar to that established in EM-profile 1.

Qualitative interpretation of VLF-EM profiles using different linear filtering such as Fraser and Karous–Hjelt filters (Figures 4 to 6) show a number of subsurface low resistivity zones in the study area, most of which are reflected as subsurface image of narrow linear features on the apparent current density cross-sections. The disposition of these linear features revealed two sets of fractures systems with dips of about 30–40°; one dipping to the west and other dipping to the east with general strike direction of N–S at about 350° and 005°. This result demonstrates the consistency between qualitative and quantitative interpretation; in terms of relative disposition of the discrete conductors, frequency and influence of different anomalies size and depth as also observed by Al-Tarazi, et al., (2008).

As part of further evaluation and synthesis, the results of the HRP-1 indicate some regions with isolated low resistivity that are indicative of fractured zones which are likely filled with conductive deposit. HRP profile 1 (Figure 7) shows anomalous resistivity sink around 500 m; center of profile 1. This is in agreement with the VLF-EM profile-1 results as well as field observation. In addition a synthesis of the EM-VLF and HRP results for profile 1 as presented in Figure 10 revealed coincidental zones of high current density and low resistivity as potentials fracture/mineralized zones. This is also a clear indication of the usefulness and complementary nature of the integrated EM and resistivity studies employed in this study.

Similarly, a synthesis of the HRP results as presented in Figure 11 shows the combined plots of the three HRP profiles with identified inferred fracture zones. A rough extrapolation and correlation of the anomalous resistivity drops revealed potential fracture systems trending roughly in N–S direction at a strike of about 320° to 350° which is consistent with the general structural trends of fracture systems in the study area. Consequently, these zone defines the potential fracture zones worthy of further investigation as to the possibility of mineralization or otherwise within the fracture systems.

On the final analyses integrating and synthesizing the results of all the EM-VLF and HRP profiles together, a number of isolated potential fracture zones, with high current density, as interpreted from both EM and resistivity surveys were identified as highlighted in Figure 12. As shown in Figure 12, it is possible to order and link the distribution of the potential fracture zones together resulting in a more or less N–S trends. This is consistent with the trends observed for the HRP profiles as presented in Figure 11.

In terms of possible gold mineralization potential, it can be concluded that zones with high current density identified on the VLF-EM profiles as well as regions of low resistivity as identified on the HRP profiles are potentially structurally controlled fracture zones that are likely to be mineralized with gold or related mineral deposits. Therefore, a follow-up geochemical exploration involving pitting and sampling at those zones as well as geochemical analyses can be recommended as parts of the next phase of the exploration strategy for gold mineralization enrichment in the study area. Such follow-up geochemical study will be required to understand the grade of the mineralization of the suspected fracture zones and the possible geochemical control. This will serves as basis for estimation of possible cut-off grade.

Furthermore, the presence of cross joints within suspected shear zones around the south-west portion of the study area (Figure 12), should be examined further to ascertain their positions more accurately and their potential for hosting mineralization. This may however, warrants additional geophysical investigation specifically targeted at determination of the geometrical parameters and disposition of the mineralized fracture zones.

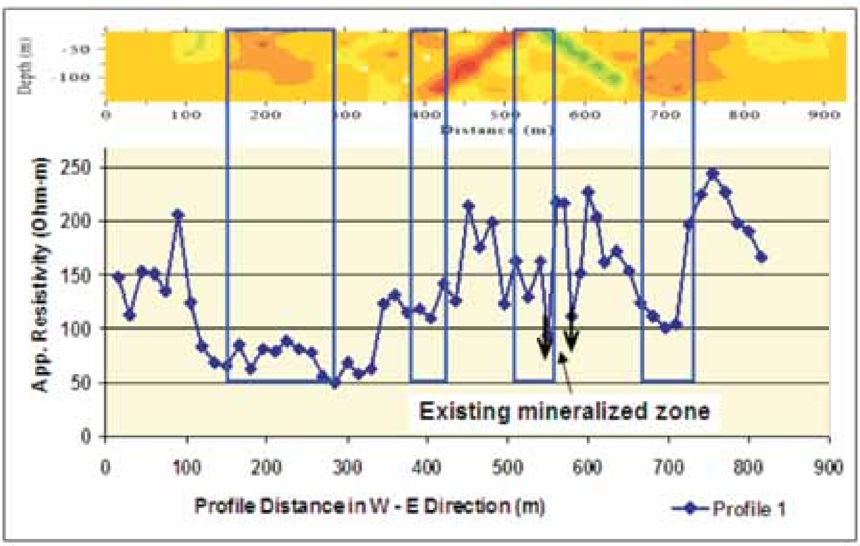

Figure 10. Combined plot of the EM-VLF and HRP results for profile 1 showing the zones of high current density and low resistivity as potentials fracture/mineralized zones

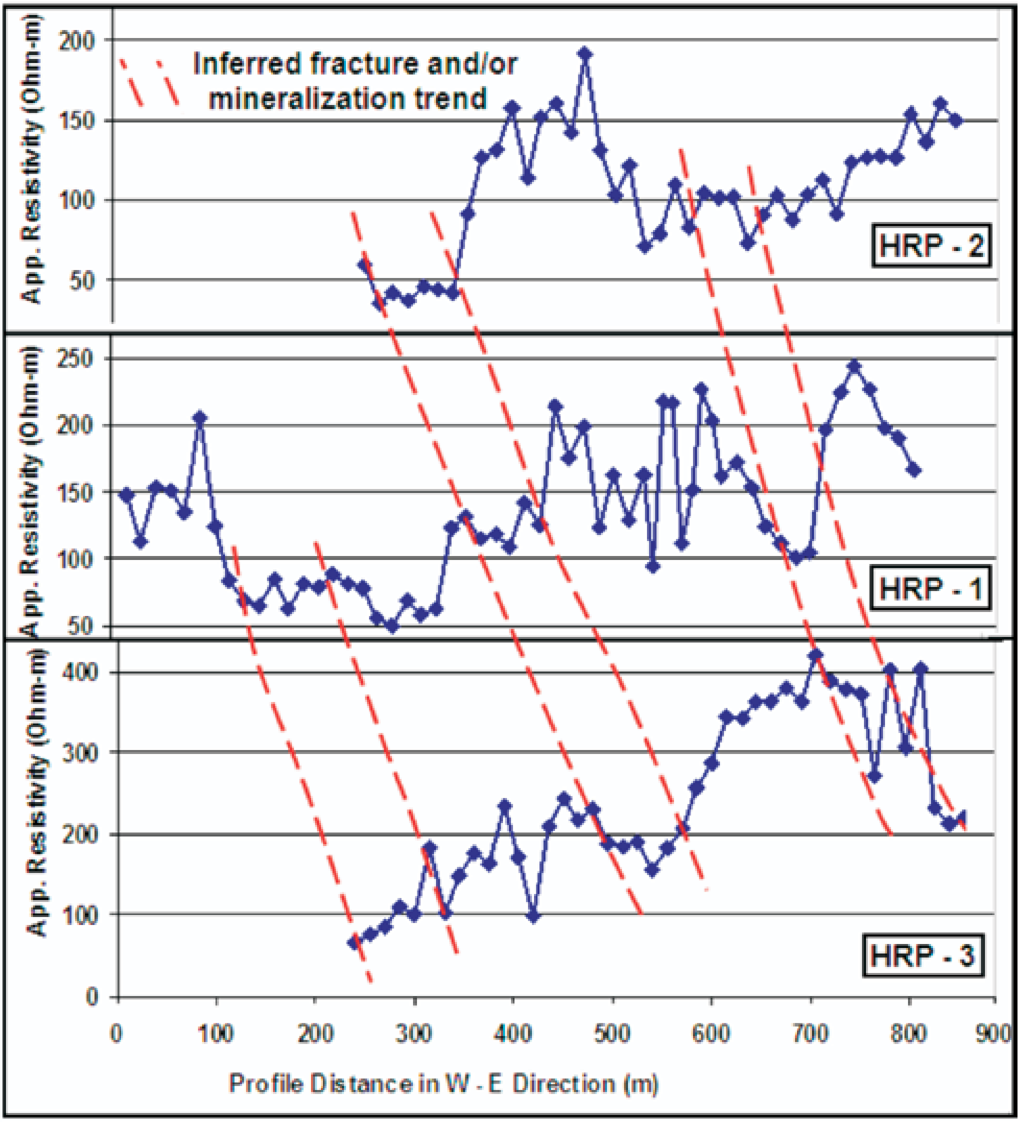

Figure 11. Combined plots of the HRP profiles showing inferred potential fracture/mineralized zones

The interpretation and recommendation presented here are based on the field geophysical measurements and observations as well as both manual and computer-aided interpretation therefrom. However, in view of a number of field limitations, it should be noted that the respective estimated location of

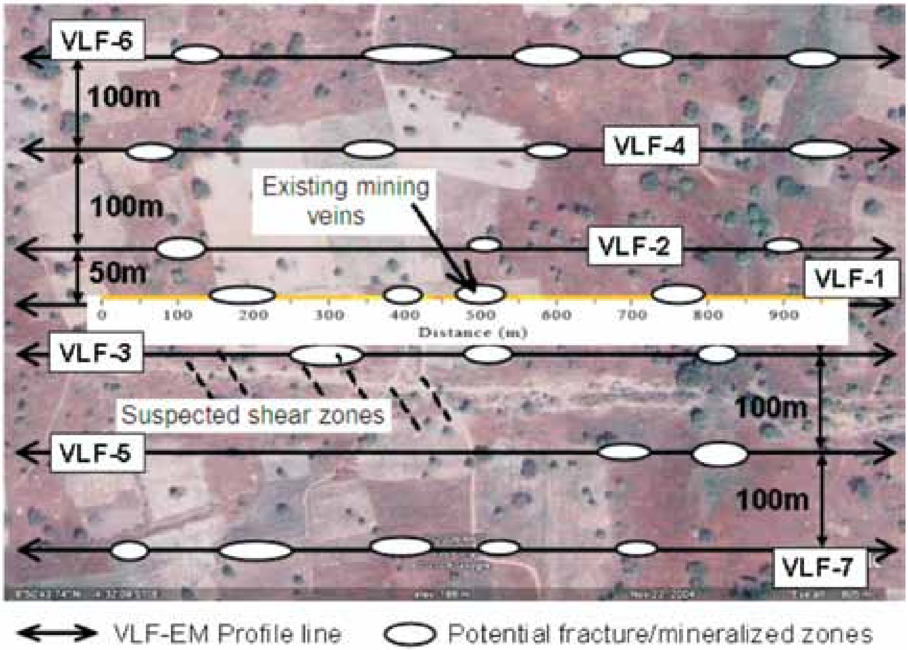

Figure 12. Isolated potential fracture zones with high current density as interpreted along the VLF-EM profiles. (NOTE: It is possible to order and link the distribution of these isolated zones together to form a more or less N–S trending fracture zones)

the identified potential fracture / mineralized zones are approximations within some margin of error of ±5 m. This can be attributed to non-linearity of the profile lines due to lack of properly cut survey lines, topographic variation along the profile lines etc. Nonetheless, irrespective of such field limitations, the results and interpretation presented herein provide enough geophysical basis for delineation of the potential fracture and/or gold mineralization zones on one hand, and on the other hand, provide basis for follow-up detail geological-geochemical exploration studies.

Acknowledgements

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Assessment of the heavy metal contamination in the surficial sediments of Lake Kalimanci (Macedonia): a preliminary study

Ocena onesnaženosti recentnega sedimenta iz Kameniškega jezera (Makedonija) s težkimi kovinami – preliminarni rezultati

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Abstract: A major disaster happened in the eastern Macedonia (Europe), when part of the Sasa Mine tailings dam collapsed and caused an intensive flow of tailings material which ended up in Lake Kalimanci. The aim of this study was to assess the heavy metal contamination (Ag, As, Cd, Cu, Mo, Pb, Sb and Zn) of the surficial sediments from Lake Kalimanci. The pollution status of the sediments was evaluated by application of two environmental indices: the enrichment factor and a geoaccumulation index. The enrichment factor values (Cd 735; Pb 386; Zn 151; Ag 146; As 48; Cu 21; Sb 10 and Mo 2) revealed extremely elevated heavy metal concentrations in the investigated samples. The geoaccumulation index indicated that surficial sediments of Lake Kalimanci can be treated as moderately to strongly polluted with Pb and Cd, moderately polluted with Zn and Ag, unpolluted to moderately polluted with Cu and As and unpolluted with Mo and Sb.

Izvleček: Na območju vzhodne Makedonije se je v deponijskem predelu rudnika Sasa zgodila huda ekološka nesreča. Del jalovinskega nasipa se je zrušil in tako povzročil silovit tok flotacijsko-jalovinskega materiala, ki je zgrmel v dolino reke Kamenice, vse do jezera Ka-

Original scientific paper

menica. Namen študije je bil oceniti onesnaženje površinskega sedimenta iz jezera Kamenica s težkimi kovinami (antimon, arzen, baker, cink, kadmij, molibden, srebro in svinec). Stopnjo onesnaženja smo določili z uporabo dveh okoljskih indeksov: faktorja obogatitve in geoakumulacijskega indeksa. Izračunane vrednosti faktorja obogatitve v raziskovanih vzorcih so bile zelo visoke (Cd 735; Pb 386; Zn 151; Ag 146; As 48; Cu 21; Sb 10 in Mo 2). Rezultati indeksa geoakumulacije so razkrili podobne vrednosti in označili površinske sedimente iz jezera Kamenica kot srednje do visoko onesnažene z Pb in Cd, srednje onesnažene z Zn in Ag, neonesnažene do srednje onesnažene s Cu in As ter neonesnažene z Mo in Sb.

Key words: heavy metals, surficial sediments, enrichment factor, geoaccumulation index, Lake Kalimanci

Ključne besede: težke kovine, površinski sedimenti, faktor obogatitve, indeks geoakumulacije, jezero Kalimanci

Introduction

Tailings dams are a special type of dam built to store mill and tailings material from mining activities. Currently, thousands of tailings dams worldwide contain billions of tonnes of waste material from mineral processing activity at mine sites. They are supposed to last forever, but since 1970 there have been 35 major failures reported around the world (Diehl, 2001; Göransson et al, 2001; Grimalt et al, 1999; UNEP/OCHA, 2000).

A major environmental disaster also happened in the eastern Republic of Macedonia. In the afternoon of 30 August 2003, part of the Sasa Mine tailings dam collapsed and caused an intensive flow of tailing materials through the Kamenica River valley. The estimated height of the tailings flow was around ten metres and the length of the flow was approximately 12 km. Some 70 000–100 000 m^3 of tailings material was discharged and spread through the Kamenica River valley, down to the city of Kamenica and into Lake Kalimanci. The damaging tailings flow comprised a large amount of heavy metals (Dolenec et al, in press) and seriously affected the surrounding environment, especially Lake Kalimanci.

When heavy metals enter an aquatic environment, they are redistributed throughout the water column, deposited or accumulated in sediments and consumed by biota (Long et al, 1996; Fichet et al, 1998; Linnik & Zubenko, 2000; Singh et al, 2005; Ghrefat & Yusuf, 2006 and

Khaled et al, 2006). A fundamental characteristic of heavy metals is their lack of biodegradability and lake sediments usually operate as pollutant storage tanks that reflect long-term impacts (Maltby, 1992 and Schmitt et al, 2003). Therefore it is important to assess the extent of heavy metal accumulation in lake sediment and to determine its environmental threat.

Our objective in the preliminary study was to define the total heavy metal contamination (Ag, As, Cd, Cu, Mo, Pb, Sb and Zn) of the surficial sediments from Lake Kalimanci and to evaluate enrichment factor (EF) and geoaccumulation index (I_{geo}) values for the heavy metals present in the sediment samples.

Materials and methods

Study area

Kalimanci artificial lake is located in eastern Macedonia, in the 2000 m high Osogovo Mountains, near the city Makedonska Kamenica and the Sasa mine (Figure 1). The surface of the lake is 42 km^2, the maximum depth is 85 m and it encompasses around 120 · 10^6 m^3 of water. It is supplied by two tributaries: the Bregalnica and the Kamenica River, which flows directly from the Sasa mine and drains a large amount of mining effluents and tailings material which have discharged into Lake Kalimanci.

Figure 1. Geographical map of the investigated area (merilo 1 : 625 000)

The sediment samples from Lake Kalimanci are dominated by: quartz, plagioclases, K-feldspars, muscovite, illite and clinochlorite. Subordinate minerals are hornblende, gypsum, bassanit, calcite, dolomite, smithsonite, pyrite, marcasite, haematite, goethite and diaspor (Dolenec et al, unpublished).

The Sasa-Toranica ore district is situated 10 km N of Lake Kamenica in the Osogovo Mountains and occupies an area of about 200 km (Figure 1). It is established as one of the largest ore districts within the Besna Kobila Osogovo Tassos metallogenetic zone. The important Pb and Zn ore bodies are usually found in quartz-muscovite-graphitic schists and also in greenschists and marbles. The ore bodies are always accompanied by variable amounts of Cu, Au, Ag, Mo and Sb. The Sasa mine has been in production for over 45 years, yielding 90 000 t of high quality Pb-Zn concentrate annually and numerous tons of tailings material (Serafimovski et al, 2005).

The tailings material from the Sasa mine is made up of quartz, pyrite, galenite, gypsum, hornblende, actinolite, albite, anortite, biotite and orthoclase. The geochemical analysis of tailings material indicated an average range of Ag 0.004 μg/g, As 69.2 μg/g, Cd 84.3 μg/g, Cu 279.3 μg/g, Mo 2.9 μg/g, Pb 5595.2 μg/g, Sb 4.2 μg/g and Zn 6970.2 μg/g (Dolenec et al, unpublished).

Sampling and analysis

Seventeen surficial sediment samples from Lake Kalimanci were taken in September 2007, three years after the tailings dam accident happened. The surficial sediments were composed of silt. The chosen sampling locations were formed into eight profiles (Figure 2), covering the area around the River Kamenica tributary in the northern site of the lake which was mostly affected by the tailings flow.

The samples were collected with the plastic corers (tube 20 cm long with a 10 cm internal diameter), tightly packed into plastic bags and stored in the laboratory at 4 ºC. The sediment samples were dried at 50 ºC for 48 h. They were then sieved through a 0.315 mm polyethylene sieve to remove plant debris and homogenised by a mechanical agate grinder to a fine powder for subsequent analysis.

The mineralogy of the sediment samples was determined at the Department of Geology, Ljubljana (Slovenia) by X-ray powder diffractometry with a Philips PW 3710 diffractometer and CuKa radiation. The diffraction patterns were identified with the data from Powder Diffraction File (1977) – JPDS system.

The geochemical analysis of the following heavy metals, Ag, As, Cd, Cu, Mo, Pb, Sb and Zn, was obtained in a certified commercial Canadian laboratory (Acme Analytical Laboratories, Ltd.) and 0.5 g of samples were leached in hot (95 ºC) Aqua Regia and analysed by ICP Mass Spectrometry. The analytical precision and the accuracy were better than ±5 % for the analysed elements.

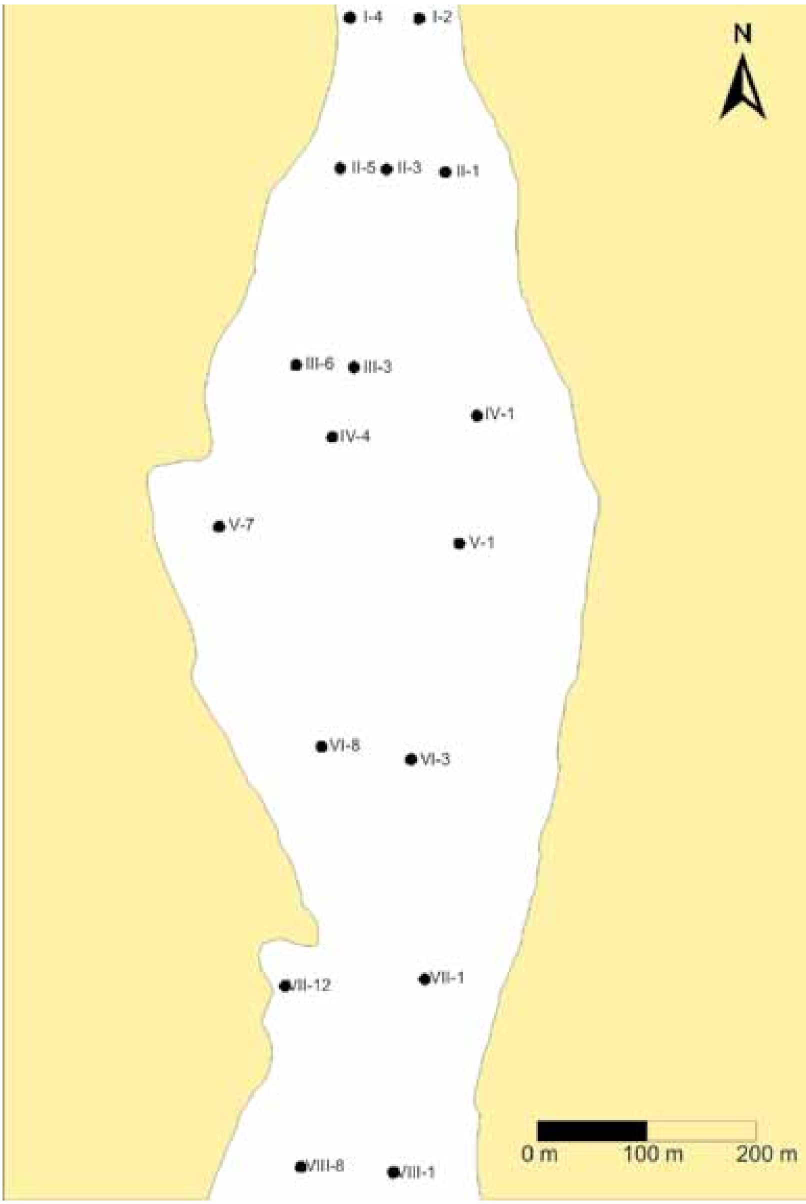

Figure 2. Sampling locations in the Lake Kalimanci

Statistical analysis
Basic statistical analysis of data was performed by use of the original statistical software program Statistica 6. Pearson multiple correlation analysis was also applied to all results.

Results and discussion

Heavy metals (Ag, As, Cd, Cu, Mo, Pb, Sb and Zn) were examined for their abundance in the surficial sediments from Lake Kalimanci.

When the accident occured, the damaging tailings flow mostly affected the northern part of the Kalimanci Lake. Consequently, the maximum concentrations of all heavy metals were determined in the northern part of the basin (Table 1, Figure 2). The maximum level of the Zn (20 900 μg/g), Pb (16 300 μg/g), Cu (1 162 μg/g), Cd (136 μg/g), Ag (17.3 μg/g), Mo (4.6 μg/g), and Sb (3.6 μg/g) was recorded in location II-3 and the highest amount of As was found in location II-1 (Table 1, Figure 2).

Table 1. Concentrations *c*/(μg/g) of the heavy metals in the investigated samples

Element *c*/(μg/g)	Ag	As	Cd	Cu	Mo	Pb	Sb	Zn
Location								
I-2	2	54.8	48.1	238	2.2	2721	1.4	5913
I-4	10.3	68.8	74	627.3	2.9	9357	2.4	10700
II-1	3.6	86.7	77.2	415	3.1	4461	2.2	9596
II-3	17.3	77.2	136	1162	4.6	16300	3.6	20900
II-5	15.2	70.1	111.6	928.7	4.2	13800	3.2	17600
III-3	11.1	73.2	89.6	723	3.7	10900	2.7	14000
III-6	10.4	57.6	86.8	692.5	3.3	9800	2.1	14000
IV-1	5.1	66.1	59	413.1	3	6695	1.7	8105
IV-4	4.2	61.6	47.6	341.4	2.3	5343	1.6	6734
V-1	3.6	61.6	40	303.2	2.4	4447	1.3	5677
V-7	8.1	66	81.1	595.7	3.7	9472	2	12600
VI-7	5.6	128.2	54.2	315.4	3.6	7885	3.3	7181
VI-11	7.1	58.6	77.6	545.7	2.5	7557	1.6	11600
VII-1	3.6	77.8	61.3	372.5	1.9	4575	1.1	10400
VII-12	4.5	66.4	53.5	398.1	2.7	5144	1.2	9326
VIII-1	3.8	69.8	47.9	311.9	2.2	5091	1.4	7224
VIII-8	4.1	61.5	46.8	327.6	2.3	4893	1.4	7056

Basic statistical information are given in the Table 2.

Correlation analysis

A Pearson correlation matrix was used to assess element associations and metal origins (Table 3). The correlation matrix presents a significantly positive correlation between Ag, Cd, Cu, Mo, Pb, Sb and Zn, demonstrating possible co-contamination from similar sources: in our case, that would be tailings material from the Sasa mine. Conversely, no correlations were noted between As and the other elements (except Sb), suggesting that As contamination might be from a different source or it had a natural origin but was not from the same pollution source or had a different depositional nature.

Table 2. Descriptive basic statistics of the heavy metals in the surficial sediments of Lake Kalimanci

Element	Valid N	Mean	Minimum	Maximum	Std. Dev.
Ag	17	7.04	2.000	17.30	4.414
As	17	70.94	54.800	128.20	16.859
Cd	17	70.14	40.000	136.00	25.773
Cu	17	512.42	238.000	1162.00	250.845
Mo	17	2.98	1.900	4.60	0.775
Pb	17	7555.35	2721.000	16300.00	3664.172
Sb	17	2.01	1.100	3.60	0.783
Zn	17	10506.59	5677.000	20900.00	4248.268

Table 3. Pearson correlation matrix showing inter-elemental relationship (*n* = 17)

	Ag	As	Cd	Cu	Mo	Pb	Sb	Zn
Ag	1.00							
As	0.03	1.00						
Cd	0.93*	0.06	1.00					
Cu	0.98*	–0.03	0.97*	1.00				
Mo	0.85*	0.34	0.84*	0.83*	1.00			
Pb	0.99*	0.14	0.91*	0.96*	0.90*	1.00		
Sb	0.80*	0.55*	0.76*	0.74*	0.91*	0.84*	1.00	
Zn	0.94*	–0.00	0.98*	0.98*	0.80*	0.92*	0.69*	1.00

*$p < 0.05$

Enrichment factor

The enrichment factor (*EF*) is a useful indicator reflecting the condition of environmental contamination. It was employed to evaluate possible anthropogenic input of metals to observed sediment (Brady, 1984), calculated according to the equation:

$$EF = (M/Al)_{sample} / (M/Al)_{crust} \qquad (1)$$

where M_{sample} and M_{crust} are the levels of the investigated metals (Ag, As, Cd, Cu, Mo, Pb, Sb and Zn) in the sediment samples and in the uncontaminated crust material, respectively, and Al_{sample} and Al_{crust} are the values of the Al in the sediment samples and in the uncontaminated crust material. Metal to aluminium ratios are widely adopted, presumably because the concentration of Al in weathering products and their parent materials are generally comparable. Al is also the normalising element assumed not to be enriched owing to local contamination. Baseline values for M_{crust} were adopted from Taylor and McLennan (1985).

EF–values lower than and around 1.0 indicate that the element in the sediment originates predominantly from the crustal material and/or weathering processes (ZHANG & LIU, 2002), whereas EF–values much greater than 1.0 display the anthropogenic origin of the element (SZEFER et al, 1996). According to Chen et al (2007), *EF* < 3 indicates minor enrichment (anthropogenic impact), *EF* = 3–5 moderate enrichment, *EF* = 5–10 moderately severe enrichment, *EF* = 10–25 severe enrichment, *EF* = 25–50 very severe enrichment, and *EF* > 50 extremely severe enrichment.

The calculation of enrichment factors showed that all studied heavy metals were enriched in surficial sediments of Lake Kalimanci. Cd had the highest average *EF*–value (735) among the investigated heavy metals, which represents extremely severe enrichment. *EF*–values of Pb, Zn and Ag (average value 387, 151 and 146, respectively) also signified extremely severe enrichment. Calculated *EF*–values for As, Cu and Sb determined very severe enrichment (average value 48) with As and severe enrichment with Cu and Sb (average values 21 and 10, respectively). Mo exhibited the lowest *EF*–values among the heavy metals studied (average value 2) and displayed moderate enrichment (Table 4).

Geoaccumulation index

The geoaccumulation index (I_{geo}) was also used to assess heavy metal pollution in surficial sediments of Lake Kalimanci. It is expressed by the following equation (MÜLLER, 1969):

$$I_{geo} = \log_2 (C_n/1.5\ B_n) \qquad (2)$$

where C_n is the measured concentration

Table 4. Enrichment factors (EF) values (average) in surface sediments of Lake Kalimanci

Element	Ag	As	Cd	Cu	Mo	Pb	Sb	Zn
EF values (average)	146	48	735	21	2	387	10	151

Table 5. I_{geo} values (average) in surface sediments of Lake Kalimanci

Element	Ag	As	Cd	Cu	Mo	Pb	Sb	Zn
I_{geo} values (average)	1.8	0.6	2.2	0.9	–0.1	2.4	–0.05	1.9

of the heavy metal (n) in the sediments, B_n is the geochemical background value in the average shale of element n, and 1.5 is the background matrix correction factor owing to lithogenic effects (Loska et al, 1997; Ghrefat & Yusuf, 2006; Gonzáles-Macías et al, 2006; Chen et al, 2007).

According to Loska et al (1997) and Gonzáles-Macías et al (2006), the geoaccumulation index (I_{geo}) can be categorised in a scale ranging from 1 to 6: $I_{geo} \leq 0$ unpolluted, $I_{geo} \leq 1$ unpolluted to moderately polluted, $I_{geo} \leq 2$ moderately polluted, $I_{geo} \leq 3$ moderately to strongly polluted, $I_{geo} \leq 4$ strongly polluted, $I_{geo} \leq 5$ strongly to very strongly polluted, and $I_{geo} > 5$ very strongly polluted.

The results (average values of the I_{geo}) revealed that surficial sediments of Lake Kalimanci were moderately to strongly polluted with Pb (2.4) and Cd (2.2), moderately polluted with Zn (1.9) and Ag (1.8), unpolluted to moderately polluted with Cu (0.9) and As (0.6) and unpolluted with Mo (-0.1) and Sb (–0.05) (Table 5).

The heavy metals in sediments are derived from two sources: natural and anthropogenic. In Lake Kalimanci, however, extremely elevated concentrations of Cd, Pb, Zn, Ag, As, Cu, Sb, Cu, Sb, and Mo in the surficial sediments clearly represent anthropogenic impact originating from the mining activities (mining effluents and tailings material) and the tailings dam accident in the Sasa mine. This anthropogenic influence was also evaluated and confirmed by the calculation of enrichment factors and the index of geoaccumulation.

Conclusion

In the present study we applied two ecological indices, enrichment factor and index of geoaccumulation, to assess and evaluate the distribution of heavy metals (Ag, As, Cd, Cu, Mo, Pb, Sb and Zn) in surficial sediments from Lake Kalimanci (Macedonia). The results indicate that all heavy metals were enriched in the sediment samples studied. According to the calculated values of I_{geo} the surficial sediments were strongly polluted with Pb and Cd and unpolluted with Mo and Sb. This pollution impact clearly originates from the mining activities (acid mine drainage) of the Sasa mine and from the Sasa tailings dam accident.

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Displacement of mined ground as a consequence of the exploitation of Pb-Zn ore in the mine Crnac

Pomik podkopanega terena kot posledica pridobivanja rude Pb-Zn v jami Crnac

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Abstract: Underground exploitation of mineral raw materials and the construction of sub-surface facilities cause changes on the ground surface. These changes on the ground surface are practically manifested as specific displacements and deformations on the surface of the mined ground. The objective of this Paper is to determine a safe working depth and to make an assessment of a prospective deformation hazard and subsidence of the ground over the mining zones of Pb-Zn ore veins in the Mine Crnac. A high-quality determination, forecasting of deformations and subsidence of a terrain is very important for the safety of underground mine workings and the protection of facilities on the surface of the ground.

Izvleček: Podzemno pridobivanje mineralnih surovin, kot tudi gradnja podzemnih objektov povzročata spremembe na površini. Praktično se te spremembe na površini izražajo kot pomiki in deformacije na območju odkopa. Cilj članka je določanje varne globine odkopavanja ter ocena potencialne nevarnosti zaradi deformacij in ugrezanja nad območji pridobivanja Pb-Zn rudnih žil v jami Crnac. Kakovostno določanje, napovedovanje deformacij in ugreznin terena je zelo pomembno za varnost podzemnih jamskih prostorov ter zaščito objektov na površini.

Original scientific paper

Key words: working environment, underground works, displacement of the ground, deformation, angular parameters, analytic dependence
Ključne besede: delovno okolje, podzemna dela, pomik terena, deformacija, vplivni koti, analitična odvisnost

INTRODUCTION

The extraction of lead-zinc ore (Pb-Zn) in the mine Crnac has been made intensively since 1967, year which is taken as the beginning of the modern exploitation.

By investigation mining at the height of 862 m there were over 20 Pb-Zn ore veins identified, with thickness from 1 m to 3.5 m. Depending on the physical and mechanical characteristics of ore and accompanying rocks of ore veins, extraction methods for each ore vein are applied separately. For the extraction of ore veins the following methods are applied: extraction with back-filling of cavities, caving method and sublevel open stope mining method.[6]

This paper shows the impact of Pb-Zn ore exploitation in the mine Crnac on the displacement of mined ground in the exploitation by open stope method on the example of the ore vein No. 3.

CHARACTERISTICS OF A WORKING ENVIRONMENT

In a geological environment of a deposit the following lithologic members are involved: amphibolites, Palaeozoic shales, serpentinites, diabases, diabase-hornstone series and tertiary effusives with their pyroclastites. Tertiary magmatic activity was manifested by the formation of significant masses of effusive rocks and a number of changes in the active rocks. The same magmatism gave rise to dumping of the Pb-Zn mineralization in the form of ore veins with 1–3.5 m thickness and 60–90^0 angles of occurrence (dipping) and with coefficients of solid ore and accompanying rocks (*f* 5–15) according to Protodjakonov.

IMPACT OF UNDERGROUND WORKS ON THE SURFACE OF THE GROUND

As a consequence of the underground mineral deposit exploitation, it comes to roof caving above the working cavity, which can frequently be manifested on the surface of the ground.[9] The first signs of ground subsidence are manifested by deflections of the terrain, subsidence or caving of a stope roof. Moreover, the subsidence is reflected by an increased pressure in the roof and sidewall.[8]

The underground mining leads to vertical and significantly mere horizontal displacements and deformations on the surface of the terrain. The shape, size and the process of terrain deformations depend on a number of factors where the main are the following:[5]

- Structure of the characteristic of a rock massif (fissuring, bedding),
- Physical and mechanical characteristics of rocks which constitute the ore massif,
- Dipping conditions of ore bodies and accompanying rocks,
- The shape and the size of ore bodies, their thickness, ratio between the size of the working cavity and the depth of works,
- Mining system,
- Damage degree of rocks,
- Terrain relief.

The above factors in each individual case define particularities of the displacement and deformation processes of the massif, by enabling the application of analytic, graphic and numerical and analogue methods for defining and studying the processes of deformation of massif and the terrain surface.[10]

The Figure 1 shows the diagram of displacement and deformation zones on the surface of the mined ground and angular parameters and displacement assessment.

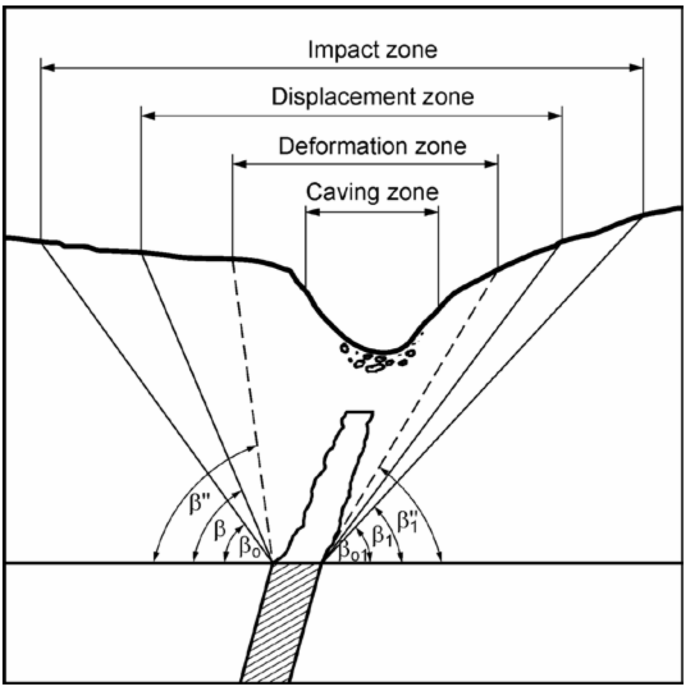

Figure 1. Diagram of displacement and deformation zones on the surface of the mined terrain

The first researches related to the impact of underground works on the surface of the terrain were from the late 19th century. These issues were dealt by a number of researchers who gave their indisputable contribution to the scientific thought in this field and served as an instrument for developing new theories in the contemporary mining, based on the mathematical processing of a large number of collected data.[1], [2], [11]

Criteria for determining angular parameters B according to I. N. Kisimov

Applying the theory of probability and mathematical statistics methods, and on the basis of measurements completed, analytical dependencies and criteria for determining angular parameters were proposed (Figure 1.) when resolving problems related to displacements of a mined terrain due to the impact of mining works. The basic criteria for a forecast calculation of displacements and deformations of a mined terrain and angular parameters of the displacement process were given by the author I. N. Kisimov:[3]

- Impact of the inclination angle of an ore body α,
- Impact of the strength of accompanying rocks f,
- Impact of the actual thickness of an ore body m,
- Impact of the depth of mining works H.

Impact of the inclination angle of an ore body α

For the open stope method (caving method and sublevel open stope mining method) it is found that the inclination angle α of an ore body is the factor which influences the most on the angle β of the deformation impact zone:

$\beta = -37.27 + 1.37\ \alpha$ ($\eta = 0.881$; $\mu_\eta = 9.68$),

$\beta_1 = 0.002\ \alpha^2 + 0.296\ \alpha + 35.572$ ($\eta = 0.682$; $\mu_\eta = 6.89$),

$\beta'' = -0.052\ \alpha^2 + 8.53\ \alpha - 264.898$ ($\eta = 0.596$; $\mu_\eta = 6.47$),

$\beta''_1 = 0.004\ \alpha^2 - 0.070^\alpha + 57.572$ ($\eta = 0.675$; $\mu_\eta = 10.55$).

Impact of the strength of accompanying rocks f

Impact of the coefficient f on the angle β is significant and is considered as the approximate to the impact of an ore body dip α, is given in the form of the expression for open stope methods:

$\beta = -17.07 + 0.97\ \alpha + 0.93\ f$ ($R = 0.896$; $\mu_R = 11.23$),

$\beta_1 = -79.03 + 1.63\ \alpha + 1.62\ f$ ($R = 0.847$; $\mu_R = 7.30$),

$\beta'' = 0.024\ f^2 - 0.086\ f + 76.955$ ($\eta = 0.484$; $\mu_\eta = 39.2$ with $f = 6–18$),

$\beta''_1 = -0.087\ f^2 - 2.456\ f + 63.031(\eta = 0.589;\ \mu_\eta = 7.96$ with $f = 8–18)$.

Impact of the actual thickness of an ore body *m*

Impact of the thickness m on the angle β is certain to the itself impact of the coefficient f:

$\beta = 67 - 0,42\ m + 0,81\ f$ (with $R = 0.375$ and $\mu_R = 3,59$ for $m = (1:3\text{m})$

Impact m to the factor α:

$\beta = 28.01 + 0.55\ \alpha + 0.29$ ($R = 0.509$; $\mu_R = 4.28$)

Impact m to the factor H:

$\beta_1 = 66.52 + 0.04\ H + 0.83\ m$ ($R = 0.529$ and $\mu_R = 5.04$

$\beta'' = 77.6 + 0.19\ m + 0.38\ f$ ($R = 0.329$ and $\mu_R = 3.09$).

Impact of the depth of mining works *H*

The change in the angle β depending on the depth H is typical for the decrease in value β at depths from 50 m to 150 m and the increase in the angle β in the interval from 150 m to 300 m; therefore the dependency of the impact H and f on the angle β is determined:

$\beta = 7.148 + 0.33\ f - 0.004\ H$

with $f = 6–18$ and $H = 100–400$ m

$\beta_1 = 0.0003\ H^2 - 0.094\ H + 76.71$ ($\eta = 0.784$ and $\mu_\eta = 13.63$) and value $H = 15–400$ m

$\beta'' = 74.25 + 0.74\ f - 0.02\ H$ with $R = 0.368$ and $\mu_R = 3.38$

$\beta''_1 = -0.0005\ H^2 + 0.152\ H + 68.162$

Determining the stability of the terrain surface due to the impact of mining works in Mine Crnac

Previous mining activities in the pit of Crnac Mine, more ore veins were excavated above the horizon $H = 862$ m (Figure 2). Extraction methods which were applied to ore mining in particular ore veins of different thickness (from 1–3.5 m) and dipping angle of ore veins from 60–90^0, were not adapted to mining conditions, and therefore it led to displacements of terrain surface above working cavities. Figure 3 shows a longitude cross-section of the stope in the ore vein No. 3 and its relation to the terrain surface where there was the displacement of the terrain surface (Figure 4.).

In order to prevent displacements of the terrain surface above the working cavity it is necessary to determine the impact of mining on the surface. In case that mining works have impact on the surface, it is necessary to define

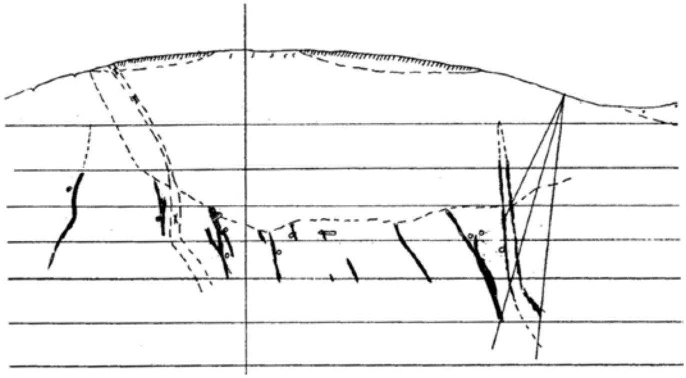

Figure 2. A geological profile of ore veins above the horizon H = 862 m

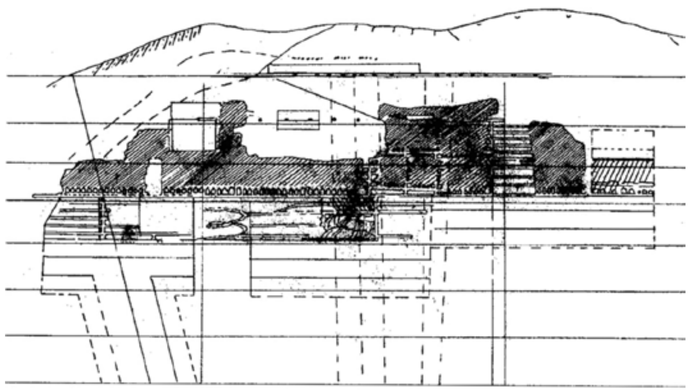

Figure 3. Longitude cross-section of a stope in the ore vein No. 3 and its relation to the terrain surface

Figure 4. Displacement of the terrain surface

zones of displacements and caving and a possibility of creating a safe depth, and when there are not any, it is important to know if there are stable areas directly above mining works.[4], [7]

The stability of surfaces directly above mining works depends on the rock excavation method and natural and technical conditions, such as: occurrence angle of the ore body α, and the strength coefficient of accompanying rocks f, mining lengths at the dip L, with mining thickness m, depth to the upper border of exploitation H, lengths of excavation in the direction of strike N, with the thickness of covering detritus h_1, the thickness of covering main rocks h_2.

According to KISIMOV there is a directly proportional interdependence between the surface stability and the parameters α, H, f, h_1, h_2 and L, m, N respectively.

The impact of these parameters may be determined when necessary data are analyzed and expressed through empirical mathematical dependencies. Certainly, the stability of the surface in mining is influenced also by fissuration of accompanying rocks, considering that all the rocks are fissured to a small or large extent, it can be accepted that the fissuration takes part through the value of empiric coefficients.

Patterns for minimal extraction depths where there are no displacements on the surface of a working cavity, bearing in mind the thickness of the ore body m, strength coefficient of roof beds f and excavated length at strike N, for the conditions of the Mine Crnac are given as follows:

- Impact of the excavated thickness:

$$H_m \geq \frac{25{,}4 \cdot (L \cdot \cos\alpha + m \cdot \sin\alpha)}{(L \cdot \cos\alpha + m \cdot \sin\alpha) + 3{,}6 \cdot m} \cdot m$$

$$H_m \geq \frac{25{,}4 \cdot (125 \cdot 0{,}174 + 3 \cdot 0{,}985)}{(125 \cdot 0{,}174 + 3 \cdot 0{,}985) + 3{,}6 \cdot 3} \cdot 3$$

$$H_m \geq 53{,}02m$$

- Impact of the strength coefficient:

$$H_f \geq \frac{5.6 \cdot (L \cdot \cos\alpha + m \cdot \sin\alpha)}{(L \cdot \cos\alpha + m \cdot \sin\alpha) + 1.9 \cdot f} \cdot f$$

$$H_m \geq \frac{5{,}6 \cdot (125 \cdot 0{,}174 + 3 \cdot 0{,}985)}{(125 \cdot 0{,}174 + 3 \cdot 0{,}985) + 1{,}9 \cdot 8} \cdot 8$$

$$H_f \geq 27{,}7m$$

- Impact of the excavated length at strike:

$$H_N \geq \frac{9.3 \cdot (L \cdot \cos\alpha + m \cdot \sin\alpha)}{(L \cdot \cos\alpha + m \cdot \sin\alpha) + 5 \cdot n} \cdot n$$

$$H_m \geq \frac{9{,}3 \cdot (125 \cdot 0{,}174 + 3 \cdot 0{,}985)}{(125 \cdot 0{,}174 + 3 \cdot 0{,}985) + 5 \cdot 600} \cdot 600$$

$$H_N \geq 45{,}57m$$

On the basis of these calculations, we obtained three different values for a minimal extraction depth, the maximum value is adapted, which is the dislocation due to the impact of the strength of the ore vein No. 3 of the Crnac Mine.

CONCLUSION

Applying the KISIMOV's pattern along with introducing local parameters of the deposit, gave real, approximate values for determining a safe exploitation depth or the possibility of the appearance of falling-in on the surface of the terrain.

Under the conditions in the Mine Crnac we obtained the results which indisputably show that a safe mining depth had not been defined, so the works on the ore extraction on the example of the ore vein No. 3 had caused the displacement of the terrain surface.

Bearing in mind that the ore exploitation above horizon N^0 : 862 m in the mine Crnac and further open stope mining method, it is necessary to define the impact of extraction on the surface of the terrain for each ore vein separately.

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Introducing clean coal technologies for reduction of greenhouse gasses emissions

Uvajanje čistih premogovnih tehnologij za zmanjšanje emisij toplogrednih plinov

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Abstract: Stabilization of climate depends on the balance between greenhouse gasses emissions and natural absorption of the earth. The longer the balance is not reached, the worse the climate will become. Playing a key role in the electricity production throughout the world, coal cannot be replaced during the next decades. Facilitating further coal use, acceptable to the market and the environment, is an important political task for the Europe.

Europe can efficiently explore the abatement potential of the carbon capture and storage technology (CCS) by expedited implementation of the demonstration program and appropriate commercial roll out of the most advantageous CCS technologies. A lot of uncertainties and barriers will have to be resolved in this process. The demonstration program of the CCS projects can explore the real potential of the technology, identify the risks and bring the public and industry confidence to this remarkable technology.

Regulatory issues related to responsibility for carbon storage, financing of demonstration projects, exchange of experiences can only be resolved by appropriate cooperation between industry, government officials, research institutions and universities. Public opinion and support should also be seen as to have an important impact on the final success of the process.

Original scientific paper

Izvleček: Za stabilizacijo klimatskih razmer se mora letna količina emisij izenačiti z zmogljivostjo Zemlje za absorpcijo toplogrednih plinov. Bolj kot bodo emisije presegale ta nivo, bolj se bodo klimatske razmere poslabševale in na višji točki (v slabšem stanju) bo potekala stabilizacija klimatskih razmer.

Premog je vedno igral ključno vlogo pri proizvodnji električne energije in takšno vlogo bo vsekakor imel tudi v prihodnje. Nikjer na svetu v naslednjih desetletjih premoga ne bo mogoče nadomestiti. Podpora pri nadaljnji uporabi premoga, sprejemljivost na trgu in v okolju pa bo pomembna politična naloga za Evropo. Za učinkovito izrabo potenciala tehnologije zajema in geološkega shranjevanja ogljikovega dioksida (CCS) v Evropi bi bilo treba hitro uvesti demonstracijski program in ustrezno načrtovati kasnejšo komercialno ekspanzijo tehnologije. Pri tem bo treba odpraviti kar nekaj negotovosti in ovir. Demonstracijski program CCS-projektov bi lahko dokazal pravi uspeh uporabnosti tehnologije, identificiral tveganja in dosegel zaupanje javnosti in industrije v tehnologijo.

Regulatorne zadeve, v prvi fazi predvsem glede odgovornosti za shranjevanje ter financiranja demonstracijskih projektov, kasneje pa tudi glede razširjanja izkušenj ter ustrezno koordinacijo na evropskem ali svetovnem nivoju, bo treba razrešiti v sodelovanju industrije, vladnih ustanov, raziskovalnih ustanov ter univerz. Pri tem ne smemo zanemariti vloge javnosti in njene podpore pri celotni rešitvi.

Key words: coal, clean coal technologies, carbon capture and storage, electricity, energy sources, competitiveness, security, reliability

Ključne besede: premog, čiste premogovne tehnologije, zajem in shranjevanje ogljikovega dioksida, električna energija, energijski viri, konkurenčnost, varnost, zanesljivost

Introduction

Energy use and energy generation represent the International Energy Agency's (IEA's) forecast that global electricity generation will nearly double from 2005 to 2030. The Agency says that fossil fuels will remain a significant part of the energy mix, comprising approximately 70 % of global and 60 % of European electricity generation.

One of the solutions being discussed to reduce greenhouse gas emissions from fossil fuel energy generation is capture and geological storage of carbon dioxide (CCS – Carbon Capture and Storage). CCS comprises technologies for capturing CO_2 emitted from power plants and industrial sites, compressing this CO_2, and transporting it to locations for suitable storing, e.g. deep underground. CCS technology is in a relatively early phase of development, with several key questions remaining, including about its costs, implementation timing, and the comparison of its suitability versus other low carbon electricity generation technologies. Public understanding of CCS is low, and there is some confusion regarding its true economics, particularly due a wide range of data on the price of technology implementation as well as due to a questionable accuracy and reliability of original information on the prices.

Greenhouse Gases and Atmospheric Warming

Greenhouse gas concentrations in the atmosphere nowadays amount to $430 \cdot 10^{-6}$ particles, expressed in CO_2 equivalent, compared to $280 \cdot 10^{-6}$ from the period before the industrial revolution. Until today, an increase in concentration has caused an increase in the Earth's temperature by more than half a degree Celsius and will, due to a sustained climate system, cause an additional temperature increase by at least half a degree Celsius over the next decades.

Even if the emission inflow does not exceed the current level, the greenhouse gas concentration will reach $550 \cdot 10^{-6}$ by the year 2050 and continue to grow afterwards. This means it will more than double in comparison to the pre-industrial age. However, the annual CO_2 emission inflow is constantly growing due to investments into CO_2 emitting infrastructure, particularly in countries with rapid economic growth. Furthermore, both energy consumption and demand for transport are increasing globally. In such conditions, the CO_2 level of $550 \cdot 10^{-6}$ can be attained by the year 2035, with at least 77 %, or even 99 %, probability that an increase of global average temperature will exceed 2 °C.

In a scenario without impacts on the course of events (BAU - Business As Usual), the greenhouse gas concentrations might exceed three times the amount by the end of the century, which would mean at least 50 % probability of global Earth's temperature increase by 5 °C. Such warming would expose the human race to an entirely unknown environment. To illustrate the scope of consequences of such temperature increase, it should be considered that today's global temperature is higher only by 5 °C compared to the last ice age.

The Impact of Global Warming on the Economy

In the past, the majority of economic models of global warming was based on the scenario of temperature increase within 2–3 ºC until the end of the century. The results of such analyses show that the costs of climate changes equals permanent loss of global GDP up to 3 %, considering the potential global product without climate changes. In such case, the developing countries would suffer a somewhat greater loss.

A breakthrough in thinking in this area was initiated in 2006 by the Stern Review showing evidence that with a preserved BAU trend, the global temperature will exceed 2–3 ºC by the year 2100. This presumption increases the probability of occurrence of other climate changes not considered so far. With an increase of global temperature up to 5 ºC, various economic models estimate the probability of average 5–10 % loss of global gross domestic product (GDP), with the loss in poor countries exceeding 10 % of GDP.

Lord Stern introduced risk economics in the global warming area as, according to his claims, averaging of various scenarios may conceal risks. He established that there is a very high probability of severe or catastrophic scenarios of event development. The probability of their occurrence cannot be entirely removed; they can only be significantly reduced. Furthermore, Stern indicates that the consequences of atmospheric warming should not be limited only to a direct impact on GDP; indirect impacts on GDP should also be studied and GDP's impacts on the inhabitants should be monitored as well.

If indirect impacts are added to direct impacts on GDP, they can be expressed as the following:

- 5 % reduction of GDP per capita due to human health deterioration and/or mortality rate increase as well as due to other environment changes,
- 3 % reduction of GDP per capita due to new scientific evidence according to which the climate system is much more responsive to greenhouse gas emissions than it has been thought so far, e.g. due to the methane release into the atmosphere or due to reduced activity of natural CO_2 sinks,
- 25 % reduction of GDP per capita due to an unproportionately larger impact of global changes on poor world regions where the percentual impact on GDP per capita is significantly larger than the percentual impact on GDP per capita in developed regions.

Hence the total impact of global changes amounts to 5–20 % reduction of GDP per capita. Stern estimates that without active interventions in emissions, the actual result will be somewhere in the upper section of this area.

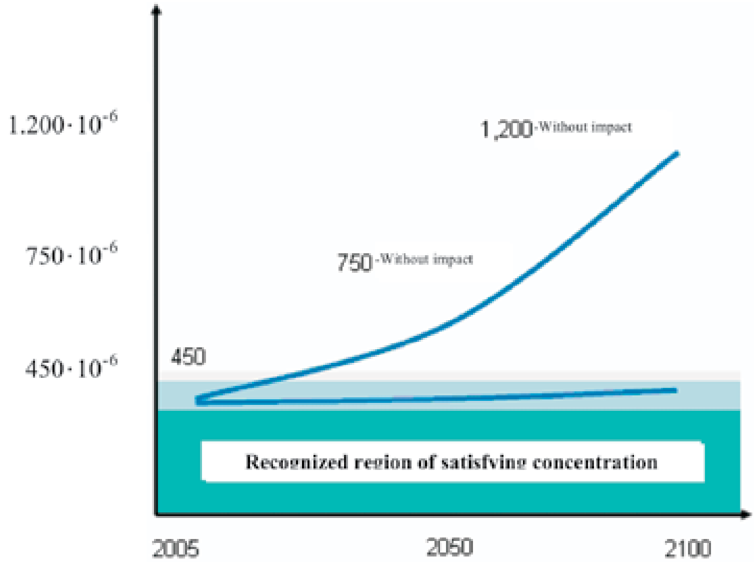

Figure 1. CO_2 prediction scenarious – scenario without impact (BAU) and stabilized concentration scenario (in 10^{-6} particles) (Katzer et al., 2007)

Stabilization of climate depends on the balance between annual amount of greenhouse gasses emissions and natural absorption capacity of the Earth. The longer the emissions keep exceeding this level, the more climate conditions will deteriorate and their stabilisation will take place at a higher level (worse condition). In a long term, annual global emissions will have to be reduced below 5 Gt CO_2, the amount absorbable by the Earth with no consequences for the atmosphere. To achieve this goal, a long-term emission reduction below 80 % of the current absolute emission level will be necessary. If we wish to stabilise CO_2 concentrations in the atmosphere at $450 \cdot 10^{-6}$ CO_2, the emission increase should stop in the next 10 years, followed by a reduction by more than 5 % per year, in order to fall to 70 % below the current level by the year 2050.

Carbon Capture and Storage (CCS) Economics

CO_2 is produced during any kind of combustion of fossil fuels, both in electricity generation and elsewhere, e.g. in transportation. Certain industrial processes, such as steel production, cement manufacture or oil refineries, are significant CO_2 polluters as well. The CCS technology prevents CO_2 produced by large stationary sources, such as coal power plants, from entering the atmosphere. The technology attempts to capture 90 % of emissions from these sources and permanently prevent their entrance into the atmosphere. CCS is designed to achieve the above-mentioned goal in three steps. In the first step, CO_2 is captured in the facility and compressed. In the second step, it is transported to the storage location. The third step is a procedure of permanent geological storage.

Every of these three steps can be performed in various manners. Fossil fuel combustion produces CO_2, water vapour and a large amount of nitrogen. In the capturing process, CO_2 must be extracted from this flow. There are three basic methods for CO_2 capture in fossil fuel combustion.

The first method is called Oxy-Fuel. In this method, the fuel burns with pure oxygen instead of air, which minimises the nitrogen content in exhaust gases. From the remaining exhaust, CO_2 separation is relatively simple. The oxygen required for such CO_2 capture is produced in situ, from air. In another capturing method, Post-Combustion Capture, CO_2 is separated from exhaust gases by using absorption solutions. The third method is called Pre-Combustion Capture. Before combustion, the fuel is processed into a mixture of CO_2 and hydrogen from which CO_2 is separated. Electricity is then generated from pure hydrogen.

For CO_2 transport, the use of transportation pipelines is most probable, with an additional option of transportation by vehicles and ships.

CO_2 can be stored in various geological formations in exploited oil or gas fields. Natural underground saltwater deposits can be used as well.

Compared to regular power plants, the CCS technology is more expensive for four reasons. First of all, equipment for CO_2 capture must be installed in the power plant. Then, the capturing process needs power supply, which increases fuel consumption. Another cost is the construction of the pipeline for CO_2 transportation, followed by the cost of CO_2 storage. All above-listed costs mean increased investment and operation costs of a CCS power plant. The differences in price are relatively large. For example, construction of a regular 900 MW thermal power plant (without CCS technology) will in the year 2020 require approximately 1.5 billion EUR investment funds. A similar power plant equipped with CCS technology will cost approximately 50 % more. Investments in pipelines, storage and operation represent a relatively low additional cost.

Greenhouse Gas Emission Potential with the CCS Technology

Considering the current global share of fossil fuels in primary energy source consumption, the current increase in energy consumption in new markets as well as the importance of reliability and economics of electricity supply, the experts predict the current share of fossil fuels to remain the same until the year 2030 and beyond, despite an increased share of renewable resources. This applies both globally and to the European Community. Approximately 30 % of electricity in Europe is currently generated from coal. According to the IEA data, the share of electricity generation from fossil fuels will, in the event of realisation of predicted electricity consumption growth, actually double by the year 2030. The fuel with the largest share among fossil fuels is coal. It represents today 40 % of the entire global primary energy source consumption and it will increase to 45 % by the year 2030.

Currently, the CCS technology is the only known technology that can be used to reduce emissions from the existing CO_2 sources, not only from fossil fuel power plants representing nearly a half of all CO_2 sources in the European Community, but also from plants like steel factories, cement manufactures and refineries.

For that reason, the CCS technology has an important CO_2 reduction potential. Various reports indicate that the CCS technology might reduce 1.4–4 Gt of CO_2 emissions globally by the year 2030, 0.4 Gt of which in the area of the European Community, representing 20 % of all possibilities of CO_2 emission reduction in the European Community.

The CCS technology requires a longer implementation period before it is fully exploited. It involves highly demanding projects; with large investments in individual facilities. Consequently, every plant equipped with the CCS technology can achieve a large emission reduction potential. In individual power plant based on the CCS technology can satisfy electricity supply needs of 1.5 million European citizens. For comparison purpose, 1400 typical 2.3 MW wind turbines would have to be built to satisfy such needs. Nuclear and coal power plants are currently typical power plants for base power generation in Europe. Shutting down of coal power plants resulting from eventual failure of the CCS technology would have serious negative consequences for the reliability of electricity system operation.

Current Situation in the Area of CCS Technologies

Despite the fact that numerous components of the CCS technology are considerably mature and proven, we currently have very few experiences with comprehensively integrated commercially feasible CCS projects in operation. If we take a look at individual areas:

- The capture technologies are based

on mature applications in chemical and refinery industry, but an integration of such technology in power plants has not yet been commercially tested in practice.

- Long-range CO_2 transport in pipelines has been successfully used in the central region of the United States of America for over 30 years. More than 5000 km of such pipelines are used, enabling increased exploitation of oil wells. Using this technology, CO_2 is injected into oil wells, increasing the amount of pumped oil.
- Geological storage of CO_2 has been tested in operation mostly in the last 10 years. The industry could benefit from the knowledge acquired through geological storage of natural gas that has been carried out in practice for several decades.

Comparison of CCS Technology Costs in Three Development Phases

Costs of early commercial projects: these projects will be the first to reach the final dimension and technology implementation, their finalisation is planned for the first years after 2020 and they are estimated to 35–50 EUR per tonne of reduced CO_2 emissions.

Costs of initial demonstration projects: due to reduced size of plants and due to emphasis on proving the applicability of technology on account of optimal economic operation, these projects will

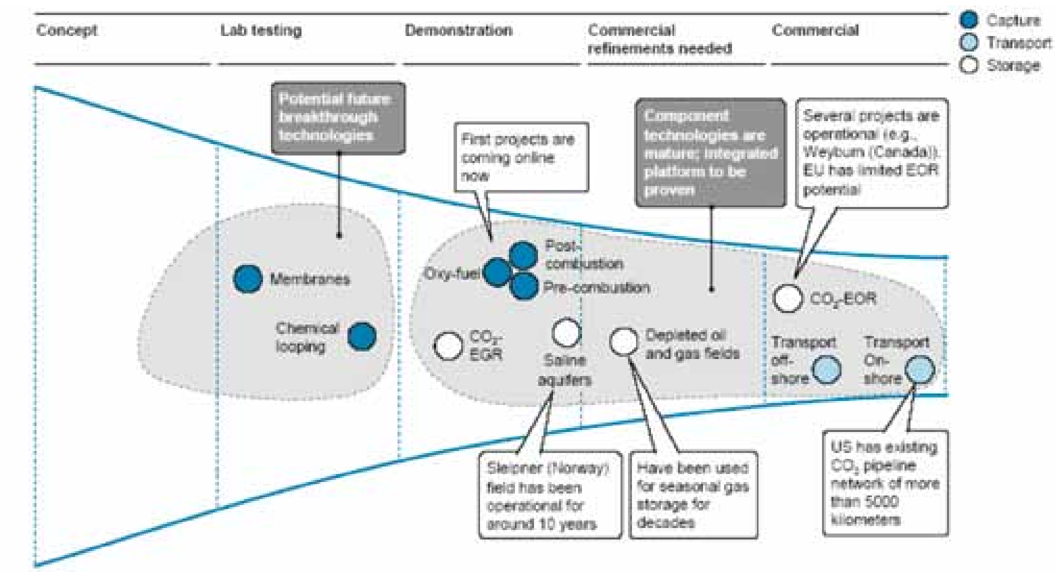

Figure 2. R&D situation of CCS technology (Carbon Capture and Storage: Assessing the Economics, 2008)

express costs between 60 EUR and 90 EUR per tonne of reduced CO_2 emissions. The costs here can vary significantly. Costs of some projects where borderline technological solutions will be tested, such as long-range transport, might also exceed the estimated framework. The finalisation of these projects can be expected in the years 2012–2015.

Cost development in the period following the early commercial phase: during this period, the costs will depend on numerous factors, such as additional experience of construction, plant expansion, availability of suitable storage location and actual breakthrough and/or mass use of CCS technologies. With a planned breakthrough involving 80 to 120 projects by the year 2030, the implementation of the CCS technology in new power plants might achieve 30–45 EUR/t of reduced CO_2 emissions. In case of larger global acceptance of CCS technologies reaching 500 to 550 projects by the year 2030, an additional cost reduction of 5 EUR/t of reduced CO_2 emissions could be gained on account of the technological breakthrough of new CO_2 capture technologies.

€/t of reduced CO_2 emissions; rounded to 5 €; considering the European scenario of CCS expansion.

Costs of other CCS technologies (e.g. modification of existing power plants into CCS, use of CCS in the industry) may significantly deviate from the above values.

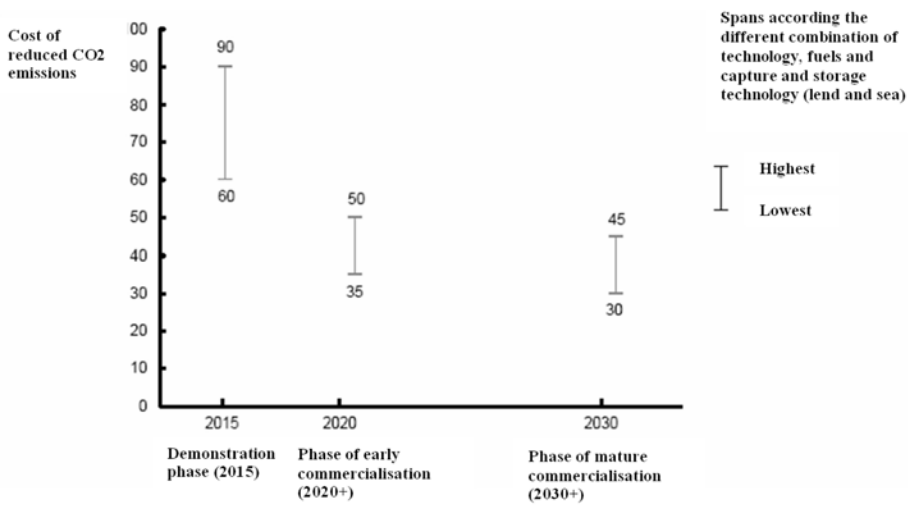

Figure 3. CCS total cost – reference case

The Technology of Coal Power Plants with Carbon Capture and Storage

A commercial realisation of clean coal technologies for capture and geological storage is currently not yet available. Several years of development and testing will be necessary to prepare a successful, widely planned implementation on a global scale. Premature attempts of implementation of clean coal technologies in the view of concern for climate changes could result in increased costs and additional environmental hesitations of local communities which might lead to delays in the final implementation of the technology.

Pulverised Coal Combustion

Pulverized Coal Combustion (PCC) is currently the most widely spread technology of coal combustion in thermal power plants. The technology is based on several decades of experience. In pulverised coal combustion, fine-ground coal is blown into the steam boiler where combustion takes place. The released is collected through water filled pipes of the boiler and through several further heat exchangers to receive high-pressure water steam for the steam turbine to power the electricity generator. Although PCC units can be built for various sizes, it can be assumed that PCC is appropriate for electricity generation in larger units (>300 MW).

Fluidised Bed Combustion

In the technologies of fluidised bed combustion (FBC), the coal is also first pulverised. The particles are somewhat larger in FBC technologies, and the velocity of blowing the air into the furnace is lower causing the coal in the furnace to float.

The FBC technologies have some environmental advantages compared to classical PCC technologies:

- The combustion temperatures are generally lower, around 427 °C, reducing the amount of nitrogen oxides,
- The cost of expensive flue gas desulphurisation (FGD) devices can be avoided by adding limestone directly to the fuel in the fluidised bed. By varying the amount of added limestone, combustion of coals with very different nitrogen content is made possible.

CO_2 Capture in Pulverised Coal Combustion Power Plants

CO_2 is separated from flue gases at low concentration and low partial pressure. One of possible approaches to separation is an amine-based chemical absorption. CO_2 separation from flue gases requires energy, mostly in the form of low-pressure steam for the amine solution regeneration. This causes lower steam parameters and net power at the turbine outlet. Therefore, generation of the same amount of power requires more coal, a larger steam boiler, turbine and other elements.

Thermal energy for CO_2 separation from amine solution reduces the power plant's utilisation rate by 5 %. Further 3.5 % of utilisation rate is used for CO_2 compression from 0.1 MPa to approximately 15 MPa (to supercritical fluid). All other requirements amount to less than 1 %.

CO_2 Capture with Oxygen Coal Combustion

The essential feature of CO_2 capture using this technology is coal combustion fired by oxygen instead of regular air. Such combustion results in high CO_2 content in flue gases, which enables a direct CO_2 compression. The air separation unit used for production of pure oxygen is the largest factor of utilisation rate reduction in oxy-fuel power plants. Therefore, the technology is only useful in combination with CO_2 capture.

Coal Gasification

Coal gasification technologies (IGCC - Integrated Gasification Combined Cycle) have been known for very long, but are only now becoming interesting for electricity generation. There are several technologically different options of coal gasification tested in large demonstration projects around the world. Gasification based on blowing pure oxygen in superpressure conditions into the sludge consisting of ground coal and water steam appears to be the most promising. In the superpressure reactor, the reduced atmosphere causes incomplete combustion, the primary product of which is a gas mixture consisting mostly of two gases: hydrogen and carbon monoxide, called syngas (synthetic gas):

$$2(CH_2) + O_2 \rightarrow 2CO + 2H_2 \qquad (1)$$

Prior to further use in a combined gas-steam process, the synthetic gas must be cleaned of solid particles, sulphur, mercury, possibly even carbon dioxide CO_2 and other admixtures. Acquired chemical compounds can be stored or used further in the chemical industry.

The coal gasification technologies have the following advantages:

- combustion of cleaned syngas has very low emissions of harmful substances in flue gases, compared to flue gas emissions from combustion of natural gas,
- with the use of the latest gas turbine technologies, high total utilisation rate of gas-steam processes (up to 48 %) can be achieved in combustion of syngas,
- coal gasification is also possible for coals with a very high sulphur content,
- the syngas combustion process sinter-glass ash locking in the majority of other chemical compounds in

flue gases
- syngas combustion offers a high potential for carbon dioxide separation and storage, and
- a potential for hydrogen generation.

CO_2 Capture in Coal Gasification Power Plants

Carbon dioxide separation and storage in the IGCC process can be achieved by converting carbon monoxide into carbon dioxide (»CO shift«) during the syngas cleaning process. After that, syngas basically consists only of hydrogen. Doubling or tripling of oxygen production modules and reformers is necessary to provide adequate availability of the entire thermal power plant. In the future, additional improvements of the process are possible, which might contribute to improved utilisation rates up to 2 %.

Modernisation of Current Coal Power Plants for CO_2 Capture

Numerous countries around the world decide on the future of the existing power plants and on the limitation of CO_2 emissions. The following options are most often discussed:
- to significantly increase the power plants' utilisation rate,
- to continue operation and achieve emission reduction in other areas,
- to shut down power plants and replace them with new ones with an installed system for capture and geological storage of CO_2,
- to modernise the existing power plants for capture and geological storage of CO_2,
- to ignore the emission reduction and pay for CO_2 emissions.

In modernisation of the existing power plants and their facilitation for CO_2 capture, the technological selection is important, as well as the maturity of used technology, operation conditions and reliability, impact on the utilisa-

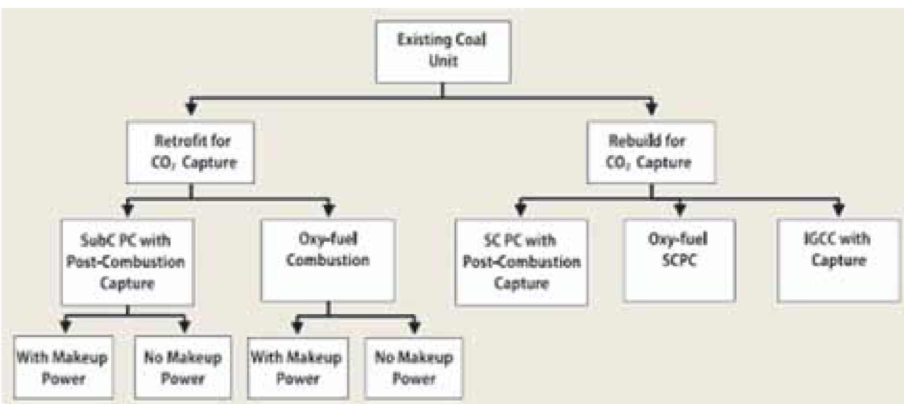

Figure 4. Thermal power plant process without CO_2 capture

tion rate and the complexity of modernisation. In the economic sense, the investment value is important, as well as the reduction of output power of the power plant and a change in price of power plant operation influencing the frequency of its operation.

Possible Realisation of Financing Mechanisms

Electric Industry Association in Europe defends the following options regarding the realisation of financing:

- financing from auction income,
- financing from the reserves of coupons for new investments related to auction mechanisms of coupon trading,
- financing from the reserves for new investments with a direct distribution of coupons

None of the listed mechanisms uses direct public funds. Emission coupons will be financed by the producers of electricity themselves or, indirectly, by the electricity consumers.

Financing of demonstration projects from auction income

In the third phase of the European emission coupon trading scheme, there will be a substantial generation of funds and their transfer from the producers of electricity to state treasuries of the EU member states. The European Commission suggests for a portion of these funds to be devoted for the development of clean technologies, including the development of demonstration CCS projects. Should these funds not suffice, they could be replaced by the funds from the reserves of coupons for new investments. In the European Community such financing mechanism has a strong support of the Electric Industry Association.

Financing from the Portion of Reserves of Coupons for New Investors

In the European emission trading scheme, 5 % emission coupons are to be reserved for new investors. In the period 2013–2020, it would mean 5 % of 14 800 million coupons, or approximately 740 million coupons. Independently of the CCS projects, it is the opinion of the Electric Industry Association that a 5 % reservation is too high, as it exceeds real expectations of new investments in the participating sectors.

A portion of the reserves for new investors could be reserved for new demonstration CCS projects, with an unchanged amount of emission coupons intended for trading by the member states. The European Commission would then elaborate a methodology for distribution of these coupons. The mechanism of coupon financing from the portion of reserves for new investors would:

- provide a coordination at the European Community level;
- create fund sources without affect-

ing the state treasuries of the member states;
- potentially avoid negative impacts on the European trading scheme; depending on a concrete proposition on the coupon allocation given by the European Commission.

Considering the amount of coupons to be reserved from the portion of reserves for new investors and intended for demonstration CCS projects, the estimates range around 500 million coupons. This proposition was recently presented in the European Parliament, the governing body adopting the amendments to the European emission coupon trading scheme.

Below are listed some possible solutions to the question of how to distribute the reserved coupons. The coupons can be sold at the central auction and the acquired income can be distributed among the projects. Another option is to hand over the coupons directly to the managers of demonstration projects to sell them at auctions by themselves.

Financing of Investments by Auction Sale of Reserved Coupons

Auction Sale of Reserved Coupons

A certain amount of coupons could be distributed by the commission or any other authorised body at a special auction, thus creating an investment fund put at the disposal of the commission or a special committee made of representatives of member states.

Funds Distribution among Competitors

As already stated in the chapter on basic principles of financing, the allocation of funds must be based on rules of competition in order to provide the highest possible value of the money spent in the programme and enable the demonstration project programme to achieve its purpose. The European Commission, the member states and organisation must define terms and conditions for the acquisition of financial funds; they must include a series of criteria. The CCS projects can, on the basis of terms and conditions, prepare competitive offers including the demanded scope of funds and the time necessary for the realisation of projects. The financial support may be given for both investments and operation of the demonstration CCS project; therefore, the competitor must define both the amount of necessary funds and the dynamics of funds' spending. The projects must be comprehensive and must comprise the entire chain of the process of CO_2 capture and geological storage; therefore, the offers can also be prepared by consortiums of managers of several different components of the demonstration CCS project. The offer price must include costs of all elements in the chain.

The fund manager may establish the best offers on the basis of the scope of the demanded funds and on the basis of a comprehensive complying with the selection criteria. The fund manager should distribute the financial funds in a manner to provide a variety of demonstration projects according to the technologies used in the capture areas, CO_2 transport and storage, and a wider geographical coverage, in the most cost-effective way.

The advantage of this method compared to direct distribution of coupons is that the funds are provided from the European coupon trading scheme, causing the least disruptions in this market. From the point of view of funds acquired for the projects, the mechanism is clear and reliable, with a minimum risk of too low or too high level of subsidisation. The mechanism is in accordance with basic principles of ETS, as it does not give away free coupons for CO_2 not released to the atmosphere. The projects are not subject to uncertainties in the emission coupon market.

Financing of Investments by Direct Coupon Distribution

In such case, the demonstration project bidders would either determine the amount of coupons that are, in their opinion, necessary for economic eligibility of the project, or provide a calculation of additional investment and operating costs. The acquirers of projects would then receive the coupons from the fund of reserved coupons, with the right of selling them at any time at the ETS market. By selling the coupons, the bidders of demonstration projects would acquire additional funds for the realisation of their projects. In order for the investors to receive timely assurance for the realisation of the projects, the projects could, during their first phase, already before the year 2012, receive a credit note and begin with the realisation. The credit notes would later be converted into actual coupons.

Advantages compared to the financing by auction sale of coupons:

- fast realisation,
- a simple system with low administrative costs,
- risks related to the emission market are carried by the projects themselves.

Criteria for Project Evaluation

In addition to economic criteria, the following elements should also be considered when defining criteria for acquisition of financial funds in the framework of European demonstration programme of CCS:

- consistency and maturity of the technological concept,
- potential for achieving long-term commercial goals,
- technical and commercial competences of partners in the project

providing a successful realisation and further commercialisation of the project,

- a commitment to a long-term management of the demonstration CCS project,
- variety and integrity of the entire programme in the following items:
  a. fuel,
  b. the size of the unit,
  c. the capture technology,
  d. transportation method,
  e. technology of geological storage,
  f. business plan,
  g. geographic dispersion.
- commitment to an exchange of acquired experience.

CONCLUSION

There are several ways how to reduce the risks appearing from climate changes. Appropriate solutions are to be determined only by suitable stimulations. Stability of concentration of greenhouse gasses in atmosphere is realizable, although the costs are rather high but can be mastered. Stimulations needed for modification of present investment samples and motion of resent global economy on reducing greenhouse gasses emissions can also be supported by various legal measurements. Activities for reducing greenhouse gasses emissions should be intensified and adopted to consequences of climate changes which can not be avoided anymore.

Reducing risks of climate changes can only be achieved by a coordinated action which means international cooperation, through international networks which support common targets. It can be achieved as a partnership between public and private sector, working class, civil company and individuals. It is still possible to prevent from the worst consequences of climate changes but only by a strong and urgent common action. Any delays would be very expensive and dangerous.

Latest respectable reports as IPCC report, Stern report and IAE report represented technology of capturing and geologic storage (CCS) as a basic potential for reduction of greenhouse gas emissions. Fossil fuels will continue to be an indispensable energy source at least till 2050, CCS represents an important factor of emissions reduction on stationary energy sources which are based on using fossil fuels. CCS technology is also one of the most important agents for reducing CO_2 in steel factories, cement factories and refineries. Their share in emission is about 15 %.

Renewable sources as wind and solar energy and other measurements as improvement of energy efficiency represent a chance to reduce emissions, but it would be too optimistic to expect that

Europe would achieve its targets on reducing greenhouse emissions only this way.

Various studies expect the potential of reducing emissions by CCS technology by 2030 will be between 1.5 Gt to 4 Gt CO_2 a year, in Europe 0.4 Gt CO_2 a year or 20 % of all the emission potential. Beside the reduce of CO_2 CCS technology can also help covering increasing energy demands and sustain energy supply in Europe. In case of using ecologic acceptable coal the dependence of imported gas would be reduced. CCS technology would also have effect on electric energy production, environmental acceptance of new technologies would be improved like using hydrogen or electric vehicles.

Today actually on meetings of large corporations, ministries and governments, where decisions about the kinds, types and characters of future coal power plants. Investments are huge, over 1000 million of USD a plant. Power plants, build today will be in use over next 60 years or more. International Energy Association (IEA) expects for the next 25 years on new power plats over 5 000 000 million USD will be spent. Considering these calculations the capacity of these new plants by 2030 will be 1800 GW. That means about 3000 large coal power plants or approximately 10 power plants each month for the next 25 years. New capacities represent a 1.5-times of all active power plants at present worldwide. It is amazing that seven of ten power plants planned to work in 2030 are still not built yet.

However, the facts listed above represent a great opportunity – in case of further investment into efficient energy use, many coal power plants can be replaced by clean renewable sources and not at last, new built power plants should be built the way that we could capture the CO_2 from them. This new concept would be different from the plants built by our ancestors.

If all the 3000 coal power plants of the new generation were built without equipment for CO_2 emission control, their emission would represent an enormous ecologic burden for our children and grand children. Through the planned life time these plants would produce over 750 billion of tones of CO_2. Consequences of these decisions would be omissions which in the next 25 years would exceed all the omissions ever done from the start of using coal till today for 30 %.

Unfortunately, improving technologies on power plants built without CCS technology according to MIT study are rather senseless due to the fact of large technical modifications even if the technology of supercritical dust or gasified coal combustion had been used.

New power plant built in 2030 – CCS technology costs are to be between 35 EUR/t and 50 EUR/t of reduced emissions CO_2. The price level is equal to expected price of CO_2 coupons during that period. The costs of early demonstration projects would be expected much higher, between 60 EUR/t and 90 EUR/t of reduced CO_2 emissions. CCS technology costs could even be more reduced in case of global spread of the technology or in case of completely new technologies, which are still being tested in labs.

Costs of sample projects can vary from a reference power plant, depending on their specific characteristics. At present, costs of diverse technologies of CO_2 capture are rather similar, but the costs of reconstruction on existing power plants will be rather much higher than on new coal facilities. Costs of reference power plant can also vary depending on the size of the plant, its location or technology. Transport distance can raise the price for approximately 10 EUR/t at 200 km distance. Relatively equalized prices of diverse capturing technologies effect on testing diverse technologies at the same time.

Building CCS into existing power plant will be economical acceptable only on new facilities with a basic high share of conversion efficiency.

There are practical realizable passages from demonstration phase to early commercial phase in 2030, but first a problem of storage and a business model should be solved. To reduce emissions of CO_2 for 0.4 Gt CO_2 by CCS technology in Europe by 2030 there should be between 80 and 120 commercial power plants built. They will probably form clusters of new and old, renewed CCS power plants and industrial projects, gathered into the same transport network and common location for storing CO_2. The speed of the expansion of CCS projects will effect on reducing emissions of CO_2 coming from the objects with CCS technology by 2030. But if the first commercial projects are not accepted soon after the demonstration phase or if delays in projecting occur because of gaining certain permissions, CCS technology will hardly be accepted before 2030.

Storage of CO_2 is probably one of the main insecurities, which could affect on advancing of CCS projects. Despite of all, experts are convinced that there is enough potential on storing CO_2 for many decades to come. Abandoned oil and gas fields are important possibilities, but they are mostly located in north sea, underground locations of salt water are more spread but less researched. It would be ideal if each main emission bunch would have its own underground reservoir of salt water, but it is also possible that transport lines to sea wells will have to be made.

For effective use of CCS technology potential in Europe demonstration program and appropriate planning of further commercial expansion of the technology should be started as soon as possible. There will be a few obstacles and doubts which will have to be abolished. Demonstration program with integrated CCS project could approve usefulness of technology, identify the risks, get public and industry trust into technology. It is necessary to open several demonstrative projects to test diverse capturing technologies and storage characteristics on diverse geologic locations connected to abandoned fuel deposits. Considering high costs for demonstration projects there is an economic difference between expected price CO_2 costs of building and operation of power plant in range of 500 mio. to 1000 mio. EUR/project. In coincidence with these demonstration projects or partly in connection with them, feasibility of storing CO_2 in underground deposits of salt water should be proved.

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Estimation of competitiveness of brown coal exploitation from the Trbovlje- Hrastnik mine

Ocena konkurenčnosti pridobivanja rjavega premoga iz Rudnika Trbovlje-Hrastnik

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Abstract: Coal is a fossil fuel, which, due to vast deposits of coal worldwide, boasts the longest exploitation time line of all fossil fuels. When it comes to power generation, coal has proven the most cost effective of all fossil fuels. A comparison of the cost of coal mined at the Trbovlje-Hrastnik mine (RTH) has been carried out using the cost of coal mined at the Ojstro mine (where mining is more cost-intensive than at the Trbovlje mines Plesko polje and III. polje). The competitiveness of the Ojstro mine coal has been assessed against the comparative advantages of the prices of produced coal and alternative energy sources, in particular the prices of imported coal and natural gas. The production price of coal from the Ojstro mine presently amounts to 3.33 EUR/GJ; in the entire studied period, this considerably exceeds the prices of coal in the European markets ranging between 1.75 EUR/GJ and 1.87 EUR/GJ in 2009, and between 2.38 EUR/GJ and 2.63 EUR/GJ in 2015. The calculations show that, considering the above assumptions, the interval of purchase price for imported coal ranges from 3.32 EUR/GJ to 3.48 EUR/GJ in 2009, and the prices will progressively climb from 4.16 EUR/GJ to 4.51 EUR/GJ in 2015. This effectively means that the

Original scientific paper

production cost of coal from the exploitation field of the Ojstro mine in 2009 is already lower or approximately the same as the purchase price for imported coal; over the coming years that ratio continues to improve in favour of coal from the Ojstro mine.

Izvleček: Premog je fosilno gorivo, ki ima zaradi svojih velikih svetovnih zalog tudi najdaljšo časovno perspektivo izkoriščanja. Tako proizvodnja kakor tudi poraba premoga v svetovnem merilu strmo narašča vse od leta 2000 dalje. Cenovno je premog izmed vseh fosilnih goriv za proizvodnjo električne energije najugodnejši energent. V Evropi je bilo do leta 1999 čutiti težnjo padanja tako proizvodnje kakor tudi porabe premoga, po tem letu pa se je težnja padanja ustavila ali celo obrnila, pri tem pa je začela naraščati vrzel med proizvodnjo in porabo, kar kaže na vseevropski porast odvisnosti od uvoženega premoga. Slovenska proizvodnja premoga ima od leta 1992 naprej težnjo upadanja, ki se bo s predvidenim zaprtjem premogovnikov v Zasavju še poglobila in bo kljub sočasnemu upadu porabe znova povečala razliko med porabo in proizvodnjo premoga, kar bo nadalje vodilo do povečane odvisnosti od tujih energijskih virov.

Konkurenčnost pridobivanja premoga v Rudniku Trbovlje-Hrastnik (RTH) smo primerjali pri stroškovno najzahtevnejši jami Ojstro, stroškovna cena za odkopavanje v jami Trbovlje (Plesko polje in III. polje) je nižja. Konkurenčnost pridobivanja premoga iz jame Ojstro temelji na primerjalni prednosti cen pridobljenega premoga in cen alternativnih energentov iz tujine, predvsem cen uvoženega premoga ter zemeljskega plina. Proizvodna cena premoga v odkopanem polju jame Ojstro, 3,33 EUR/GJ, je v celotnem preučevanem obdobju bistveno višja od cen premoga na evropskih trgih, ki so v letu 2009 od 1,75 EUR/GJ do 1,87 EUR/GJ, v letu 2015 pa bodo med 2,38 EUR/GJ in 2,63 EUR/GJ. Izračuni kažejo, da je glede na omenjene predpostavke interval nabavne cene premoga iz uvoza v letu 2009 od 3,32 EUR/GJ do 3,48 EUR/GJ, z leti pa bodo meje intervalov naraščale in bodo v letu 2015 dosegle vrednosti od 4,16 EUR/GJ do 4,51 EUR/GJ, kar pomeni, da je proizvodna cena premoga iz odkopnega polja jame Ojstro že v letu 2009 manjša ali približno enaka nabavni ceni premoga iz uvoza, razmerje med obema cenama pa se z leti izboljšuje v korist premoga iz odkopnega polja jame Ojstro. Upoštevajoč proizvodno ceno premoga iz odkopnega polja jame Ojstro je že v letu 2010 manjša kot nabavna cena zemeljskega plina, kot premogu alternativnemu energetskemu viru, razmerje med obema cenama pa se bo z leti še izboljševalo v korist premoga iz odkopnega polja jame Ojstro.

Key words: brown coal, competitiveness, electricity power supply and demand, energy sources, cost comparison
Ključne besede: rjavi premog, konkurenčnost, povpraševanje in oskrba z električno energijo, energijski viri, primerjava stroškov

Introduction

Up until and including the year 2009, Rudnik Trbovlje-Hrastnik (RTH) will supply the thermal power plant Termoelektrarna Trbovlje (TET) with coal in the planned amount of 0.6 million ton per year. Despite all economic and environmental disadvantages of coal, the EU will not significantly reduce the current consumption of domestic and imported coal. It would be reasonable to treat coal reserves in the Republic of Slovenia in a similar way. Replacing coal with other fossil fuels (probably with gas) will inevitably decrease the self-sufficiency in the Republic of Slovenia and increase the import dependence in electricity production as well.

Even after the year 2009, RTH intends to continue exploitation of coal from the Trbovlje mines (III. polje, Plesko polje), the Ojstro mine and from the already closed-down Hrastnik mine where there are still considerable coal reserves available. Considering the competitive conditions on the energy market, it will be reasonable to exploit all coal reserves.

In September 2008, our team at the Faculty of Natural Sciences and Engineering in Ljubljana elaborated the study "Justifiability of exploitation of the remaining coal reserves in the mines Ojstro and Trbovlje after the year 2009 and the closed-down section of the Hrastnik mine - Phase I", followed by Phase II and Phase III of this Study in March 2009. The objective of the Study was an assessment of feasibility and economic justifiability of continued exploitation after the year 2009, upon expiration, pursuant to the valid law, of state subsidies for pre-emptive dispatching of electricity from TET and upon termination of coal exploitation pursuant to the Act Regulating Gradual Closure of the Trbovlje-Hrastnik Mine.

In Phase I of the Study, the following activities were carried out:

- Evaluation of the approved expert report on coal reserves,
- Estimation of exploitation reserves in the coal layer Ojstro and Trbovlje,
- Determination of the necessary scope of additional exploration regarding coal reserves,
- Determination of the scope of preparatory works, from the technological, time schedule and financial aspect,
- Determination of excavation time schedule in relation to the coal's quantitative and energy value,

In Phase II of the Study, the following activities were carried out:

- Estimation of exploitation reserves in the coal layer of the already closed-down section of the Hrastnik mine,
- Determination of the scope of exploration and safety measures in the process of coal exploitation,
- Assessment of competitiveness of coal exploitation based on the data acquired from the Study and data on prices and transport costs for alternative energy fuels (imported coal and natural gas).

In Phase III of the Study, the following activities were carried out:

- Assessment of significance of electricity produced from this energy source for stable electricity supply in Slovenia and in the market relevant for Slovenian electricity suppliers and consumers.
- Assessment of influence of eventual opening works on the production, added value, employment rates as well as export and import currents of the Slovenian economy.

The Study provided answers to the following questions:

- Quantities of exploited coal and its calorific value,
- Indication of the scope of geological, geomechanical and hydrogeological research,
- Indication of the scope of opening facilities,
- Elaboration of time schedule and economic evaluation of costs for preparation works and excavation as well as economic model for the trend of its own price for GJ of produced energy.

The final result of the Study is the assessment of eligibility of continued exploitation.

Statistical indicators of global production and consumption of coal

Coal is a fossil fuel, which, due to vast deposits of coal worldwide, boasts the longest exploitation time line of all fossil fuels. According to Energy Information Administration (EIA), the world's coal production reached 7,036 million »short ton« (1 short ton = 907.18 kg) in the year 2007, while the consumption amounted to 7,193 million »short ton«.

Both production and consumption of coal have been demonstrating a strong upward trend on a global scale since the year 2000, when they were both at a level of approximately 5.000 million »short ton«. Figure 1 illustrates global production and consumption of coal from the year 1992. When it comes to electricity generation, coal has proven the most cost effective of all fossil fuels. Figure 2 illustrates the price of fossil fuels used for electricity production from 1995–2008.

Until the year 1999, Europe witnessed a downward trend of both production and consumption of coal, but after that year, the downward trend was stopped or even reversed. Figure 3, indicating European production and consumption of coal in Europe from 1992–2007, also illustrates an increase of the gap between production and consumption, indicating a pan-European increase in dependence on imported coal.

In the year 2006, 306,200 TJ of primary energy was used in Slovenia. Domestic energy sources were sufficient to cover 47 % of all Slovenian needs, and 53 % of energy needs were covered by imported sources which are mostly used for transport and heating. The main energy source in Slovenia is crude oil and its derivatives representing a more than

Figure 1. World coal production and consumption 1992–2007 (MST), Source: Energy Information Administration

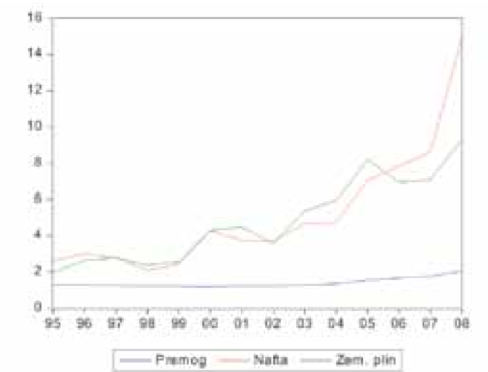

Figure 2. Fossil fuel prices for electricity production from 1995–2008 ($/MBtu), Source: Energy Information Administration

Figure 3. Coal production and consumption in Europe 1992–2007 (MST), Source: Energy Information Administration

34 % share, followed by nuclear energy and solid fuels with approximately 20 % each, natural gas with 13 % and renewable energy sources with 10 %.

As indicated in Figure 4, Slovenian coal production has been, since the year 1992, experiencing a downward trend which will fall even more after the planned closing of mines in the Zasavje region by the year 2015 – pursuant to the Act Regulating Gradual Closure of the Trbovlje-Hrastnik Mine and Development Restructuring of the Region (Official Gazette of the Republic of Slovenia, No. 61/2000) – and will, despite simultaneous decrease of consumption, again enlarge the difference between consumption and production of coal, which will lead to an increased dependence on imported energy sources.

With the purpose of studying the relevance of re-opening of the mine's exploitation fields, the price competitiveness of coal exploitation in the area of the Ojstro mine has been evaluated in comparison with alternative energy sources such as imported coal and natural gas. In the following text, we assessed the significance which the electricity produced from the studied energy source has in Slovenian electricity market. And finally, we assessed the influence that the eventual opening works in the exploitation field of the Ojstro mine might have on various macroeconomic variables of the Slovenian economy.

Figure 4. Coal production and consumption in Slovenia 1992–2007 (MST), Source: Energy Information Administration

Assessment of price competitiveness of coal exploitation from the Ojstro mine

The competitiveness of coal exploitation from the Ojstro mine is based on the comparative advantage of the prices of produced coal and foreign alternative energy sources, in particular the prices of imported coal and natural gas. Therefore, the following estimation of coal price trends in the European market has been made, together with the estimation of trends of purchase prices for imported coal in the period 2009–2015, and followed by analogue estimates of price trends for the alternative energy source, natural gas. The reference point for estimating the coal price trends are the prices of Richards Bay and ARA coal in European Energy Exchange EEX. For the year 2009, the price of both products has been calculated as an average of quarterly futures contracts in the current year.

Equally, coal prices until the year 2013 have been acquired from prices contained in annual futures contracts. For the years 2014 and 2015, a 3 % growth of coal prices is predicted. Since the prices are given in USD/t, a conversion into EUR/GJ was also made. The production price of coal in the area of exploitation field of the Ojstro mine amounts to 3.33 EUR/GJ (Dervarič, 2008: Table 11), with an assumption that the average energy value of coal for electricity production is 27 GJ/t (Energy Conversion Facts), and, furthermore, that the exchange rate EUR/USD is 1.29 and remains unchanged during the studied period. Final results are listed in Table 1, with prices in EUR/GJ in the last two lines. It is evident that in the entire studied period, the production price of coal from the Ojstro mine, which amounts to EUR 3.33 EUR/GJ, considerably exceeds the prices of coal in the European markets ranging between 1.75 EUR/GJ and 1.87 EUR/GJ in 2009, and between 2.38 EUR/GJ and 2.63 EUR/GJ in 2015. The calculations have been made using exclusively exchange prices of coal which significantly differ from the purchase price of coal in the global market; namely, to calculate an adequate purchase price, it is strictly necessary to add sea shipping and railway transport charges as well as various handling charges to the exchange prices of coal. The distribution of additional charges is shown in Table 2.

Table 1. Coal price evaluation in European market, Source: EEX, EIPF (February, March 2009)

	2009	2010	2011	2012	2013	2014	2015
	USD/t						
RB	61.11	68.81	73.13	76.88	78.13	80.47	82.89
ARA	65.26	74.40	80.35	85.20	86.45	89.04	91.71
	USD/GJ						
RB	2.26	2.55	2.71	2.85	2.89	2.98	3.07
ARA	2.42	2.76	2.98	3.16	3.20	3.30	3.40
	EUR/GJ						
RB	1.75	1.98	2.10	2.21	2.24	2.31	2.38
ARA	1.87	2.14	2.31	2.45	2.48	2.56	2.63

Note:

- RB – Richards Bay, South Africa;
- ARA – Amsterdam-Rotterdam-Antwerpen (60 % Africa, 30 % Colombia, 10 % Australia)
- The exchange rate EUR/USD is 1.29 and is assumed to remain unchanged throughout the entire period.
- The average energy value of coal amounts to 27 GJ/t.

Table 2. Imported coal price evaluation, Source: Slovenian Railways' tariffs, EIPF

	2009	2010	2011	2012	2013	2014	2015
Richards Bay ($/t)	61.11	68.81	73.13	76.88	78.13	80.47	82.89
Cargo shipping, charges ($/t)	21.39	24.08	25.60	26.91	27.35	28.16	29.01
Railway transport, charges ($/t)	17.67	17.67	17.67	17.67	17.67	17.67	17.67
Handling charges ($/t)	15.48	15.48	15.48	15.48	15.48	15.48	15.48
Total charges ($/t)	54.54	57.24	58.75	60.06	60.50	61.32	62.16
Coal purchase price ($/t)	115.65	126.05	131.88	136.94	138.63	141.79	145.05
Coal purchase price ($/GJ)	4.28	4.67	4.88	5.07	5.13	5.25	5.37
Coal purchase price (EUR/GJ)	3.32	3.62	3.79	3.93	3.98	4.07	4.16
ARA ($/t)	65.26	74.4	80.35	85.2	86.45	89.04	91.71
Cargo shipping, charges ($/t)	22.84	26.04	28.12	29.82	30.26	31.16	32.10
Railway transport, charges ($/t)	17.67	17.67	17.67	17.67	17.67	17.67	17.67
Handling charges ($/t)	15.48	15.48	15.48	15.48	15.48	15.48	15.48
Total charges ($/t)	55.99	59.19	61.28	62.97	63.41	64.32	65.25
Coal purchase price ($/t)	121.25	133.59	141.63	148.17	149.86	153.36	156.96
Coal purchase price ($/GJ)	4.49	4.95	5.25	5.49	5.55	5.68	5.81
Coal purchase price (EUR/GJ)	3.48	3.84	4.07	4.25	4.30	4.40	4.51

Note:

- RB – Richards Bay, South Africa;
- ARA – Amsterdam-Rotterdam-Antwerpen (60 % Africa, 30 % Colombia, 10 % Australia)
- The exchange rate EUR/USD is 1.29 and is assumed to remain unchanged throughout the entire period.
- The average energy value of coal amounts to 27 GJ/t.

Table 3. Gas price evaluation in Europe (2010–2015), Source: Bloomberg, Financial Times, EEX, EIPF

Ø spot 02/2009	2010	2011	2012	2013	2014	2015
USD/MMBtu						
4.10	4.85	5.52	5.84	5.84	5.84	5.84
USD/GJ						
3.88	4.59	5.23	5.53	5.53	5.53	5.53
EUR/GJ						
3.01	3.56	4.05	4.29	4.29	4.29	4.29

Note:

- The exchange rate EUR/USD is 1.29 and is assumed to remain unchanged throughout the entire period.
- Conversion factor is 1 MMBtu = 1.05506 GJ.

The calculation of purchase prices for imported coal is again based on prices of Richards Bay and ARA coal in European Energy Exchange EEX as listed in Table 1. Considering average sea shipping charges, an average share of sea shipping is calculated in the coal's purchase price in the amount of 35 % of purchase price, furthermore, handling charges in the amount of 12 EUR/t (i.e. EUR 1.2 per each started 100 kg of actual mass) and railway transport charges in the amount of EUR 13.7 per ton at the distance of 161–170 driven km and amount of 15 t should be added. Additionally, the items for handling charges and railway transport are assumed to be fixed, while the dynamics of sea shipping charges follows the dynamics of price growth. The results are listed in Table 2.

The calculations shown indicate that considering the above-mentioned assumptions, the interval of purchase price for imported coal ranges from 3.32 EUR/GJ to 3.48 EUR/GJ in the year 2009, and the prices will progressively climb from 4.16 EUR/GJ to 4.51 EUR/GJ in 2015. Considering the production price of coal from the exploitation field of the Ojstro mine amounting to 3.33 EUR/GJ, it is lower or approximately the same as the purchase price for imported coal already in 2009, and over the coming years that ratio continues to improve in favour of the Ojstro mine.

Another energy fuel competitive to coal from the exploitation field of the Ojstro mine is natural gas. Similarly as with imported coal, the price dynamics for the time period 2010–2015 has been estimated for natural gas, based on data for spot prices and prices contained in futures contracts.

The reference point for the current spot price of natural gas was acquired as an average of daily spot prices in February 2009. We acquired the data on prices contained in futures contracts for natural gas supply from EEX website as an average of prices in futures contracts GUD Natural Gas Futures and NCG Natural Gas Futures for the years 2010–2015 and used these prices to calculate interim growth rates. Considering the assumption that the dynamics of the spot price will converge towards the dynamics of prices of futures contracts for natural gas, we estimated, on the basis of the above-mentioned interim growth rates, the price dynamics of natural gas in the studied period. Basic data on natural gas prices is expressed in USD/MMBtu. Therefore, the factor 1 MMBtu = 1.05506 GJ (Bioenergy Conversion Factors(was used in conversion. The results are listed in Table 3.

The calculations shown in Table 3 indicate that considering the above-mentioned assumptions, the price of natural gas will range from 3.65 EUR/GJ to 4.29 EUR/GJ in the period 2010–2015. Considering the production price of coal from the exploitation field of the Ojstro mine amounting to 3.33 EUR/GJ, it is lower than the purchase price for natural gas (as an energy source alternative to coal) already in 2010, and with years, the ratio between both prices is improving to the benefit of coal from the exploitation field of the Ojstro mine.

ESTIMATION OF ECONOMICS OF ELECTRICITY PRODUCED FROM COAL MINED FROM THE OJSTRO MINE

The estimation of economic viability of the Ojstro mine coal being used for power generation purposes is based on the assumption that the coal intended for electricity production would be used in the thermal power plant Termoelektrarna Trbovlje (TET). At the same time, however, the overall electricity market in Slovenia should be analysed in terms of electricity supply and demand. The following text therefore briefly presents the construction of both functions in the Slovenian electricity market based on the study by BOLE, VOLČJAK (2006), followed by their upgrade in terms of the EU's environmental conditions regarding CO_2 emissions, both with a special accent on TE Trbovlje as the principal consumer of coal from RTH.

The function of electricity supply is a function of limit costs in all production volumes, except in production of peak electricity (in the event of "peaks" of electricity consumption) when it is necessary to switch on the production unit - power plant with the highest limit costs. Namely, the price for electricity from a limit unit should exceed the variable costs for the amount paid by a consumer for electricity in the periods of highest loads. The amount is, naturally, high enough to (usually) cover the fixed costs for all (including limit) producers. Basic production units (for production in "range") have low limit costs and high fixed costs. In "peak" production units, the amount of costs is exactly reversed. Limit costs of hydro power plants and the nuclear power plant are usually considerably lower than in thermal power plants.

In case of hydro power plants, limit costs also include the opportunity costs of water use and, in Slovenia, also concession charge costs. In thermal power plants, however, the additional fuel is by far the largest component of limit costs. In the future, opportunity costs of greenhouse gas emissions will be important for thermal power plants, i.e. costs of additional purchase of rights, which might significantly increase the thermal power plants' limit costs.

It can be expected that limit costs of individual production units will increase with growth of electricity production, particularly if production approaches the production unit's maximum capacity. However, foreign empirical studies do not confirm such limit costs increase of individual production units (power plants) in actual production volumes. The electricity supply functions are therefore horizontal in parts. The construction of the electricity supply function is described in detail in Bole, Volčjak, 2006.

In the construction of the supply function, the power plants are categorised according to the height of their limit costs, i.e. according to the order of their switching into the network (supply) in an efficient regulation of schedule; first the hydro power plants on the Drava river, then hydro power plants on the rivers Sava and Soča, the nuclear power plant Krško (NEK), the thermal power plant Šoštanj, TE-TO Ljubljana and Trbovlje and, finally, at "peaks" in the total consumption or in the event of sudden failure (as a system reserve), the power plant Brestanica. "Total consumption" means here the sum of domestic threshold consumption, plus differences between export and import of electricity; the threshold production is naturally higher than total consumption for transmission losses (approximately 2 %). The function was further expanded by import supply. The thus constructed supply function is shown in Figure 5 as the blue stair-step curve *S*.

When analysing the market, the function of electricity demand should also be assessed. The demand function is specified in the normal manner, with a price variable and other factors - demand variables. In tests for both electrical products, some explanatory variables known from foreign empirical research were tested as well (hourly variables of wind strength, temperature and cloudiness, monthly variables of industrial production, total domestic consumption, GDP), but except the spot price of electricity, only the variables of temperature and industrial production were statistically significant. The construction of the function is further described in BOLE, VOLČJAK, 2006.

After the liberalisation of the electricity market, the gross currents of electricity across borders of Austria, Croatia and Italy have increased considerably, even in short periods (days, months). Therefore, when analysing the equilibrium in the market in the more recent period, it is necessary to consider the overall (gross) electricity market. Due to substantially higher electricity prices in Italy, electricity is normally (net) exported across the border with Italy and net imported across the borders with Austria and Croatia. The demand function is therefore expanded by export demand from Italy. The thus constructed demand function is shown in Figure 5 as the magenta curve *D*, with the horizontal section representing export to Italy.

The equilibrium in the electricity market is established in the point of intersection of the functions (curves) of supply and demand. It is evident from Figure 5 that with the current electricity prices, the total production of TET is included in the switching schedule of Slovenian electricity producers, as the equilibrium point is situated to the right and above the section of supply by TET. This means that the limit costs of TET, which depend on the price of coal from RTH, are still low enough to enable the sales of the entire production of TET.

The second phase of limiting CO_2 emissions in the EU began already last year. The increase of prices of emission certificates will cause a relative rise of prices of electricity from thermal power plants in relation to other electricity producers.

Such change in limit costs of electricity producers (i.e. shift in the electricity supply) would be of secondary meaning to TET, as long as the size of change in limit costs didn’t influence the schedule of production-supply of “peak” electricity. However, if the change in limit costs caused a change of TET’s position in the electricity production schedule, the consequences could be drastically large for RTH, as they would cause either a reduction in coal’s purchase price that would enable TET to keep its position in the production schedule, or a reduction in consumption of coal from RTH for an entire shift of TET’s position in the electricity supply schedule through the balanced realisation of electricity in the market.

The nature of supply from domestic electricity producers prevents the prices of emission certificates to change the TET's position in the production schedule. But it is necessary to consider, in the analysis of the schedule, the gross function of electricity supply, i.e. the import electricity as well. As the limit costs (the price) of import electricity exceed the TET's limit costs, TET has until now entered the electricity supply schedule before the total supply of import electricity.

An increase of limit costs of import electricity in the event of increase in the price of emission certificates would be considerably lower than in TET, as the import electricity is derived from economies where coal is little used for electricity production (e.g. Austria) or where commitments for CO_2 emission reductions are substantially less strict, either due to non-development or non-membership in the EU (e.g. Bulgaria and Bosnia). A larger increase in prices of emission certificates could therefore cause the import electricity supply to start entering the electricity supply before TET, which would prevent TET from entering entirely into the electricity supply. The equilibrium point (intersection of supply and demand) in the electricity market is namely in the initial section of the import electricity supply. Furthermore, for the period until the year 2014, no visible shift of the gross demand function is expected, as there are no changes planned for cross-border transmission capacities with Italy and therefore they won't provide any larger export of electricity to Italy, which would actually cause a sufficient shift of the gross electricity demand function to the right and made it possible for the total production of TET to enter into the electricity supply even after the increase of prices of emission certificates. Let us study the possible effects of changed prices of emission certificates on the electricity supply by looking at two scenarios of reduction of available CO_2 certificates (European Commission, 2004). The first one is the "Kyoto forever" scenario where the volume of CO_2 emission in the EU would reduce by 5.5 % below the level from the year 1990 and remain there until 2030. The second scenario, "the Gothenburg initiative", predicts reduction of CO_2 emission in the EU by 13 % until 2020 and by 21 % until 2030. Figure 6 shows CO_2 emission for both alternative scenarios and for a spontaneous scenario without interventions. The necessary decrease of emitted certificates in both scenarios is illustrated in Figure 7. A significant reduction of available emission certificates would probably substantially increase their price. The estimates of the bottom limit of the certificate price increase by 2030 amount to 41 EUR/t of CO_2 in the first scenario and exceed 136 EUR/t in the second scenario (in prices from 2000).

The dotted lines in Figure 5 indicate the predicted change of the electricity supply function resulting from increase of certificate prices in both scenarios. It is obvious that an increase of limit costs of TET in the event of predicted consequences of the first scenario ("Kyoto forever") for the emission certificate price would be to small to change the schedule of TET's entering into the electricity supply. But at the same time, in the event of predicted increase of emission certificate price, the second scenario could, in the years 2014 and 2015 and definitely two or three years later, compromise TET's position in the electricity production schedule, as TET's limit costs would be substantially higher than electricity import price. This would cause the total production of TET to be excluded from the schedule of producers' entering in the energy system.

Analysis of the impact of eventual opening works in the Ojstro mine on Slovenian economy

The analysis of economic impact assesses the contribution of business activity, project or investment or change in production scope to the economy of a region or state. The analysis is based on the system of input-output models that constitute a part of national accounts of the economy. Input-output models show mutual connections between the sectors of the economy. They indicate the structure of production, production costs and revenues generated in the production process, currents of products and services produced within the framework of domestic economy, and currents of products and services with foreign countries. Using the input-output models, it is possible to establish the structure of production of a certain sector, share of added value, salaries and other labour costs, indirect and direct taxes and the number of workplaces necessary for the production of certain amount of output.

In the input-output modelling, direct and indirect effects should be distinguished. Indirect effects are additional revenues, workplaces, salaries and taxes directly generated or paid by the company carrying out a new project or investment, as in this case RTH with its investment into opening and exploration works in the area of the Ojstro mine. Direct effects are changes in the revenues of other companies in Slovenia, in the revenues of the entire population or in collected taxes resulting from the investment into the opening

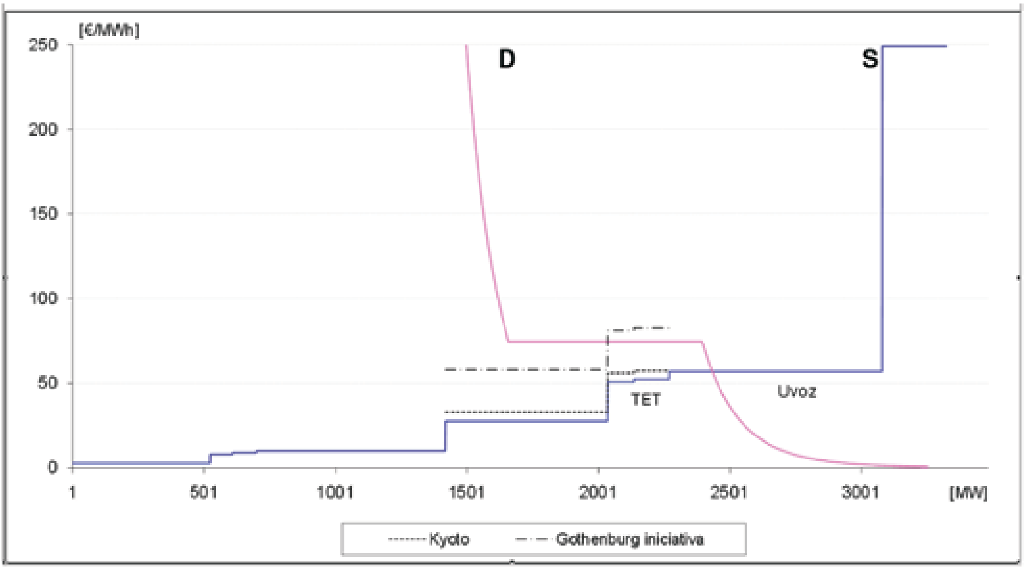

Figure 5. Gross electricity market (demand and supply) in the emission certificate reduction scenarios, Source: Bole in Volčjak (2006), European Energy and Transport – Scenarios on Key Drivers

Note: the ordinate represents the volume of allocated certificates in the volume share in 2006

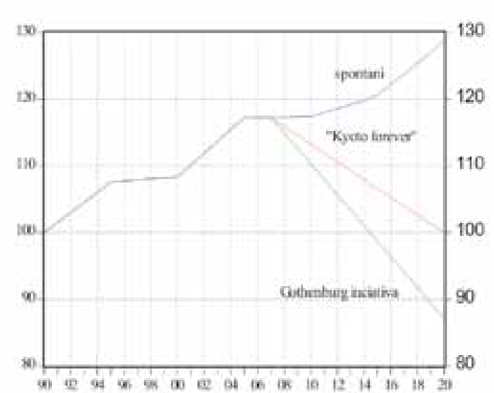

Figure 6. CO_2 emission reduction scenarios, Source: European Commission, 2004, EIPF

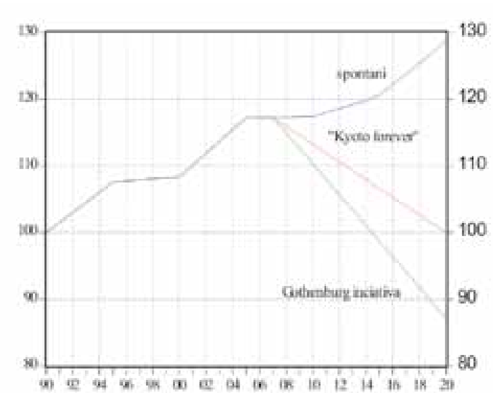

Figure 7. Emission reduction of allocated certificates at CO_2 emission shorten, Source: European Commission, 2004, EIPF

and exploration works. Indirect effects are derived from three factors. First, the company RTH acquires the inputs needed for investment and further production from the suppliers. This increases their revenues. Suppliers also acquire a part of their inputs from sub-suppliers. The effect of increased demand thus moves upwards on the value chain. Second, the employees at the company RTH and the employees at the company's suppliers spend their revenues and thus increase the demand for goods and services of numerous companies in Slovenia and their revenues as well. Similarly, the population's increased demand is transferred upwards on the value chain and influences an even larger number of companies. Total effects are the sum of direct and indirect effects. They represent an overall change in the economic activity of the country (value of production, added value, employment rates, import-export currents) resulting from RTH's investment in opening and exploration works.

The necessary opening works and their costs as well as exploration costs by individual exploitation fields in the area of the Hrastnik mine are itemised in detail in the Study (DERVARIČ, 2008), so Table 4 shows only their summary for the area of the exploitation field of the Ojstro mine. The opening and exploration costs in the area of the Ojstro mine have been estimated to the amount of EUR 2 million.

Table 4 also shows the potential production of the exploitation field of the Ojstro mine amounting to 730.000 t. Considering the actual calorific value of exploited coal in the amount of 11 GJ/t, the last column contains an average cost of opening and exploration per energy unit and amounts to 0.249 EUR/GJ.

Table 4. R&D costs at Ojstro pit, (DERVARIČ 2008)

Field	Production	Calorific value	Opening and exploration costs	Opening and exploration costs
	(t)	(GJ/t)	(€)	(€/GJ)
the Ojstro mine	730,000	11	2,000,000.00	0.249

Table 5. R&D costs at Ostro pit and their impact on slovenian economy

Sector of the economy	Change in production value (in 1000 EUR)	Change in share of added value (in basis points)	Change in number of employees	Change in import (in basis points)
A Agriculture, forestry	19.23	0.63	1	0.23
B Fishing	0.05	0.00	0	0.07
CA Mining of energy-producing materials	2036.96	18.59	11	49.08
CB Mining of ores and stones, except energy materials	10.10	0.05	0	0.41
DA Manufacture of food products, beverages, prepared feeds for farm animals and tobacco products	12.61	0.22	0	0.11
DB Manufacture of textiles, leather clothes, textile products and articles of fur	38.71	0.52	1	0.41
DC Manufacture of leather, foortwear, leather products, except apparel	3.31	0.04	0	0.12
DD Processing of wood, manufacture of products of wood, except furniture	84.99	1.19	2	1.52
DE Manufacture of pulp, paper and paperboard and articles of paper and paperboard	18.85	0.34	0	0.20
DF Manufacture of coke, refined petroleum products, nuclear fuel	53.34	0.00	0	0.44
DG Manufacture of chemicals, chemical products, man-made fibres	55.11	1.05	0	0.33
DH Manufacture of rubber and plastic products	29.62	0.39	0	0.25
DI Manufacture of other non-metallic mineral products	74.07	0.80	1	0.75
DJ Manufacture of metals and fabricated metal products	476.88	4.91	5	1.18
DK Manufacture of machinery and equipment	155.70	5.15	6	2.00

DL Manufacture of electrical and optical equipment	103.90	1.75	2	0.64
DM Manufacture of transport equipment	6.74	0.09	0	0.07
DN Manufacture of furniture and other manufacturing, recycling	20.90	0.69	1	0.52
E Electricity, gas and water supply	102.75	3.19	1	1.07
F Construction	88.73	2.53	4	0.41
G Wholesale and retail trade, repair of motor vehicles and other household goods	41.37	7.74	8	0.65
H Accommodation and food service activities	11.36	0.50	1	0.22
I Transport and storage	60.33	2.12	2	0.28
J Financial intermediation	58.68	2.31	1	0.53
K Real estate activities, rental and business service activities	243.82	8.65	4	0.51
L Public administration and defence, compulsory social security	2.89	1.16	1	0.19
M Education	3.43	1.38	1	0.24
N Human health and social work activities	1.49	0.54	1	0.11
O Other public, common and personal service activities	23.44	1.65	2	0.45
P Private households as employers of personnel	0.00	0.00	0	0.00
TOTAL	3839.37	68.18	55	62.99

In calculation of impacts of eventual opening works at the exploitation field of the Ojstro mine on Slovenian economy, the planned size of investment for opening and exploration works in the amount of EUR 2,000,000.00 was taken into account and the Supply table at purchasers' prices from the year 2005, issued by the Statistical office of the Republic of Slovenia and partitioned to 30 sectors, was used. The results are listed in Table 5.

The second column of Table 5 shows the absolute change in value of production by economy sectors. It is evident that, as expected, the investment impact is the strongest in the sector »Mining of energy-producing materials«, with an increase in production by approximately EUR 2,037,000. The observed investment also has a strong impact (over EUR 100,000) on production in the sectors »Manufacture of metals and fabricated metal products« (EUR 477,000), “Real estate activities, rental and business service activities” (EUR 244,000), “Manufacture of machinery and equipment” (EUR 156,000), “Manufacture of electrical and optical equipment” (EUR 104,000) and “Electricity, gas and water supply” (EUR 103,000). The eventual opening works have a slightly less strong impact on the construction sector, where there is a production increase by EUR 89,000 and on the sector “Processing of wood, manufacture of products of wood, except furniture” which would have an increase of EUR 85,000. In other sectors, the impact on production is less pronounced or negligible. The entire effect of production increase amounts to EUR 3,839,000.

It is evident from the third column of Table 5 that the structure of added value is changed the most in the sector “Mining of energy-producing materials” where its share increases by 18.6 base points. A change (an increase) in share of added value can also be noted in the sectors “Real estate activities, rental and business service activities” (8.7 base points), “Wholesale and retail trade, repair of motor vehicles and other household goods” (7.7 base points), “Manufacture of machinery and equipment” (5.2 base points) and “Manufacture of metals and fabricated metal products” (4.9 base points). In other sectors, the effect on added value is less pronounced or negligible.

The effects on Slovenian employment are shown in the fourth column of Table 5. The results have been rounded to the whole number and show the strongest effect in the sector “Mining of energy-producing material” where the number of employees is increased by 11. In the sector “Wholesale and retail trade, repair of motor vehicles and other household goods”, the number of employees is increased by 8 persons, in the sector “Manufacture of machinery and equipment” by 6 persons and in the sector “Manufacture of metals and fabricated metal products” by 5 persons. In other sectors, the effect on employment is less pronounced or negligible. The total effect of the investment on Slovenian employment is 55 newly employed persons.

The fifth column of Table 5 shows the investment’s effect on import currents of the Slovenian economy. It is evident that the import is increased by nearly half a percent in the sector “Mining of energy-producing materials”. An increase of import can also be noted in the sector "Manufacture of machinery and equipment" (2 base points) and in the sector "Processing of wood, manufacture of products of wood, except furniture" (1.5 base points). In other sectors, the impact on import is less pronounced or negligible.

Conclusion

The calculations show that, considering the above assumptions, the interval of purchase price for imported coal ranges from 3.32 EUR/GJ to 3.48 EUR/GJ in 2009, and the prices will progressively climb to 4.16–4.51 EUR/GJ in 2015. This effectively means that the production cost of coal from the exploitation field of the Ojstro mine in 2009 is already lower or approximately the same as the purchase price for imported coal; over the coming years that ratio continues to improve in favour of coal from the Ojstro mine.

The projection of coal price trends shows that the coal at the RTH location, mined from the already closed-down Hrastnik mine can be sold at maximum 3.32 EUR/GJ, representing economy of costs that would be still acceptable. The coal could also be exploited in the long term (i.e. after 2015), at 3.32 EUR/GJ at the actual location of TET. However, any additional transport costs would increase the price of coal and result in operating loss.

Summary

Coal price forecasts indicate that RTH coal (the Ojstro mine, Plesko polje, III. polje) and even the coal from the already closed-down Hrastnik mine could be sold at a maximum of 3.32 EUR/GJ. That price would make the cost of operation economically viable. The coal could be mined in the long term (i.e. after 2015) at 3.32 EUR/GJ at the actual location of the Trbovlje thermal power plant. Any additional transport costs, however, would push the cost of coal upwards and result in operating loss.

The assessment of economic viability of the Ojstro mine coal being used for power generation purposes is based on the assumption that electricity would be generated at the local thermal power plant i.e. Termoelektrarna Trbovlje (TET). At the same time, however, the overall electricity market in Slovenia should be analysed in terms of electricity supply and demand and in conjunction with the existing or proposed CO_2 emissions standards applicable in EU, and in the context of TET as the principal consumer of RTH coal. At the current prices of electricity the entire TET output feeds into the power grid of Slovenian electricity producers as the power system equilibrium point is located to the right and above TET's supply segment. This effectively means that TET's break-even costs, which are directly subject to the price of RTH coal, are still low enough to make TET competitive in the market.

Under the initial CO_2 emissions scenario proposed by EU, the increase of TET's break-even costs would not be significant enough to change TET's role and function in the Slovenian power supply system. However, the second scenario with the proposed price increase of emission certificate allowances would push TET's break-even costs considerably above the price of imported electricity, which could seriously threaten TET's position as a supplier of electricity to the Slovenian market as early as 2014 and 2015, and definitely two or three years after that. As a result, the entire TET output would be excluded from the Slovenian power generation and distribution grid.

When determining the impact of reopening the Ojstro mine on the Slovenian economy, the investment involved in the reopening of the mine and associated exploration works has been estimated at EUR 2,000,000. The biggest effects of the investment would be felt in the sector "Mining of energy-producing materials", boosting production output by roughly EUR 2,037,000. The proposed investment would also give a significant production boost (in excess of EUR 100,000) to the following industry sectors: "Production of metals and fabricated metal products" (EUR 477,000); "Real estate activities, rental and business service activities" (EUR 244,000); "Manufacture of machinery and equipment" (EUR 156,000); "Manufacture of electrical and optical equipment" (EUR 104,000); and "Electricity, gas and water supply" (EUR 103,000). The impact on production output in other sectors would be less pronounced or negligible. The proposed investment would boost overall production by EUR 3,839,000. The biggest change in the share of value added would occur in the sector "Mining of energy-producing materials" (up 18.6 points). A change (increase) in the share of value added is also indicated in the following sectors: "Real estate activities, rental and business service activities" (up 8.7 points); "Wholesale and retail trade, repair of motor vehicles and other household goods" (up 7.7 points); "Manufacture of machinery and equipment" (up 5.2 points); and "Production of metals and fabricated metal products" (up 4.9 points). The impact on value added in other sectors would be less pronounced or negligible. The biggest impact on employment can be noted in the sector "Mining of energy-producing materials", resulting in 11 new jobs. Eight new jobs would be created in the sector "Wholesale and retail trade, repair of motor vehicles and other household goods", six in the sector "Manufacture of machinery and equipment", and five in the sector "Production of metals and fabricated metal products". The impact on employment in other sectors would be less pronounced or nil. The total effect of the proposed investment on national employment would be 55 new jobs. Imports would increase by just under half a percent in the sector "Mining of energy-producing materials". Also noteworthy are the impacts on imports in the sector

"Manufacture of machinery and equipment" (up 2 points) and the sector "Processing of wood, manufacture of products of wood, except furniture" (up 1.5 points). The impact on imports in other sectors would be less pronounced or negligible.

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Karakterizacija historičnih ometov kot del konservatorsko-restavratorskih posegov in arheoloških poizkopavalnih analiz

Characterisation of historical mortars as a part of conservation-restoration interventions and archaeological post-excavation analyses

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Izvleček Karakterizacija historičnih ometov je po navadi del širših preiskav pri raziskavah določenega objekta. Rezultati, ki jih pridobimo s temi preiskavami, so ključnega pomena pri odločanju za najprimernejši konservatorsko-restavratorski poseg na določenem objektu, arheologom pa dajejo podatek o kronologiji, izvoru materiala in tehnologiji izdelave. V prispevku so poleg opisa metodologije preiskovanja historičnih ometov predstavljeni tudi značilni rezultati analiz vzorcev ometov, ki so bile opravljene v okviru nekaterih konservatorsko-restavratorskih projektov ali poizkopavalnih arheoloških analiz v zadnjih letih v Sloveniji. Zaobjema karakterizacijo historičnih ometov, ki temelji na določanju petrološke ter mineralne sestave agregata in veziva. Pridobljeni podatki imajo tudi veliko dokumentacijsko vrednost, saj dajejo pregled informacij o sestavi različnih ometov iz različnih obdobij na območju Slovenije. Vsi ti podatki nam govorijo o smiselnosti vzpostavitve baze historičnih ometov.

Review paper

Abstract Characterisation of historical mortars is most often carried out for particular case studies. The analysis of historical mortars refines our knowledge of mortar composition and thus gives important information about the technology of mortar manufacturing of some period, indicates provenience of the applied raw material and eventually enables us to reconstruct original mortar. This study summarizes some results of historical mortars research that was part of several conservation-restoration projects or archaeological excavations during the past few years in Slovenia. Characterisation of these mortars based on petrological and mineralogical composition of used aggregates and binders. As systematic long-term collection of data about historic mortars can provide additional knowledge, creation of specific databases of historic materials, based on international cooperation and networks seem to be an important task for the future research on historic materials.

Ključne besede: historični ometi, mineralna sestava, kulturna dediščina, karakterizacija
Key words: historical mortars, mineral composition, cultural heritage, characterisation

UVOD

Karakterizacija historičnih ometov je po navadi del širših preiskav pri raziskavah določenega historičnega objekta in poteka v okviru konservatorsko-restavratorskih projektov ali poizkopavalnih arheoloških analiz. Rezultati, ki jih pridobimo s temi preiskavami, so ključnega pomena pri odločanju o najprimernejšem konservatorsko-restavratorskem posegu na določenem objektu, arheologom pa dajejo podatek o kronologiji, izvoru materiala in tehnologiji izdelave. Ti podatki nam omogočajo med drugim ločiti originalni omet od kasnejših preslikav ali sekundarnih slojev ter morebitno rekonstrukcijo originalne sestave ometa. Pomembna je tudi identifikacija procesov oz. produktov degradacije. Pridobljeni podatki imajo veliko dokumentacijsko vrednost, saj dajejo nabor informacij o sestavi različnih ometov iz različnih obdobij na nekem območju. Vzpostavitev baze v mednarodnem okviru bi omogočala informacije in umestitev analiziranih ometov v časovni in prostorski okvir, katere prvi predlogi so bili že predstavljeni na konferencah (VÁLEK, 2008).

Prvi začetki sistematičnega študija historičnih ometov segajo v leto 1981, ko je ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property) dal pobudo za vzpostavitev strategije preiskovanja historičnih ometov za potrebe obnove kulturne dediščine (Palomo et al., 2002). Od takrat naprej nastajajo številni prispevki, ki obravnavajo študij in karakterizacijo ometov iz raznih objektov (Luxán et al, 1995, Güleç et al., 1997, Riccardi et al., 1998, Van Balen et al., 1999, Degryse et al., 2002, Elsen et al., 2004, Benedetti et al., 2004, Meir et al., 2005, Paama et al., 2006), rimskih ometov (Charola et al., 1999, Hughs et al., 1999, Farci et al., 2005, Silvá et al., 2005, Sanchez-Morales et al., 2005, Genestar et al., 2006, Velosa et al., 2007, Zamba et al., 2007), hidravličnosti (Alvarez et al., 1999, Maravelaki-Kalaitzaki et al., 2005, Cardiano et al, 2004, Riccardi et al., 2007, Böke et al., 2008), tehnologije izdelave (Moropoulou et al, 2000, Pavía et al, 2008), propadanja (Arioglu et al., 2006) ali formuliranja novih ometov za konservatorsko-restavratorske postopke in vrednotenje mikrostrukture (Al-Saad, 2001, Maravelaki-Kalaitzaki et al., 2004, Maravelaki-Kalaitzaki, 2007). Več referenc o karakterizaciji, restavriranju in konserviranju historičnih ometov lahko bralec najde v zborniku »Historical mortars conference« (Bokan-Bosiljkov et al., 2008).

Prispevek v prvi vrsti obsega opis metodologije za celovito karakterizacijo vzorcev ometov in nam podaja vrsto informacije, ki jo lahko pridobimo z določeno preiskovalno metodo. Poleg tega so v prispevku predstavljeni tudi posamezni značilni primeri rezultatov analiz ometov, ki so bile opravljene v okviru nekaterih konservatorsko-restavratorskih projektov ali poizkopavalnih arheoloških analiz v zadnjih letih v Sloveniji. Ta je temeljila predvsem na določanju petrološke in mineralne sestave agregata in veziva v ometih. Vzorci ometov se razlikujejo glede na njihovo različno namembnost ter na različno časovno obdobje nastanka na geografsko različnih lokacijah. Odvzeti so bili s številnih objektov, ki so datirani od rimske dobe do baroka. V prispevku se uporablja skupni izraz ometi za vse vzorce, ki so sicer vezivne malte, malte za lepljenje kamnitih delov, podložne malte pri mozaikih, stenskih poslikavah, fasade ter za različne omete in opleske.

Delitev ometov

Omet je vrsta gradiva, ki ga nanesemo na nosilno konstrukcijo (stene, strop), da jo zaščitimo in povečamo njeno uporabno vrednost. Omete sestavljata agregat in vezivo, lahko pa so dodani še razni dodatki, ki spreminjajo lastnosti ometa oz. mu dajejo želene lastnosti. Ometi oz. gradiva, ki imajo podobno sestavo in funkcijo kot ometi, so še:

- malte, ki vežejo npr. zidake v trdno gradbeno konstrukcijo,
- ometi za izdelavo fasad,
- tlaki in estrihi za oblaganje tal (pohodnih površin),
- opleski oz. beleži in malte kot podlage za poslikave in mozaike.

Za vse so značilne naslednje sestavine: agregat, vezivo, voda in dodatki.
Omete delimo glede na:

- mineralno in petrološko sestavo agregata in veziva,
- porazdelitev velikosti delcev agregata,
- razmerje agregat/vezivo,
- vrsto in količino dodatkov.

Našteti parametri vplivajo na tehnologijo izdelave ometov, na njihovo mesto vgraditve, na vrsto uporabe in tudi na trajnost oz. na način propadanja.

Glede na vrsto veziva v ometu le-te delimo po RILEM-klasifikaciji (Réunion Internationale des Laboratoires et Experts des Matériaux, Systèmes de Construction et Ouvrages (angleški izraz: International Union of Laboratories and Experts in Construction Materials, Systems and Structures)) na malte oz. omete z vezivom iz:

- apna,
- apna in latentno hidravličnega materiala (tuf, vulkanski pepel, keratofir, roženci, diatomejska zemlja, žlindre, elektrofiltrski pepel, drobljena žgana glina),
- hidravličnega (cementnega) apnenega materiala,
- naravnega »rimskega« cementa,
- hidravličnega materiala (portlandskega cementa),
- sadre,
- gline,
- materialov organskega izvora,
- več različnih vezivnih materialov – kompozitno vezivo.

Več informacij o posamezni vrsti veziv lahko najdemo v članku PALOMO et al., 2002.

Prvi podatki o uporabi apna izhajajo iz časa neolitika, ko so odkrili ogenj in spoznali, da kamni, ki ob stiku z vodo otrdijo, lahko kalcinirajo, vidnejšo vlogo pa je uporaba dobila v bronasti dobi (CAZZALA et al. 2002, UROŠEVIČ, 2005). Presenetljivo je, da so že v prazgodovini (predvsem na Bližnjem vzhodu in v Mezopotamiji) tako dobro poznali gradbene materiale in gradbene tehnike. Egipčani so apnene omete le redko uporabljali, čeprav obstajajo podatki o uporabi le-teh pri gradnji piramid pred 2000 leti pr. n. š. Egipčani so bili prvi, ki so za vezivo uporabljali sadro in tako izpodrinili uporabo apna, čeprav drži, da se v nekaterih sadrinih ometih pojavi tudi apno. V času Grkov se je uporaba apna v gradbeništvu zelo razširila. V rimski dobi so se izboljšale metode (KRIŽNAR, 2006), ki so jih uporabljali Grki, in sicer za pridobivanje apna, tehnike nanašanja ometa, njegovo glajenje/poliranje, nanašanje v več plasteh, tudi dodajanje aditivov osnovni masi. V osemnajstem stoletju pa se je poleg apnenega veziva začel tudi razvoj hidravličnih veziv (hydraulic lime binder), ki so vsaj delno nadomestila apneno vezivo oziroma apnene omete. V devetnajstem stoletju je z razvojem portlandskega cementa hidravlični omet povsem izrinil apnenega. Vrsto hidravličnega veziva so sicer poznali že v 10. stoletju pred našim štetjem. To je bila vrsta cementa, žganega iz karbonatne in silikatne surovine do 1250 °C, ki je imela nekaj hidravličnih lastnosti.

Pregled preiskovalnih metod

Navadno je izbira metode odvisna predvsem od informacije, ki jo želimo pridobiti, in od količine vzorca, ki ga imamo na voljo. Medtem ko je določanje anorganske komponente ometov že dodobra osvojeno, pa se je pomen poznanja organskih dodatkov (kot so npr. proteini) pokazal šele v zadnjem času.

Osnovna analiza ometov v obliki poliranih zbruskov se začne z optičnim mikroskopom, ki nam prikaže strukturo in teksturo vzorcev ter da osnovno informacijo o kvalitativni in kvantitativni mineralni ter petrološki sestavi. Tako lahko opazujemo obliko, velikost in porazdelitev zrn agregata, ocenimo razmerje agregat/vezivo ter razmerja med posameznimi komponentami agregata. Lahko ugotovimo vrsto veziva in morebitnih dodatkov. Z optičnim mikroskopom ugotavljamo tudi stopnjo in vrsto poroznosti, kohezijo med sestavnimi deli ometa in razpokanost. Oblika in lega razpok nakazuje tudi verjetne vzroke za njihov nastanek. Te so lahko nastale kot posledica karbonatizacije ob strjevanju ometa, lahko pa so tudi posledica sekundarnih patogenih reakcij, zaradi katerih omet propada in izgublja trdnost.

Povprečna mineralna sestava ometa se določa z metodo rentgenske praškovne difrakcije (XRD), ki nam omogoča tako kvantitativno kot kvalitativno analizo.

Za natančnejšo analizo ometa, predvsem dodatkov ter veziva, pa uporabimo kombinacijo vrstične elektronske mikroskopije (SEM) in energijske disperzne spektroskopije (EDS). Metoda nam omogoča, da pri velikih povečavah dobimo vpogled v mikrostrukturo in kemijsko sestavo področij, ki nas bolj detajlno zanimajo.

Organske dodatke kot primarne vhodne surovine ali utrjevalce lahko določimo s FTIR-spektroskopijo. Metoda omogoča tudi določanje kvalitativne in kvantitativne mineralne sestave ometov. Nadaljnje preiskave vključujejo različne kvalitativne in kvantitativne mineraloške in kemične analize, ki med drugimi vključujejo preiskave z DTA/

TGA (MONTOYA et al., 2004), mikroramansko spektroskopijo (BOSCHETTI et al., 2008), PIXE (SONCK-KOOTA et al., 2008) in XRF (HOFFMAN et al., 1990).

Karakterizacijo dopolnjuje ugotavljanje mikrostrukture historičnih ometov (določanje poroznosti in porazdelitve por) in preverjanje kompatibilnosti ometov za obnovo, kamor poleg mineralne sestave spadajo tudi njihove mehanske in fizikalne lastnosti (MOROPOULOU et al., 2003).

Obstajajo tudi številne študije datiranja ometov z uporabo ^{14}C (HEINEMEIER et al., 1997, NAWROCKA et al., 2005, ZAURIDAKIS et al, 2007) ali luminiscence (ZACHARIAS et al., 2002, FEATHERS et al., 2008).

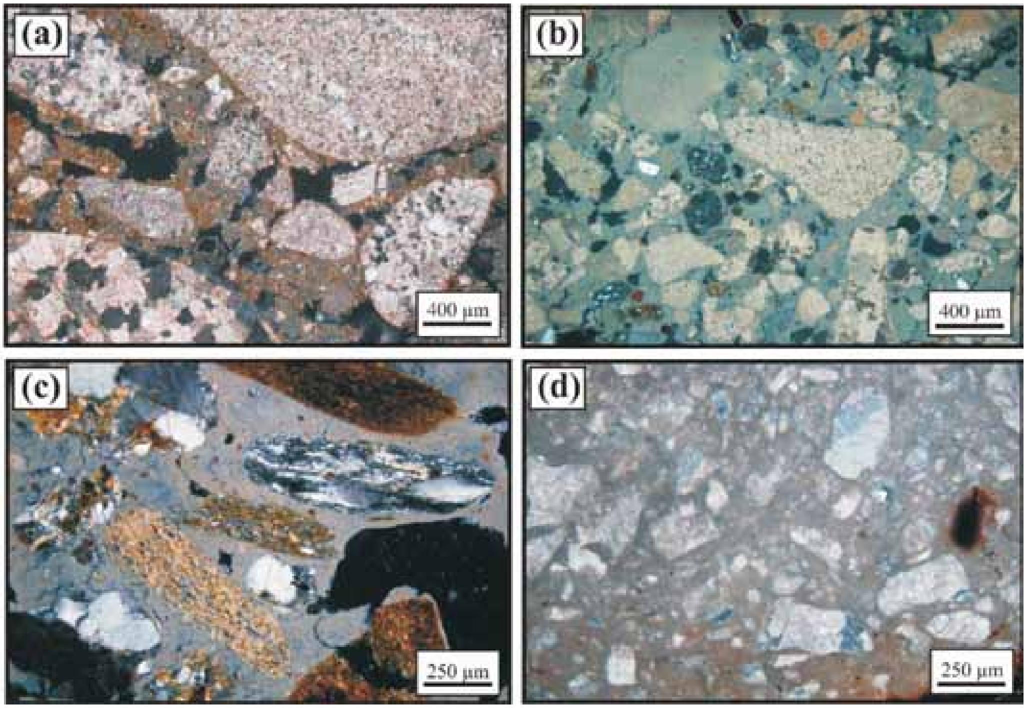
SESTAVA OMETA

Agregat

Agregat je skelet ometa in mu daje trdnost, poleg tega določa njegov barvni ton. Njegova poroznost pa vpliva na način in hitrost karbonatizacije. Osnovna naloga agregata je izboljšati mehanske lastnosti veziva (ometa ali malte). Agregat vpliva na volumensko stabilnost, trdnost in strukturne lastnosti (STEFANIDU et al., 2005). Zato je treba poznati njegovo mineralno/petrološko sestavo, razmerje vezivo/agregat, sortiranost ter velikost in obliko zrn agregata (ELICES et al., 2008).

Vrsta in oblika agregata nam lahko nakazujeta njegov izvor. Zaobljena zrna agregata so jasen znak, da je bil le-ta odvzet v rečni strugi oz. je bil odvzet v gramoznici kot drobnozrnata frakcija. Oglata zrna lahko kažejo na kratko transportno pot zrna do mesta, kjer je bil agregat odvzet za izdelavo ometa, ali pa kažejo na to, da je bil agregat pridobljen z drobljenjem kamnine – drobljenec. Opozoriti je treba, da so zrna, ki jih sestavljajo minerali z visoko trdoto, vedno manj zaobljena kot tista z nižjo trdoto. Tako med minerale z visoko trdoto prištevamo kremen, amorfno obliko kremenice – roženec in glinence ter po analogiji tudi kamnine iz teh mineralov (litična zrna magmatskih in metamorfnih kamnin). Med minerale z nizko trdoto spadajo karbonati (kalcit in dolomit) oziroma kamnini iz teh mineralov – apnenec in dolomit. Nizko trdoto imajo tudi litični delci glinavca. Zato so tudi ti delci zaobljeni.

Sestava agregata tudi v predstavljenih primerih variira glede na geografsko pozicijo objekta, časovno obdobje graditve objekta, kot tudi glede na vrsto aplikacije. Na podlagi dosedanjih raziskav lahko sklepamo, da so vhodne surovine za omete ponavadi pridobivali iz lokalnih virov. Najpogostejše je to pesek iz bližnjih rečnih strug. Tako na primer v okolici Radovljice prevladuje agregat s prevladujočo karbonatno komponento (sliki 1 a in 1 b), na območju Ljubljane pa agregat s prevladu-



Slika 1. Mikroskopske fotografije poliranih zbruskov prikazujejo različne vrste agregata. a) Prevladujoč karbonaten agregat v rimskem ometu za zidanje-malta. Presevna svetloba, prekrižani nikoli. b) Prevladujoč karbonaten agregat v rimskem ometu. Presevna svetloba, prekrižani nikoli. c) Prevladujoča zrna silikatnega agregata v ometu baročnih stenskih poslikav. Presevna svetloba, prekrižani nikoli. d) Drobljenec apnenca, uporabljen pri intonaccu rimske stenske poslikave. Presevna svetloba, prekrižani nikoli.

jočo silikatno komponento (slika 1 c). Silikatno komponento večinoma tvorijo litični delci raznih metamorfnih, magmatskih ter sedimentnih kamnin ter zrn glinencev, kremena in sljude iz kamnin zaledja porečja.

Dodatek drobljenega agregata (slika 1 d) ni tako zelo pogost v preiskanih vzorcih. Drobljeni so bili v glavnem le dodatki, kot so npr. žgane gline, sadra, marmorji ali žlindre. Po literaturnih podatkih je za omet najprimernejši drobljenec, saj se na hrapavo površino (nasprotno od sedimentov, ki imajo gladko površino) apno bolje oprime in je omet tako kompaktnejši (Križnar, 2006).

Velikost delcev in sortiranost se razlikujejo glede na namembnost različnih ometov. Tako je agregat v ometih dobro sortiran, z manjšimi zrni, medtem ko je v maltah slabo sortiran, delci pa so večji. Opleski agregata ne vsebujejo. Prav tako je slabša sortiranost značilnost ometov in malt, v katerih je bil kot vezivo uporabljen cement – hidravlično vezivo ali pa apneno hidravlično vezivo. Ti dve vrsti veziva sta postali aktualni šele v prejšnjem stoletju. Tako lahko tudi iz vrste uporabljenega veziva oz. glede na sortiranost agregata sklepamo na starost ometa.

Razmerje agregat/vezivo nam poda možen različen izvor preiskovanega ometa, na podlagi katerega je bilo možno potrditi različne gradbene faze objektov, iz katerih so bili vzorci ometa odvzeti (ZALAR, 2008, ZALAR et al., 2009 b).

Dodatki

Ometu so včasih primešali tudi razne dodatke in tako z njimi poskušali izboljšati njegove lastnosti. Ti dodatki so lahko bili anorganski (zdrobljena opeka, tufi, marmor, sadra, žlindre) ali organski (slama, živalska dlaka, kazein, sladkor, olje, kri). Včasih so dodajali tudi pigmente. Tako je bila tudi pri nekaterih preiskovanih primerih ugotovljena prisotnost posebnih dodatkov, da bi z njimi izboljšali oz. pridobili točno določene lastnosti ometa. Dodatki lahko deloma ali popolnoma nadomestijo agregat ali pa so le dodani vezivu.

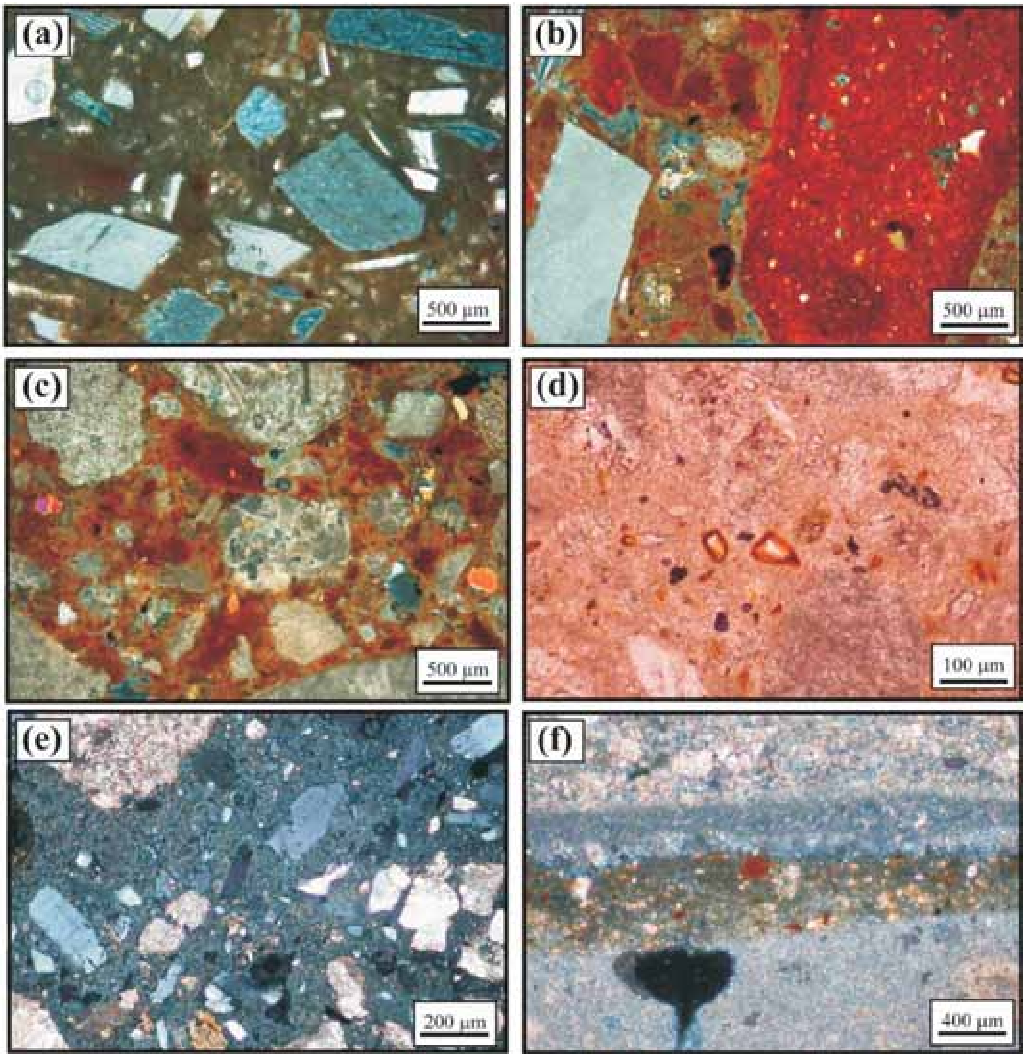
Anorganski dodatki

Poznamo reaktivne, latentno hidravlične (žlindra, žgana glina) ter inertne anorganske dodatke. V zunanji plasti belega glajenega ometa, ki je bil odvzet iz rimske vile, je bil kot agregat uporabljen drobljen marmor (KRAMAR et al., 2008), kot prikazuje slika 2 a. Posamezna zrna so bila dodana tudi v zunanji plasti rdečih stenskih poslikav iz istega objekta (slika 2 b). Po Vitruviusu (prevod 1960) naj bi dodatek marmorja izboljšal učinek poliranja. Sicer agregat marmorja med strjevanjem ometa ne vstopa v reakcijo in je inerten dodatek.

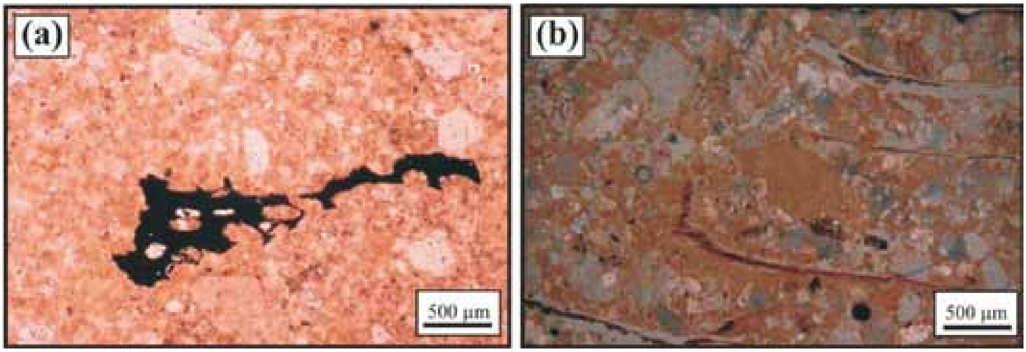
Za objekte iz rimske dobe iz rimskih term, kjer je bila potrebna vodoodbojnost materialov, je značilen dodatek drobljene žgane gline, kar prikazujeta sliki 2 b in 2 c (KRAMAR et al., 2008, ZALAR, 2009 a, LUX et al., 2009). Okoli teh zrn je pogost reakcijski rob (slika 6 b). V nekaterih fasadnih ometih cerkva je opazen dodatek steklaste žlindre (slika 2 d). Znano je, da sta žgana glina in odpadna steklasta žlindra iz metalurških procesov latentno hidravlična materiala, ki v prisotnosti apna v stiku z vodo otrdita. Poteče t. i. pucolanska reakcija. Med reakcijo hidratacije se vedeta enako kot tuf (pucolan).

Kot anorganski dodatek je znan tudi kalcijev sulfat (anhidrit), ki veže vodo ter pri tem preide ponovno v sadro (slika 2 e). S tem preprečimo, da bi omet med strjevanjem pokal.

Opleskom se za pridobitev določene barve dodajajo različni pigmenti, ki so lahko anorganski ali organski (slika 2 f).



Slika 2. Mikroskopske fotografije poliranih zbruskov predstavljajo različne anorganske dodatke. a) Inerten anorganski dodatek: debelozrnat kalcit-drobljen marmor v rimskem belem poliranem ometu. Presevna svetloba, prekrižani nikoli. b) Delci drobljene žgane gline pri ometih za talne mozaike iz rimskih term. Presevna svetloba, prekrižani nikoli. c) Fina frakcija opeke v vezivu intonacca rimske poslikave. Presevna svetloba, prekrižani nikoli. d) Steklasta žlindra v fasadnem ometu. Presevna svetloba, vzporedni nikoli. e) Zrna sadre v ometu. Presevna svetloba, prekrižani nikoli. f) Pigment kot posebni dodatek v oplesku, ki daje oplesku značilno obarvanost. Presevna svetloba, prekrižani nikoli.



Slika 3. a) Delec lesa v rimskem ometu, ki je najverjetneje posledica kontaminacije. Presevna svetloba, vzporedni nikoli. b) Delci trstike v stropnem ometu iz rimske vile. Presevna svetloba, vzporedni nikoli.

Organski dodatki

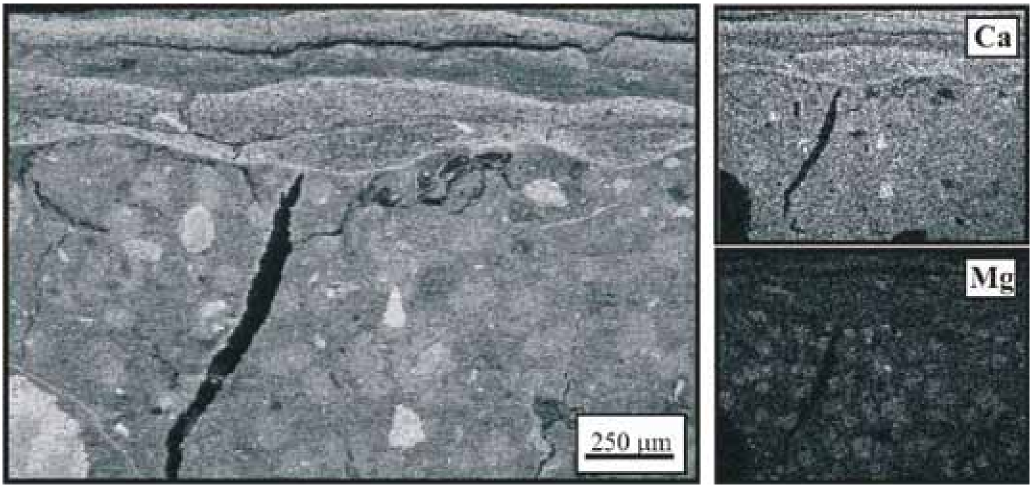
Med dodatke organskega izvora prištevamo predvsem delce lesa (slika 3 a). Ti so lahko naključno prisotni kot posledica onesnaženja maltne mešanice ali ostanek pri pridobivanju apna. V nekaterih primerih pa so opazni delci trstike (slika 3 b), ki so bili uporabljeni za boljšo vezivno sposobnost oziroma natezno trdnost ometov. Tako so bili pri stenskem ometu iz rimske vile ugotovljeni delci trstike. Številni so tudi primeri uporabe proteinskih dodatkov vezivu, ki so pogosti pri baročnih ometih (KUČKOVÁ et al., 2009).

Vezivo

Vezivo veže agregat, ki kompozitu daje prožnost in ustrezno konsistenco ter s tem omogoča njegov nanos na nosilec – zid ali na drug konstrukcijski element. Vezivo je najpogostejše apneno ali hidravlično, poznamo pa tudi druge vrste veziv, kot so npr. sadra, ilovica ali razna organska veziva.

Pri večini preiskovanih vzorcev historičnih ometov je vezivo iz gašenega apna - apneno vezivo (slika 5 a). Preiskava z elektronskim mikroskopom pokaže, ali vezivo v posameznih plasteh vsebuje poleg kalcija tudi druge elemente, kot je na primer magnezij (slika 4). Prisotnost magnezija dokazuje, da se je za žganje apna, ki so ga uporabili v preiskovanih vzorcih ometov kot vezivo, uporabljal tudi dolomit ali pa apnenec z dolomitom (slika 5 b). Takšno vezivo sestavljata minerala portlandit – $Ca(OH)_2$ ter brucit – $Mg(OH)_2$, ki v stiku z zrakom oz. CO_2 iz zraka že v kratkem času karbonatizirata. Nastala $CaCO_3$ in $MgCO_3$ dajeta ometu trdnost.

Vezivo je v nekaterih vzorcih dokaj razpokano. Razpokanost veziva se kaže predvsem v ometih, kjer je bilo kot vezivo uporabljeno apno. V apnenih ometih se razpoke pojavijo na mestih, kjer je plast apnenega veziva de-

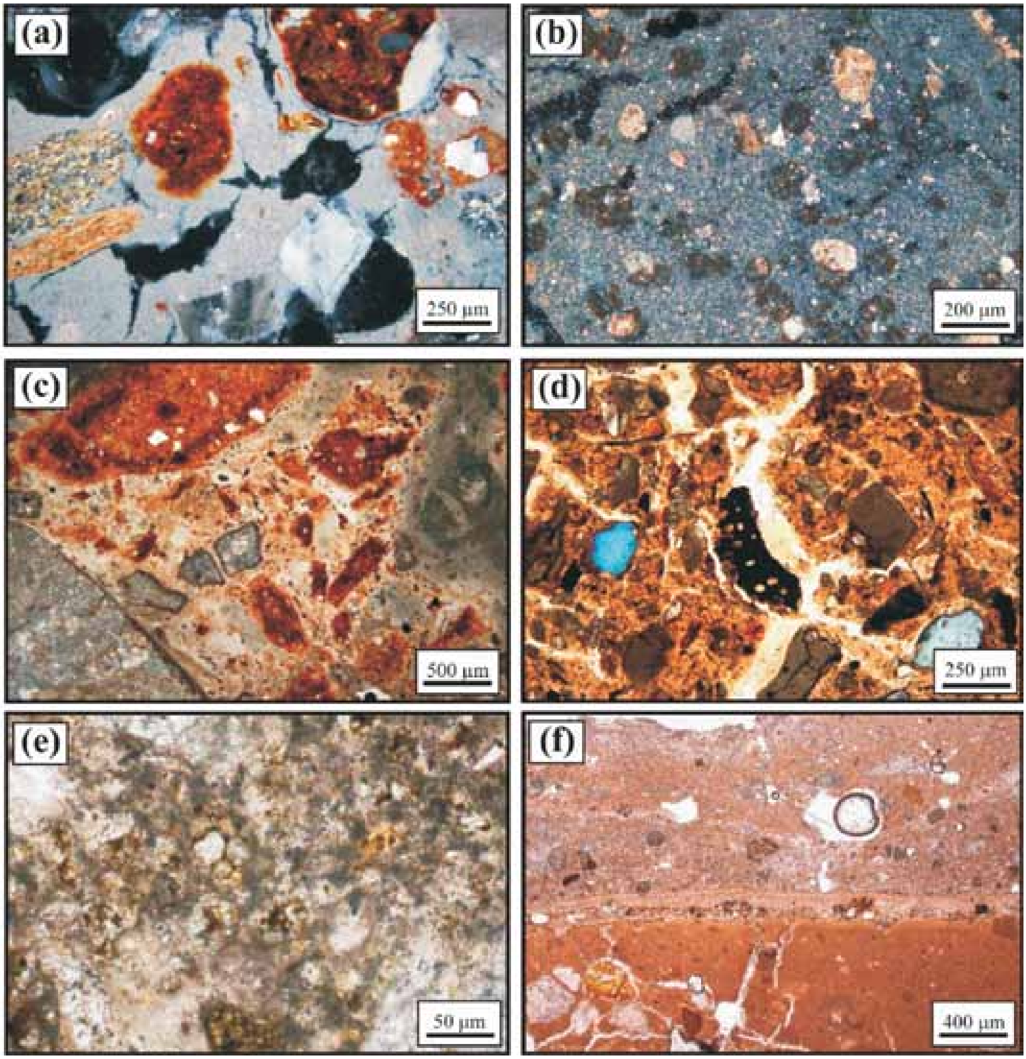


Slika 4. SEM-EDS-analiza vzorca ometa prikazuje območja v vezivu, bogata z magnezijem, ki nakazuje na nastanek brucita. Desno zgoraj: porazdelitev kalcija. Desno spodaj: porazdelitev magnezija, ki nakazujejo mesta pojavljanja brucita. Skupki brucita so veliki okoli 200 µm.

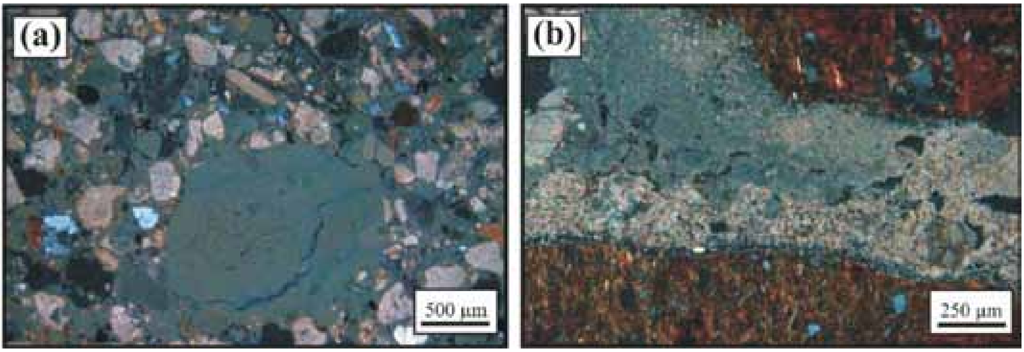
belejša (zaradi slabe karbonatizacije), na stiku med vezivom in agregatom in v apnenih skupkih – grudicah, aglomeratih. Razpoke zmanjšujejo trdnost ometa in dokazujejo slabo kakovost veziva, zmanjšujejo toplotno in zvočno izolacijo ter povečujejo sposobnost vezanja vlage. V vzorcih so pogoste t. i. grudice karbonatiziranega apna, ki variirajo tako po velikosti kot po količini (slika 6 a) in nakazujejo, da je bilo vezivo slabo gašeno ali slabo homogenizirano. Grudice so lahko tudi slabo žgan koščček apnenca, ki je ostal pri pridobivanju apna (Elsen, 2006).

Večji skupki grudic apna nakazujejo na uporabo živoapnene tehnike (Moropoluou et al, 1996). To vezivo tudi ni razpokano in je izredno trdno. Tak način so uporabljali Rimljani in je bil po vsej verjetnosti uporabljen pri zidavi vile rustike v Mošnjah (Kramar et al., 2008).

Glede na lastnosti, ki so jih želeli pridobiti pri ometih, so dodajali v vezivo dodatke. Vezivno sredstvo so bili v preteklosti različni latentno hidravlični materiali ali naravni cement. Sestavljajo ju kalcijevi silikati hidrati, ki sicer dajejo vezivu trdnost in mehansko odpornost, vendar imajo slabšo toplotno in zvočno izolacijsko sposobnost ter slabšo sposobnost absorpcije vode. Tako je npr. v vzorcih, ki so bili odvzeti iz prostorov rimskih term, kjer naj bi bila zagotovljena vodoodbojnost materialov, agregat iz zdrobljene opeke. V tem primeru je bilo tudi ugotovljeno,



Slika 5. a) Razpokano apneno zračno vezivo. Presevna svetloba, prekrižani nikoli. b) Temno obarvana območja v vezivu nakazujejo magnezit, ki nastane pri uporabi dolomitnega apna. Presevna svetloba, prekrižani nikoli. c) Kompaktno latentno hidravlično vezivo z zdrobljeno žgano glino. d) Malta za lepljenje kamnitih elementov, kjer je kot vezivo uporabljena naravna smola. Presevna svetoba, prekrižani nikoli. e) Klinkerjevi minerali v podaljšani malti. Presevna svetloba, vzporedni nikoli. f) Več plasti opleska z različno vrsto veziva (od spodaj navzgor): apneno vezivo, apneno hidravlično vezivo (tri plasti). Presevna svetloba, vzporedni nikoli.



Slika 6. a) Razpokana grudica apna. Presevna svetloba, prekrižani nikoli. b) Reakcijski rob okoli opeke. Presevna svetloba, prekrižani nikoli.

da fina frakcija zdrobljene žgane gline vodi do pucolanske reakcije v vezivu (Hughes et al., 1999, Kramar et al., 2008). Glede na posebno namembnost določenega ometa je bilo uporabljeno tudi hidravlično vezivo. Vezivo v teh ometih je kompaktno in ni razpokano, kar je sicer značilno za apnene omete.

Pri inkrustracijskih maltah na raznih baročnih oltarjih je bila kot vezivo uporabljena naravna smola (slika 5 d), ki je omogočala lepljenje kamnitih elementov (Kramar et al. 2007) .

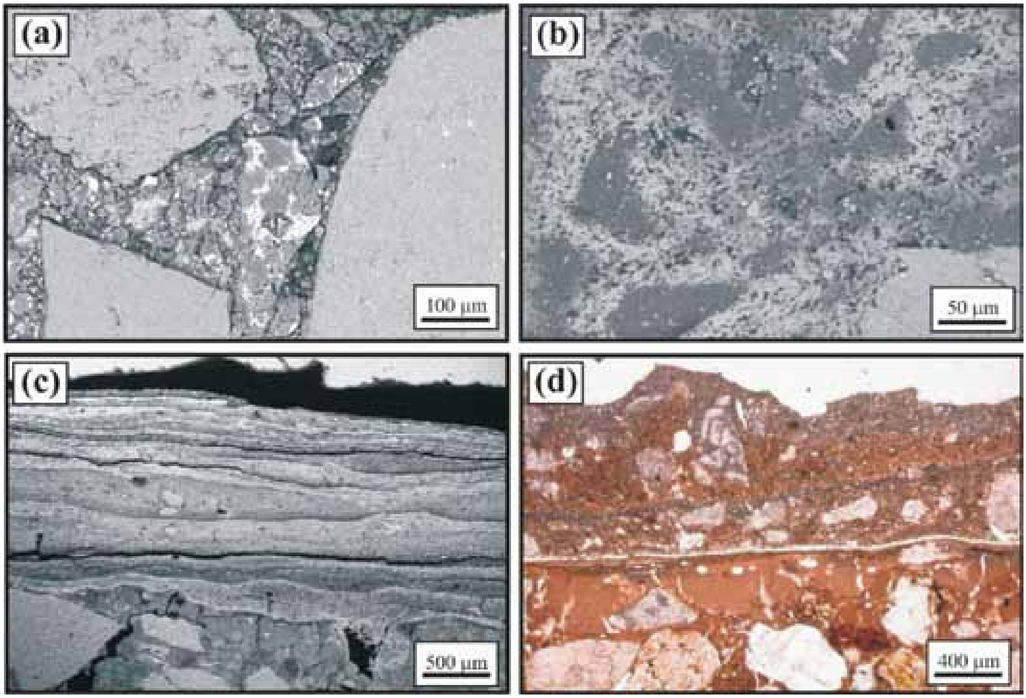
V ometih, ki so bili vgrajeni v zadnjih sto letih, je pogosto cementni klinker. Lahko gre za t. i. podaljšano malto (kot vezivo sta bila v ustreznem razmerju uporabljena apno in cement) ali pa za čisto cemento malto (sliki 5 a in 7 a). Slednja je dokaz za poseg, ki je bil izveden v zadnjem času.

Propadanje ometa

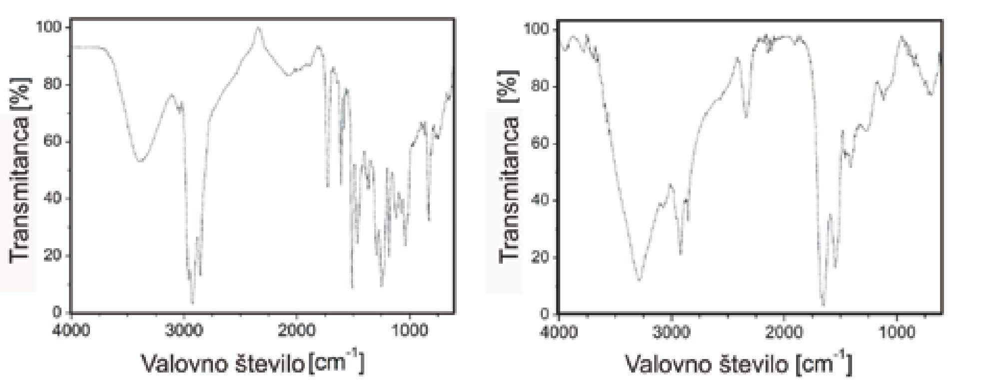
V ometih kot posledico razgradnje največkrat najdemo v vodi topne soli. Najpogostejše je to sadra, ki je nastala z reakcijo kalcija iz veziva in žveplovega oksida iz ozračja. Sadra se pogosto pojavlja v obliki plasti na površini ometa. Če je v ometu tudi magnezij, lahko pod površino ometa nastajajo različni magnezijevi sulfati hidrati (Kramar, 2006). Zaradi kristalizacije soli se ometi, malte in opleski luščijo.

Materiali za restavriranje - utrjevalci in domodulacije

Velikokrat je zaradi konservatorsko-restavratorskih posegov pomembna informacija o prisotnosti morebitnih sekundarnih materialov, ki so bili uporabljeni pri posegih v preteklosti (slika 7). Tako



Slika 7. a) Klinkerjevi minerali v cementi malti, kar velja kot neprimerno nadomeščanje originalne apnene malte. SEM-BSE. b) Sadrino vezivo v domodulacijski malti. SEM-BSE. c) Opleski nad ometom. SEM-BSE. d) Več plasti ometa in opleska. Vzorec je vzet iz fasade restavriranega objekta. Videti je, da je bila fasada obnovljena vsaj trikrat. Med posameznimi plastmi so vidne različno debele plasti sadre, ki je prekrila fasado zaradi reakcije apna iz fasade in žveplovega oksida iz ozračja. Zadnja plast sadre (na sliki zgoraj) je najdebelejša. Omet za fasado vsebuje debelozrnat agregat. Vmes so tudi tanke plasti pigmentiranega opleska brez dodanega agregata. Presevna svetloba, vzporedni nikoli.



Slika 8. a) FTIR-spekter epoksidne smole, ki je bila uporabljena pri utrjevanju stenskih poslikav pri preteklih restavratorskih posegih. b) FTIR-spekter proteinov, prisotnih pri ometih stenskih poslikav, ki so verjetno posledica utrjevanja z amonijevem kazeinatom (LESAR-KIKELJ et al., 2009).

lahko ugotovimo prisotnost preslikav oz. domodulacijskih mas in morebitnih materialov za utrjevanje (slika 8).

Sklepi

Rezultati, ki jih lahko pridobimo s preiskavami sestave historičnih ometov, so ključnega pomena pri odločanju za najprimernejši konservatorsko-restavratorski poseg na določenem objektu, arheologom pa dajejo podatek o kronologiji, izvoru materiala in tehnologiji izdelave. Pridobljeni podatki imajo tudi veliko dokumentacijsko vrednost, saj dajejo pregled informacij o sestavi različnih ometov in ometom podobnih gradbenih materialov iz različnih obdobij na območju Slovenije. Podatek o sestavi ometov omogoča tudi pridobitev recepture ometa za rekonstrukcije, ki se približuje sestavi originalnega ometa.

Sestava ometov variira glede na geografsko pozicijo objekta, časovno obdobje graditve objekta, kot tudi glede na vrsto aplikacije. Vhodne surovine za omete so ponavadi pridobivali iz lokalnih virov. Večina ometov je apnenih. Glede na določene lastnosti, ki so jih želeli pridobiti pri posameznih ometih, so dodajali v vezivo različne dodatke. Rezultati preiskav kažejo, da so pri gradnji rimskih term uporabljali kot posebej dodani agregat v malti žgano glino in s tem dosegli njeno vodoodbojnost. Vsi ti podatki nam govorijo o smiselnosti vzpostavitve baze historičnih ometov, ki bi bila ključnega pomena pri nadaljnjih preiskavah historičnih gradbenih materialov.

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The effect of inoculants on hardness and machinability of grey cast iron with flak graphite

Vpliv cepljenja sive litine z lamelnim grafitom na trdoto in obdelovalnost

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Abstract: Grey cast iron with flak graphite precipitates carbon in the form of graphite or cementite during the solidification process. If the cementite appears in the microstructure in the form of ledeburit, the mechanical machining of castings becomes impaired. In this research paper we described the conditions that contribute to forming of ledeburitic cementite in thin wall castings casted by the process of automatic casting. We produced workpieces with the help of two inoculants differentiated by their content of barium, calcium and aluminium. During the test we observed the quality of inoculation by using chemical and metalographic research and stepped as well as wedge samples. We also studied the machinability. The results of these tests showed that the occurance of precipitation of cementite and machinability depends on the amount and on the type of added inoculants. Thus the difference in hardness in various wall thicknesses is smaller in the case of using inoculant which contained less barium and no aluminium.

Izvleček: Pri sivi litini z lamelastim grafitom se med strjevanjem izloča ogljik v obliki grafita ali cementita. Če se cementit pojavi v mikrostrukturi v obliki ledeburita, se poslabša mehanska obdelava ulitkov. V raziskovalni nalogi smo preiskovali pogoje, kdaj pride do tvorbe ledeburitnega cementita v tankostenskih ulitkih, ulitih po postopku avtomatskega litja. Izdelali smo preizkušance z uporabo

Professional paper

dveh različnih cepiv, ki sta se razlikovali po vsebnosti barija, kalcija in aluminija. Med preizkusom smo spremljali kakovost cepljenja s kemičnimi in mikroskopskimi preiskavami ter s stopničastimi in klinastimi vzorci. Hkrati smo spremljali tudi obdelovalnost. Rezultati preiskav so pokazali, da je pojav izločenega cementita in s tem tudi obdelovalnost odvisna od količine in vrste dodanega cepiva. Tako je razlika v trdoti pri različnih debelinah stene manjša v primeru uporabe cepiva, ki je vsebovalo nižji odstotek barija in ni bilo legirano z aluminijem.

Key words: grey cast iron, inoculation, ledeburitic cementite, machinability

Ključne besede: siva litina, cepljenje, ledeburitni cementit, obdelovalnost

Introduction

Grey cast iron with flak graphite precipitates carbon in the form of cementite and graphite during the process of solidification. The form of precipitated carbon has an effect on mechanical properties of grey cast iron out of which the most important are tensile strength and hardness. If cementite is present in perlite, we talk about perlitic grey cast iron. It is undesirable for cementite to be precipitated in the »free« form. The occurance of free precipitated cementite (This is cementite into ledeburite.) increases the hardness to a great extent and cast iron with this kind of microstructure is hard to be machined.[1]

There are many factors[2] that influence precipitation of the ledeburitic cementite in the grey cast iron with flake graphite, such as input raw materials, chemical composition of the produced cast iron, furnaces for manufacturing the grey cast iron, the pouring temperature of casting, wall thickness, amount of inoculants,… The cooling speed is essential. Different speed in cooling can in spite of the same chemical composition of the cast iron cause differently formed graphite and the microstructure of base.[3] If the cooling is carried out too fast or if the inoculation is carried out incorrectly, ledeburitic cementite can occur. The result is white solidification – solidification into ledeburite. Thin walled castings[4] are very susceptible to precipitation of cementite from ledeburite. Solidification into ledeburite can be avoided if the grey cast iron is added different modificators known as inoculants. These are alloys of FeSi75Al 0.3, CaSi, FeSiMn… We know different types of inoculants,[2] out of which mostly used nowadays are complex inoculants that besides silicon also contain barium, zirconium, strontium and rare earths.[5, 6] The type of inoculants have an effect on formation of nucleation and dendrites of austenite. The increased number of austenitic dendrites causes a bigger number of eutectic cells. Thus a primary solidified austenite has an effect on nucleation.[7] Manganese and sulphur also have an effect on nucleation because it has been proven that graphite can start growing on particles of MnS.[8] As shown above, the right amount of crystal nucleus can be achieved with the right chemical composition of the base melt, the right choice of inoculants and optimal addition of inoculants. Thus we prevent the occurance of hard spots and excesive hardness especially in thin walled castings because of reduced undercooling during the solidification process. This ensures that the graphites flakes grow evenly in the metal base. The precipitated graphite is in this case of type A. With increased undercooling the microstructure shows undesired forms of graphite and it can lead to precipitation of ledeburitic cementite.

In this paper we described the results of the research of castings that were claimed back because there was ledeburitic cementite in the microstructure. Although there was not much of it, these castings could not be turned on the automatic CNC machine. Our tests were started by first searching for reasons of this fault and how to react in the production process to ensure that the produced castings would be of good quality. The type of inoculation[9] and type of inoculants have a major effect on precipitation of cementite. This means that it was necessary to determine which inoculant is the most appropriate for the production in our foundry and determine the minimum amount of inoculant that has to be added to the casting to ensure that the microstructure will contain no ledeburitic cementite.

Experimental work

Because of claiming back the castings due to not good machinability we analyzed these pieces. Chemical analysis did not show any deviations from the standard requirements of customers. But it was a different case with hardness and microstructure. It showed that on the edge ledeburitic cementite was occured.

To improve the manufacturing process of the claimed back castings, we produced specimens and observed the occurance of cementite. Because the distance from the casting system (place of casting) also has an effect on precipitation of cementite from ledeburite, we first checked the occurance of cementite on different spots of casting and then also on the different castings of the match plate. We realized that solidification into ledeburite occured on all the castings regardless of where they were positioned on the match plate.

We prepared different specimens which all had the same starting chemical composition and we only varied the quantity and type of inoculant. Table 1 shows the chemical composition of non inoculated cast iron.

Table 2 shows the number of produced specimens and type as well as quantity of added inoculants.

Table 3 shows chemical composition of the inoculant used.

We made four different specimens for the test. Table 1 shows the chemical composition of the base cast iron. The temperature of casting the base cast iron was 1421 °C. We casted specimen 1 with the base cast iron. The time of casting these samples was from 12 s to 13 s. To produce specimen 2 we added 0.06 % of inoculant from producer 1 to the base cast iron. Specimen 3 contained 0.09 % of the inoculant from the

Table 1. Chemical composition of the non inoculated cast iron

Alloy type	Chemical composition (mass fraction, *w*/%)									
	C	Si	Mn	S	Cr	P	Cu	Sn	Ni	Mo
Base grey cast iron	3.48	1.99	0.53	0.06	0.12	0.10	0.4	0.01	0.09	0.02

Table 2. Specimens type

Number	Specimen type	Quantity of the inoculant
1	Specimen 1	Without inoculant (base cast iron), *w*/%
2	Specimen 2	0.06 % of inoculant − producer 1
3	Specimen 3	0,09 % of inoculant − producer 1
4	Specimen 4	0.09 % of inoculant − producer 2

Table 3. Chemical composition of the inoculants

Type of inoculant	Chemical composition (*w*/%)			
	Si	Al	Ca	Ba
Producer 1	60–65		2.2–2.7	2–2.5
Producer 2	69.4	1.82	1.7	6.09

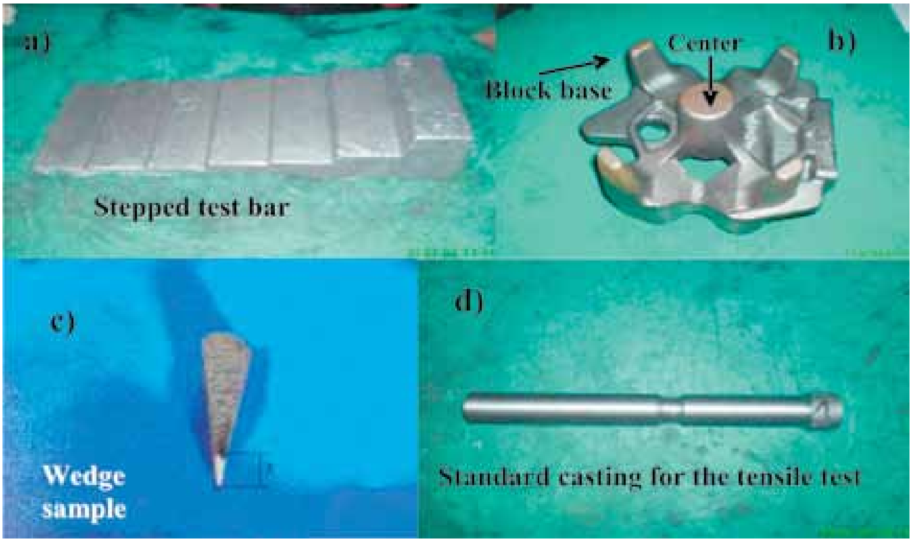

Figure 1. Presentation of samples for testing the quality of grey cast iron

same producer, while specimen 4 contained 0.09 % of the inoculant from producer 2. This means that specimen 4 was different from specimen 3 because we changed the producer of the inoculant while the added quantity of the inoculant stayed the same. We added the inoculant into the form.

We studied the quality of the inoculation by using:

- stepped test bar (figure 1 a),
- wedge samples (figure 1 c),
- standard specimens (trial bar) for the tensile test (figure 1 d) and
- castings (compressor block, figure 1 b).

Results and discussion

Hardness of stepped test bars are in Table 4. Figure 2 shows that hardness increases with reducing the wall thickness. Hardness measurements also show that optimally inoculated sample has the smallest difference in hardness between 50.8 mm and 3.2 mm thick wall in specimen 3 and it accounts for only HB = 44.

Hardnesses of castings are in table 5. The measurements showed that the hardness is lower in the center of the casting than on the base. The difference in hardness is large, if the casting is not well inoculated. This is confirmed by measurements of hardness in specimens 1 and 2.

Table 4. Hardness of the stepped test bar

Step thickness (mm)	Hardness (*HB*)			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4
3,2	297	278	229	231
6,3	241	229	222	222
12,7	224	222	219	217
25,4	211	209	209	211
38,1	195	197	193	195
50,8	189	189	185	187

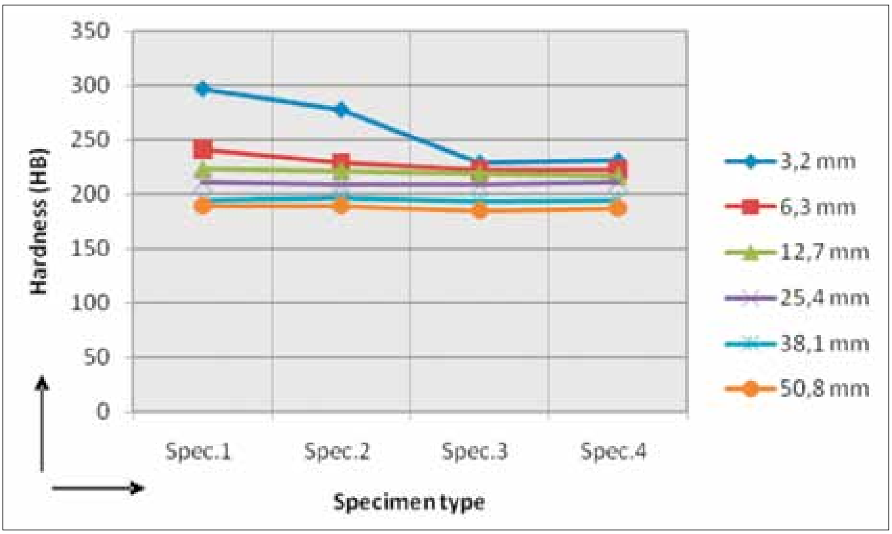

Figure 2. The influence of the type and quantity of the inoculant on hardness at different wall thickness of the castings

As visible from table 5 and figure 3, the quality of inoculant also plays a part on the difference in hardness between the center of the castings and its base because specimens 3 and 4 have the same inoculants but of different producers. This can also be seen in qualitative profile of hardnesses where the smallest difference between the hardness of the center and of the base is *HB* =17 which means that the quality of the inoculant in specimen 3 is the best.

Table 5. Hardness on the castings

Specimen type	Hardness of castings (*HB*)		Difference (*HB*)
	Center	Base	
Specimen 1	215	301	86
Specimen 2	213	285	72
Specimen 3	209	226	17
Specimen 4	207	229	22

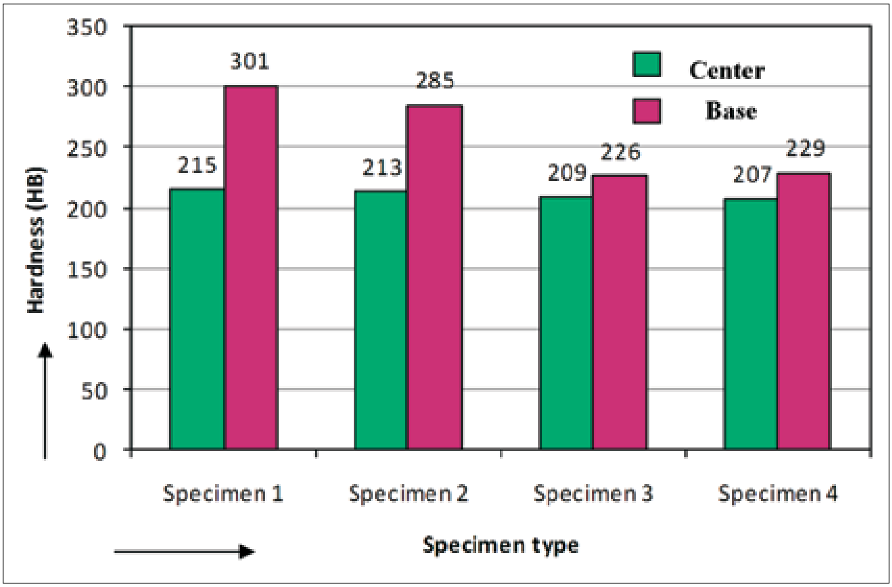

Figure 3. Hardnesses on the casting

Figure 4 shows the height of white solidification, breaking of the step at the thinnest wall spot of the step bar sample and microstructure at the critical part of the casting, i.e. on the base of the casting. It can be seen that in the microstructure of specimen 3 there is the most roughly formed perlite which means that the hardness is the lowest.

Figure 5 shows the dependence of hardness on wall thickness of the step bar sample and specimen 3. The diagram only contains the thickness of the castings for the center and the base. Step bar sample and specimen 3 were cast with the same molten metal. The picture shows that in case the casting is properly inoculated, the hardness of the

Height of solidification into ledeburite	Breaking of the step bar sample at the thickness of 3.2 mm	Microstructure of the base of the compressor

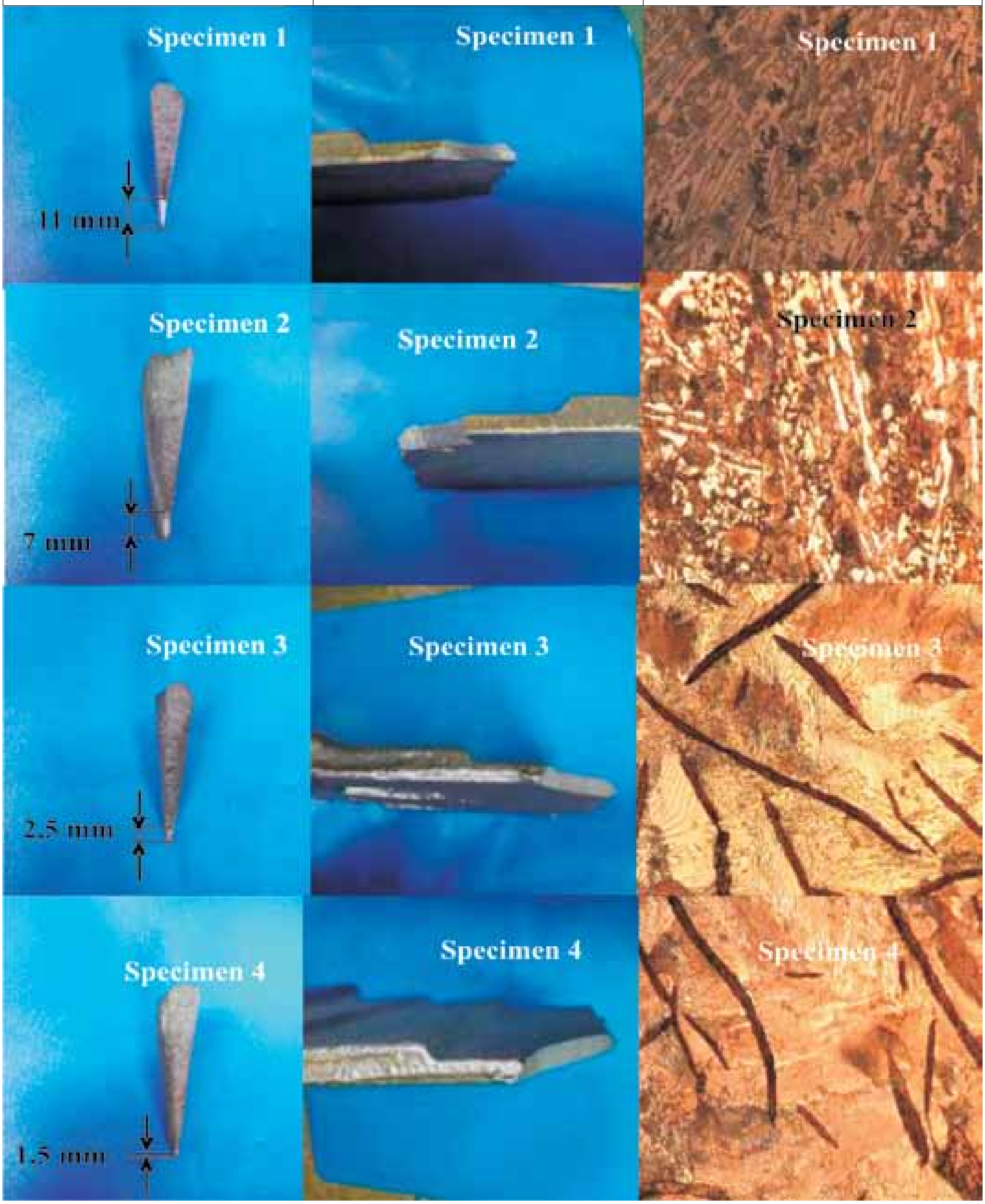

Figure 4. The influence of the type and quantity of the inoculant on the height of solidification into ledeburite, hardness and microstructure of castings (magnification 500-times)

casting and the step bar sample at the same wall thickness, don't differ. It can even be calculated by equation 1.

$$HB_{\text{of steps}} = f(\text{wall thickness}) = -0.910 \cdot f + 230.2 = HB_{\text{casting}} \qquad (1)$$

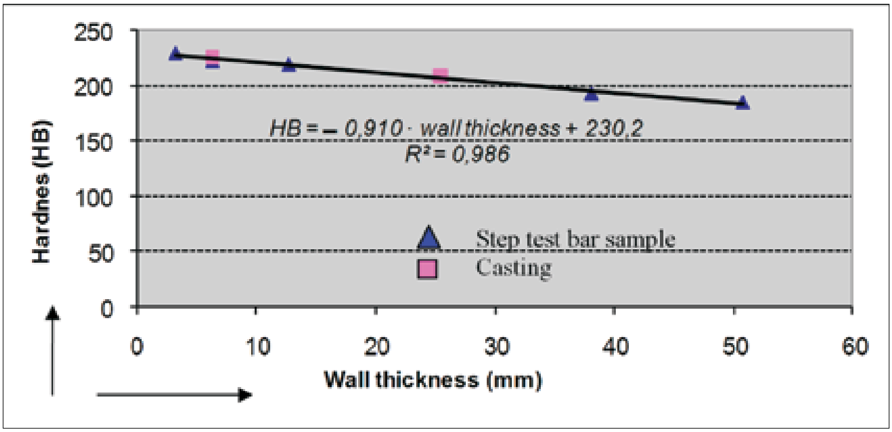

Figure 5. Interdependence of the hardness and the wall thickness

Conclusions

Because of relatively high prices of inoculants in the production process it is essential to determine the minimum quantity of the added inoculant needed for the casting to solidify without the ledeburite. We studied the effect of inoculation of the complex inoculants based on barium produced by two different suppliers. The research showed that the quantity of the added inoculant has an effect on the formation of ledeburitic cementite which impairs the mechanical machinability. Inoculants help to balance the hardness on the castings. The measurements showed that the difference in hardness of the castings at different wall thicknesses is smaller in cases, where inoculants with less barium were used and they also were alloyed with calcium and also contained no aluminium.

Summary

This paper describes the influence of ledeburitic cementite on the castings of unacceptable quality. Occurance of ledeburitic cementite is undesired because such castings cannot be machined with removing material. Thin walled castings are especially sensitive to precipitation of cementite. The observed casting had the wall thickness of 6 mm to 7 mm on the base and 25 mm in the center. This difference is big

enough to cause precipitation of ledeburitic cementite at unproperly carried out inoculation. Correct solidification in walls that thick can be regulated in the production process with a suitable type and quantity of the inoculant.

To prevent the problems in the production process, we made grey cast iron with flak graphite. We varied the quantity and type of inoculant during the test. After the test we observed solidification by studying chemical and microstructural composition of cast iron as well as step bar and wedge samples. We cast this casting with the same type of cast iron that was used for step bar and wedge samples. We measured the hardness on the test samples by Brinell. The hardness analysis shows that the hardness in step bar sample at the same thickness are comparable with the hardness of the casting. The hardness of the casting can be determined with the help of step bar sample by this equation:

$$HB_{\text{of steps}} = f(\text{wall thickness}) = -0.910 \cdot f + 230.2 = HB_{\text{casting}}$$

Hardness measurements and microscopic test showed that the most suitable inoculant for the chosen casting was the one that besided iron and sillicon contains also 2 % to 2.5 % of barium and 2 % to 2.7 % of calcium.

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Prve nadzorne meritve premikov in deformacij v realnem času z oddaljenim dostopom v Sloveniji

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Kadar posegamo v okoljski prostor, se moramo zavedati, da lahko s tem vplivamo tudi na stabilnostne razmere na tem območju. Poleg antropogenih vzrokov pa imajo vpliv na stabilnostna stanja tudi naravni pojavi, v prvi vrsti temperaturne spremembe, voda in potresi.

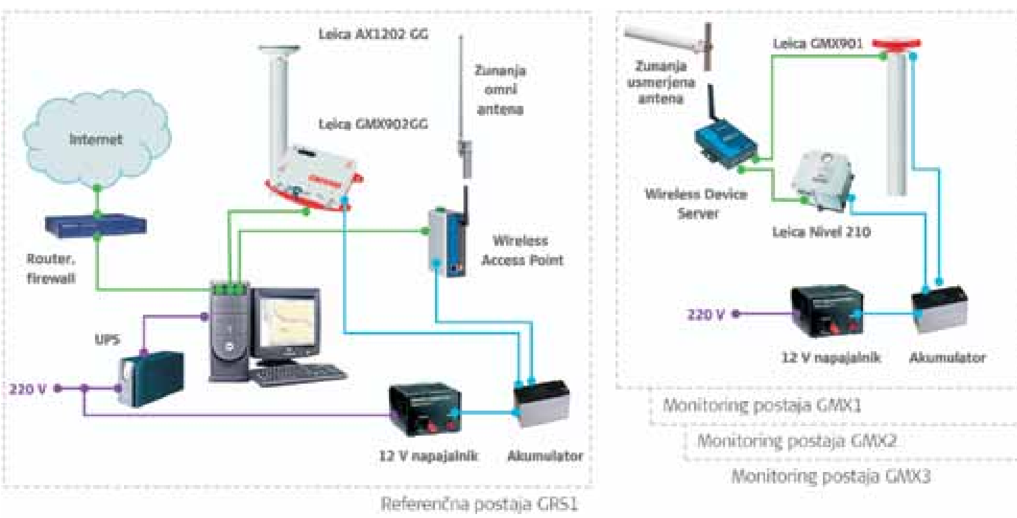
Za zagotavljanje stabilnih razmer in varnosti moramo spremljati čim večje število parametrov, ki vplivajo na spremembe v okolju. Tako za optimalno preventivno ukrepanje kot tudi pravilno kurativno ravnanje so ključnega pomena podatki, pridobljeni v realnem času.

Namen postavitve sistema nadzora v kamnolomu Lipica II je spremljanje in analiza premikov na osnovi opazovanj mreže enofrekvenčnih GPS-sprejemnikov in senzorjev nagiba v realnem času. Pridobljeni podatki so potrebni za zagotavljanje varnosti pri površinskem in podzemnem pridobivanju naravnega kamna ter vplivov odkopavanja na površje in širše okolje. Sistem omogoča ločeno merjenje dvoosne inklinacije ter spremljanje pomikov določenih območij terena v prostoru. Na sliki 1 je prikazana opazovalna točka v kamnolomu Lipica II.

Slika 1. Opremljena opazovalna točka v kamnolomu Lipica II

Sistem sestavljajo stabilna točka – GRS1 in tri opazovane točke – GMX1, GMX2 ter GMX3. Stabilna točka je uporabljena kot izhodišče baznih GPS-vektorjev, po katerih se določajo koordinate opazovanih točk. Sprememba smeri ali dolžine vektorja pomeni premik merjene točke. Stabilno točko oz. referenčno postajo GRS1 sestavljata GNSS-sprejemnik (GPS+GLONASS) Leica GMX902GG ter antena Leica AX1202GG, ki sta neposredno priključena na centralni računalnik. Na opazovanih točkah pa so nameščeni GPS-sprejemnik Leica GMX901, senzor nagiba Leica Nivel 210, sistem za brezprekinitveno napajanje ter oprema za brezžično komunikacijo, po kateri je postaja povezana s centralnim računalnikom. Detajlnejši prikaz postavitve sistema je prikazan na shemi (slika 2).

Na centralnem računalniku sta nameščena programa Leica GNSS Spider in Leica GeoMoS. Za upravljanje z GNSS/GPS-sprejemniki, zbiranje in obdelavo podatkov GPS-meritev ter računanje koordinat opazovanih točk v realnem času uporabljamo programski paket Leica GNSS Spider. Leica GeoMoS je osrednji program, ki je namenjen za upravljanje najrazličnejših geodetskih in geotehničnih senzorjev. Zajema koordinate iz GNSS Spiderja ter opazovanja senzorjev nagiba, njihovo shranjevanje, predstavitev in analizo. Dodatne možnosti Leica GeoMoS vključujejo tudi samodejno alarmiranje in pošiljanje sporočil po SMS-u in e-pošti. Do centralnega računalnika, ki upravlja celotni sistem in je nameščen na sami lokaciji, dostopamo oddaljeno po medmrežju. Tako so nam kjer koli in kadar koli na voljo vsi rezultati.



Slika 2. Shema nadzornega sistema

Po preliminarnih rezultatih sodeč se je metoda izkazala z večjo natančnostjo, kot je tista, podana od proizvajalca opreme. Tako lahko z obdelavo 24-urne meritve dosežemo natančnost 0,1–0,4 mm, torej v najslabšem primeru zaznamo premik večji od 1,2 mm z 99-odstotno verjetnostjo. Prednost nadzora v realnem času se kaže v tem, da lahko kadar koli, ne glede na to, kje se nahajamo, po medmrežju spremljamo dogajanje na terenu. Zaradi množice podatkov lahko iščemo korelacije z drugimi dogodki, ki se pojavljajo sočasno (dež, potresi, miniranje, temperaturno raztezanje…).

Predstavljena metodologija ima široko uporabnost v geoznanosti. Sistem lahko uporabljamo za nadzor velikih objektov na slabo nosilnih tleh, za opazovanje lezenja in plazenja hribinskih gmot, spremljanje vedenja objektov in hribinskih gmot med miniranjem, opazovanje brežin okoli večjih izkopov, ugotavljanje pomikov in posedanja pri gradnji ali postavljanju velikih temeljev in objektov, kot tudi za nadzor površja nad vsakršnim podzemnim kopom ali gradnjo podzemnega prostora.

Nadzorne meritve izvaja Katedra za rudarsko merjenje in geofizikalno raziskovanje Oddelka za geotehnologijo in rudarstvo pod vodstvom doc. dr. Milivoja Vulića. Sodelujejo tudi podjetje Geoservis, d. o. o., ki je podarilo potrebno opremo, in podjetje Marmor Sežana, d. o. o. V projekt je sedaj vključenih štirinajst ljudi, od tega pet doktorjev znanosti s področij geotehnologije in rudarstva, geologije, geodezije in gradbeništva. V sklopu projekta sta v izdelavi magistrsko in diplomsko delo, kar pa ne preseneča, saj študijski programi Naravoslovnotehniške fakultete vsebujejo vsebine, povezane z nadzorom v realnem času. Več informacij lahko najdete na svetovnem spletu www.geo.ntf.uni-lj.si/mvulic/rt_monitoring.

Zahvala sodelujočim pri pripravi slavnostne akademije ob 90-letnici študijev na Naravoslovnotehniški fakulteti

Ob 90-letnici Univerze v Ljubljani in študijev na Naravoslovnotehniški fakulteti smo praznovali tako kot vsako leto, tudi god sv. Barbare, zaščitnice montanistov. Ob teh dveh priložnostih smo na Naravoslovnotehniški fakulteti pripravili slavnostno akademijo, ki je bila v hotelu Mons v Ljubljani. Te akademije so se udeležili poleg rektorja Univerze v Ljubljani prof. dr. Stanislava Radovana Pejovnika in župana mesta Ljubljane g. Zorana Jankovića še nekateri dekani ljubljanskih fakultet, predstavniki premogovnikov in industrije, diplomanti in študentje Naravoslovnotehniške fakultete ter drugi gosti.

Na slavnostni akademiji so imeli priložnostne govore: dekan NTF, rektor UL, župan mesta Ljubljane in generalni direktor premogovnika Velenje, predstavljeni pa so bili tudi posamezni oddelki NTF.

Pri predstavitvi oddelkov smo vsi predstojniki podali videnje razvoja strok v prihodnje, kritično ocenili sedanje stanje in se seveda ozrli v preteklost. To je vsekakor pomenilo prebiranje starih zapisov in brskanje po spominih mnogih ljudi, njihovih zapiskih, govorih ob preteklih obletnicah in še kaj. Spričo časovne stiske in, kot sem hitro ugotovil, mojega luknjičavega poznanja zgodovine začetkov študijev rudarstva, geologije in metalurgije na UL, sem se zatekal po pomoč k mnogim. Pri tem mi je veliko pomagal dekan prof. dr. J. Likar, ki je vzpostavil stik s tistimi, ki veliko vedo o začetku študijev na UL sploh. O začetkih Tehniške fakultete, na kateri je bil tudi Oddelek za rudarstvo (in plavžarstvo?), sta mi prijazno z mnogimi podatki pomagala g. Kersnič (sin pokojnega prof. dr. Kersniča) in g. Šubelj. Obema najlepša hvala. Pogovori na to temo s prof. dr. U. Bajžljem so bili več kot koristni, saj so mi pomagali osvetliti povezanost študijev rudarstva in metalurgije, pa tudi geologije. Pri brskanju za starimi seznami predavanj po dolgem in počez so mi prijazno pomagale ga. U. Gliha, ga. B. Bohar - Bobnar in gdč. N. Štrekelj.

Pisanje mojega govora ob predstavitvi Oddelka za materiale in metalurgijo na slavnostni akademiji je bila zelo zahtevna naloga. Bila bi še težja, če ne bi bilo pomoči prof. dr. J. Lamuta in njegovega vedenja o zgodovini metalurgije na UL. Predstavitev Oddelka za materiale in metalurgijo ter spremljajoči plakati ne bi bili tako imenitni brez oblikovalske žilice mlade raziskovalke gdč. A. Šalej. Za gradivo pri pripravi predstavitve se zahvaljujem kolegom g. A. Lajovicu, prof. P. Mrvarju, doc. M. Knapu, doc. J. Medvedu pa za kipec sv. Barbare. Hvala tudi kolegoma prof. B. Koscu in prof. P. Fajfarju ter ge. V. Krapež, ker so me razbremenili pri opravljanju nalog predstojnika, tako da sem se lahko posvetil pripravi predstavitve Oddelka za materiale in metalurgijo. Zahvala velja tudi vsem neimenovanim, ki so mi pri tem kakor koli pomagali.

Predstojnik Oddelka za materiale in metalurgijo
izr. prof. dr. Boštjan Markoli

In memoriam

Prof. dr. Janez Stržišar

(23. 1. 1950–29. 7. 2008)

V zadnjih vročih julijskih dneh leta 2008 se je prof. dr. Janez Stražišar mnogo prezgodaj poslovil od tega sveta, saj njegova starost še zdaleč ni bila visoka, da bi to laže razumeli. Kruta bolezen, ki se je zajedla v njegovo telo, je nezadržno napredovala, tako da je življenje dragega sodelavca hitro ugašalo ter 29. 7. 2008 tudi za zmeraj ugasnilo.

Prof. dr. Janez Stražišar je luč sveta zagledal v Ljubljani 23. 1. 1950, kjer je tudi odraščal in sprejemal učenje kot pomemben del svojega življenja. Nadarjen in vešč učenja je hitro napredoval in si iz leta v leto pridobival znanje: najprej na Tehniški srednji šoli v Ljubljani, nato na Univerzi v Ljubljani, natančneje, na tedanji Fakulteti za naravoslovje in tehnologijo na Oddelku za kemijo, kjer je leta 1973 po uspešno končanem študiju najprej diplomiral, nato leta 1976 magistriral in leta 1983 tudi doktoriral. Raziskovalna vnema in veselje do inovativnega dela sta ga vodila tudi v tujino v Veliko Britanijo na Univerzo Dundee, kjer se je izpopolnjeval v svoji stroki, ki jo je neizmerno cenil in razvijal do zadnjega diha.

Svoje bogato strokovno znanje, povezano z znanstvenoraziskovalnim delom je udejanjal na Institutu ″Jožef Stefan″ in v podjetju KLI Logatec do leta 1978, ko se je odločil za pedagoško in znanstvenoraziskovalno delo na matični fakulteti oz. natančneje, na Oddelku za montanistiko, Odseku za rudarstvo. Njegova znanstvenoraziskovalna usmeritev je bila tesno povezana s Katedro za mehansko procesno tehniko in bogatenje mineralnih ter sekundarnih surovin, ki jo je vodil tako, da jo je neprestano plemenitil in ji dodajal vrednost v več segmentih raziskav, predvsem povezanih z geotehnologijo.

Pokojnikova pedagoška pot se je strmo vzpenjala od asistenta do leta 2002, ko je bil izvoljen v naziv rednega profesorja za področje Geotehnologija in rudarstvo.

Bogate in trajne sadove je pustil na področju znanstvenoraziskovalnega dela, saj je bil več let vodja domačih in mednarodnih temeljnih ter aplikativnih raziskovalnih projektov, vodja programske skupine ter vodja raziskovalne skupine Oddelka za geotehnologijo in rudarstvo. Izsledke in rezultate svojega dela je v sodelovanju z drugimi sodelavci redno objavljal v periodičnih znanstvenih in strokovnih revijah ter o njih poročal na domačih in mednarodnih posvetovanjih.

Čeprav je bil mnogokrat do sebe in do svojega dela strog, vendar skromen, je bila odmevnost njegovega znanstvenega in raziskovalnega dela obratno sorazmerna ne samo doma, temveč tudi v tujini, kar kaže na njegovo visoko raziskovalno usposobljenost in ne nazadnje na trdno in pokončno osebnost znanstvenika. Poleg znanstvene in pedagoške dejavnosti je z veseljem vodil matično katedro, Odsek za rudarstvo, Oddelek za montanistiko, Oddelek za geotehnologijo in rudarstvo ter bil prodekan Naravoslovnotehniške fakultete za različna področja. Vedno je znal ohraniti trezno komunikacijo s sodelavci in drugimi, čeprav so bili časi razdruževanja Fakultete za naravoslovje in tehnologijo težki. Podobno se je odzival tudi zadnja leta, ko je zopet prisotna želja po razdruževanju matične Naravoslovnotehniške fakultete. Za vse prispevke k ohranjanju in razvoju rudarske in geotehnološke stroke ter za plemenito opravljeno delo smo mu sodelavci Oddelka za geotehnologijo in rudarstvo globoko hvaležni, kakor tudi za nasvete, ki jih je nesebično posredoval študentom in strokovnjakom z različnih gospodarskih področij.

Njegovo znanstveno usmeritev in nikoli dokončano delo je z razumevanjem sprejemala tudi njegova družina, ki mu je bila vedno v ponos in hkrati v oporo pri premagovanju različnih ovir, ki so sestavni del znanstvenega, raziskovalnega in pedagoškega dela na fakulteti.

Naj bodo te besede trdna podlaga za ohranitev spomina na spoštovanega in cenjenega sodelavca.

Srečno!

Predstojnik Oddelka za geotehnologijo in rudarstvo
izr. prof. dr. Jakob Likar

In memoriam

Prof. dr. Rudi Ahčan

(19. 1. 1918–2. 11. 2008)

Pokojni profesor doktor Rudi Ahčan je bil več desetletij vodilni strokovnjak na področju odkopavanja premoga v bivši Jugoslaviji, kot tudi širše v evropskem in svetovnem prostoru. Pred devetdesetimi leti, 19. 1. 1918, se je rodil v rudarskem Zagorju ob Savi. Po osnovni šoli je najprej uspešno končal klasično gimnazijo v Ljubljani, po maturi pa se je vpisal na Rudarski odsek Tehniške fakultete Univerze v Ljubljani.

Med 2. svetovno vojno je bil večkrat zaprt, med drugim tudi v Zagrebu. Diplomsko delo je leta 1943 uspešno zagovarjal ter bil nato kratek čas zaposlen pri železnici v Ljubljani, nato pa je bil od avgusta leta 1944 do konca vojne na prisilnem delu v Nemčiji.

Strokovna vnema in predanost poklicu sta ga vodili po različnih rudnikih v Jugoslaviji. Začel je kot asistent v rudniku Zabukovica leta 1945, nadaljeval v Premogovniku Velenje, nato pa je bil leta 1947 premeščen za upravnika jam v Rudnik uglja Tito v Banoviće.

Strokovna pot ga je leta 1950 pripeljala v Istro, kjer je bil postavljen za tehničnega vodjo jame Raša in nato za vodjo rudarskih del. Strokovnost je uspešno dokazal leta 1951, ko je opravil strokovni izpit v Zagrebu ter bil nato v letih od 1953 do 1958 vodja študijskega oddelka v Premogovniku Velenje ter od leta 1959 do 1963 tehnični direktor Rudnika rjavega premoga Zagorje. Povsod ga je odlikovala izjemna inženirska inovativnost ter prefinjen tehnični občutek pri analiziranju in razvijanju novih učinkovitih tehnologij podetažnega odkopavanja premoga, saj gre pripisati ravno njemu največji delež pri razvoju Velenjske odkopne metode, ki je danes zaščitena s patentom ter poznana širši strokovni javnosti v svetu.

V času aktivnega strokovnega dela je bil večkrat na specializacijah v tujini, predvsem v Franciji, Zvezni republiki Nemčiji, Poljski in Belgiji. Strokovno bogata življenjska pot, tlakovana s praktičnimi izkušnjami, ga je leta 1963 pripeljala na Rudarski inštitut v Beogradu, kjer je bil imenovan za upravnika biroja za znanstvenoraziskovalno delo. Kot izjemno sposoben in stroki predan strokovnjak je bil leta 1964 izbran za člana ekspertne skupine s področja produktivnosti in vodenja v premogovnikih pri Komiteju za premog Evropske ekonomske skupine v Ženevi.

Znanstveno dokazovanje je kronal leta 1965, ko je bil promoviran za doktorja tehniških znanosti na Univerzi v Beogradu. Pedagoško in znanstveno delo je nadaljeval leta 1966, potem ko je bil izvoljen za izrednega in nato leta 1972 za rednega profesorja na naši fakulteti. Več generacij študentov je imelo možnost prejemati njegovo znanje, saj ga je znal nesebično posredovati ne samo nam študentom, ampak tudi kolegom v praksi.

Sodelovanje na strokovnih posvetovanjih doma in v tujini je vseskozi spremljalo njegovo »premogu« predano delo, tako da je odmev njegove znanstvene in strokovne dejavnosti segal daleč zunaj tedanje Jugoslavije. Predaval je na različnih univerzah in inštitutih v Moskvi, Clausthalu, Katowicah, Leobnu, Ženevi in drugje. Svoje znanje je na predavanjih posredoval strokovni javnosti tudi v Indiji, ZDA in v drugih državah, kjer so bili organizirani svetovni kongresi s področja rudarstva.

Njegov ugled v strokovnem okolju ter pripravljenost delati za dobro rudarske stroke sta pripomogla k temu, da mu je bilo zaupanih več upravnih in družbenih funkcij na tedanji Fakulteti za naravoslovje in tehnologijo. Bil je predsednik upravnega odbora Fakultete za naravoslovje in tehnologijo, predstojnik Oddelka za montanistiko, predsednik znanstvenih odborov Rudarskega inštituta v Beogradu in Ljubljani itd.

Pokojni profesor Ahčan se je upokojil 29. 6. 1988 po 49 let trajajočem intenzivnem, uspešnem in za stroko izjemno pomembnem delu. Njegovo bogato in z inženirskim delom prežeto življenje je ugasnilo 2. 11. 2008.

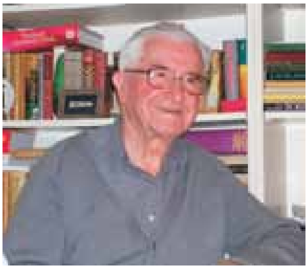
SREČNO!

Predstojnik Oddelka za geotehnologijo in rudarstvo
izr. prof. dr. Jakob Likar

In memoriam

France Gregorač, dipl. inž. rud.

(19. 1. 1921–26. 6. 2009)



France Gregorač se je rodil 19. januarja 1921 v Tacnu pod Šmarno goro, nato pa se je družina preselila v Ljubljano. Po maturi na klasični gimnaziji se je odločil za študij rudarstva.

Okupacija, udeležba v boju proti okupatorju od leta 1941, internacija, služenje vojaškega roka v KNOJ-u so mu preprečili redni študij na rudarskem oddelku Tehniške fakultete v Ljubljani. Nadaljeval ga je po štirih letih, ko se je jeseni 1946 vpisal v 5. semester. Odločil se je za študij na področju bogatenja ekonomskih mineralnih surovin in v oktobru 1950 diplomiral pri prof. Viktorju Gostiši. Zadnji dve leti študija je bil na katedri za tehnično oplemenitenje ekonomskih mineralnih surovin pomožni asistent pri prof. Gostiši. Delo na fakulteti je nadaljeval tudi po diplomi. Z odločbo ministrstva za znanost in kulturo je bil s 1. januarjem 1951 imenovan za rednega asistenta. V tem letu je prevzel tudi predavanja Enciklopedija tehničnega oplemenitenja ekonomskih mineralov za študente 2. letnika metalurgije. Nato so ga v marcu 1952 administrativno premestili na mesto upravnika rudnika azbesta »Ozren« v Bosanskem Petrovem selu. Po petmesečnem delu se je vrnil na fakulteto, takoj nato pa je bil zopet premeščen na delo tehnologa v separaciji Rudnika Mežica.

Rudnik Mežica se je namreč znašel v težki situaciji. Ruda je bila siromašna, zahteva pa je bila, da naj bi rudnik rentabilno obratoval. France se je vključil v izvajanje načrta razvoja rudnika od 1952 do 1962, ki ga je izdelal glavni tehnolog inž. B. Pirkmaier. Posvetil se je bogatenju rude in povečanju njene predelave. Želel si je, da bi bila ruda, ki so jo rudarji izkopali s težkim delom, popolnoma izkoriščena. Treba je bilo povečati obstoječo flotacijo (s troselektivnim sistemom flotiranja) in ji dodati nov del z dvoselektivnim sistemom za predelavo starih jalovišč (hald) ter tudi vgraditi težkotekočinsko separacijo.

Ta je pod njegovim vodstvom začela redno obratovati 1. maja 1954, celotna rekonstrukcija separacije pa je bila dokončana leta 1959. France je postal glavni inženir za separiranje in tudi namestnik direktorja Rudnikov svinca in topilnice Mežica. Uspeh prve in edine take separacije v državi se je razvedel doma in v svetu. To je bil uspeh visoke strokovnosti vodstva in zagnanosti delavcev rudnika, uspeh snovalca desetletnega načrta razvoja rudnika, posebno pa Franceta, ki je bil osrednji, vodilni dejavnik uresničevanja tega načrta, zlasti glede doseganja učinkovitejšega obogatenja mežiške rude.

Ob svojem rednem delu se je lotil tudi drugih izzivov, ki so se pojavljali v rudniku. Pripravil je mnoge projekte, opravljal številne aplikativne in preizkusne raziskave rudnin iz raznih jugoslovanskih rudnikov in tudi od drugod (Češka, Italija, Alžirija) ter bil recenzent in svetovalec. S štipendijo Agencije za atomsko energijo IAEA na Dunaju je bil od septembra 1961 do marca 1962 na Imperial College of Science and Technology, Mineral Technology Department v Londonu pri prof. M. G. Flemingu. Z mentorjem dr. J. A. Kitchnerjem je študiral površinsko reakcijo galenita z uporabo radioizotopov. Radioizotope je po poročilih v literaturi vpeljal doma za tekoče ugotavljanje gostote separacijske suspenzije s sodelovanjem tedaj Nuklearnega instituta »Jožef Stefan« z napravo, ki jo je ta razvil in tudi uspešno izdelal že jeseni 1961 oziroma maja 1962.

Bil je član strokovne komisije pri združenju rudnikov barvaste metalurgije, se seznanil z vso problematiko separiranja tovrstnih rud iz rudnikov v Jugoslaviji in sodeloval pri reševanju njihovih problemov in pri skrbi za strokovni dvig zaposlenih v separacijah. Redno se je udeleževal mednarodnih in domačih kongresov s predavanji, z razpravami in drugimi prispevki. O svojih raziskavah je že od leta 1952 objavljal poročila v domačih in tujih strokovnih časopisih.

Popolnoma utemeljeno je samozavestno sodil, da je dosegel rudnik Mežica s svojo separacijo zavidljivo svetovno raven delovanja in najvišji strokovni ugled v mednarodni družbi strokovnjakov za področje bogatenja mineralnih surovin. Bil je v najboljših odnosih z rudniki doma, z zahodno Evropo, Ameriko, s sosednjimi državami. Rudnik Mežica in njegove strokovnjake so mednarodno zelo cenili.

O ravni njegovega znanja in dosežkov priča dejstvo, da je bil v zborniku referatov XVI. mednarodnega kongresa junija 1988 v Stockholmu povzet članek, v katerem so bila obravnavana razmerja med gostoto, viskoznostjo in stabilnostjo suspenzije pri težkotekočinskem separiranju in določena pravila medsebojnega uravnavanja ter nadziranja pri določanju najugodnejših okoliščin pri tem načinu separiranja. Ta ista vprašanja je obravnaval France že 30 let prej v zborniku člankov 5. vsedržavne konference v Tatranski Lomnici novembra 1958. Njegove napotke iz poročil so s pridom uporabljali tudi pri upravljanju drugih rudnikov, kamor so ga vabili na oglede in posvete.

Leta 1965 je prešel v podjetje Rudis v Trbovljah, kjer naj bi prevzel vodstvo pri novi flotaciji v Djebel Gustaru v Alžiriji. V Alžiriji je bil na povabilo Rudisa leta 1963 s skupino geologov in Rudis je po ugodnih rezultatih preizkušanja vzorcev rude in halde predlagal ponovno vzpostavitev dela na rudniku Djebel Gustar, kar so Alžirci sprejeli. Rudis je izdelal projekt in prevzel izvedbo, postavljanje flotacije pa je vodil France od začetka jeseni 1966 do 1969, ko so jo po zagonu prevzeli Alžirci.

France se je vrnil v Trbovlje, spet izdeloval idejne projekte separacijskih naprav, sodeloval kot svetovalec pri izdelavi projektov in raziskavah, leta 1972 pa odšel za pet let in pol na popolnoma drugačno rudarsko delo v Nemčijo, kjer je Rudis sodeloval pri graditvi rudniških jaškov in pripravi prog v premogovnikih Vestfalije.

Po upokojitvi se je kot strokovni sodelavec Rudarskega inštituta vrnil k svojemu najljubšemu področju – separiranju. Sredi leta 1980 ga je družba Termit povabila za svetovalca pri postavljanju nove separacije. Tehnološki postopek pranja in separiranja kremenovih peskov je usposobil do stopnje, ki zagotavlja nemoteno delovanje, potrebno kapaciteto in stalno kvaliteto. To je omogočilo, da je Termit vodilno slovensko podjetje za pridobivanje in predelavo kremenovih peskov. Pri Termitu je l. 1985 prevzel še vodstvo varnosti pri delu in se ob tem ukvarjal s skrbjo za okolje in z napredkom tehnologij bogatenja rudnin. V podjetju so ga cenili kot izkušenega strokovnjaka, rudarja z dušo in srcem ter odprtega in toplega človeka, kar je zastopnica podjetja lepo poudarila v besedah slovesa.

Leta 2000 je izdal knjižico o svojem strokovnem delu z naslovom Vzponi in padci – izsek iz življenja strokovnjaka. Dodal ji je predavanje Težkotekočinsko separiranje Pb – Zn rude Rudnika Mežica, ki ga je imel na 5. vsedržavni konferenci leta 1958 v Tatranski Lomnici. Oba spisa sta pomembno pričevanje o rudarstvu ter ozračju v Jugoslaviji in Sloveniji, kot tudi o odnosih s svetom v desetletjih po drugi svetovni vojni.

Ob svojem širokem strokovnem delu je sodeloval tudi pri družbenem življenju, za kar so mu bila podeljena številna priznanja. Za prizadevno in uspešno raziskovalno ter ustvarjalno delo mu je bil podeljen red dela z rdečo zastavo.

Bil je pogumen borec, zgleden državljan, pol stoletja odličen rudarski strokovnjak, predvsem pa dober mož in oče, pošten, vztrajen, zanesljiv, skromen človek, zvest humanističnim idealom.

Od Franceta smo se poslovili prav na dan rudarjev 3. julija 2009.

Ignacij Gregorač

In memoriam

Prof. dr. Anton Zalar
(28. 5. 1943–16. 7. 2009)

Prof. dr. Anton Zalar se je rodil 28. 5. 1943 v Ljubljani. Po končani srednji šoli se je leta 1962 vpisal na Fakulteto za naravoslovje in tehnologijo, smer metalurgija, kjer je leta 1969 diplomiral. Na isti fakulteti je začel podiplomski študij, ki ga je končal leta 1987 in bil promoviran v doktorja znanosti s področja metalurgije. Svojo poklicno pot je začel l. 1970, ko se je zaposlil na Inštitutu za elektroniko in vakuumsko tehniko v Ljubljani. Ob reorganizaciji tega inštituta je nastal tudi Inštitut za tehnologijo površin in optoelektroniko, katerega direktor je bil v obdobju 1995–2003. V tem letu je bil skupaj s svojo raziskovalno skupino pripojen k Institutu »Jožef Stefan« v Ljubljani. Ukvarjal se z razvojem in karakterizacijo tankoplastnih struktur, analizo površin, razvojem elektronskih komponent ter vakuumsko tehniko. Uvedel je raziskovalno metodo Augerjevih elektronov (AES). Pionirsko pa je njegovo delo na področju profilne analize tankih plasti. O njegovi predanosti znanstvenoraziskovalnemu delu priča več kot 140 izvirnih znanstvenih člankov, avtorstvo dveh patentov in skupno več kot 350 bibliografskih enot.

Prof. dr. Anotn Zalar ni bil le raziskovalec in znanstvenik, pač pa tudi zelo uspešen pedagog. Tako sem imel l. 1992, še kot študent, čast biti na njegovem predstavitvenem predavanju ob imenovanju za docenta s področja fizikalne metalurgije na takratni Fakulteti za naravoslovje in tehnologijo. Svojo pedagoško kariero je nato nadaljeval tudi na Naravoslovnotehniški fakulteti tako na dodiplomskem kot na podiplomskem študiju, kjer je na študente prenašal svoje bogato teoretično znanje in praktične izkušnje. Leta 2004 je bil promoviran v naziv rednega profesorja za fizikalno metalurgijo. V njegovi predavateljski karieri je pri njem na dodiplomskem in podiplomskem študiju diplomiralo skupaj pet kandidatov.

Prof. dr. Antona Zalarja se bomo kolegi, sodelavci in prijatelji spominjali kot veselega in sočutnega človeka, ki je bil vedno pripravljen pomagati, po drugi strani pa kot izjemnega znanstvenika in pedagoga. Za njim je ostala praznina, ki jo ne bo mogoče zapolniti. Naj počiva v miru.

Predstojnik Oddelka za materiale in metalurgijo
izr. prof. dr. Boštjan Markoli

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INSTRUCTIONS TO AUTHORS

RMZ-MATERIALS & GEOENVIRONMENT (RMZ- Materiali in geookolje) is a periodical publication with four issues per year (established 1952 and renamed to RMZ-M&G in 1998). The main topics of contents are Mining and Geotechnology, Metallurgy and Materials, Geology and Geoenvironment.

RMZ-M&G publishes original Scientific articles, Review papers, Preliminary notes, Professional papers **in English**. In addition, evaluations of other publications (books, monographs,...), In memoriam, Professional remarks and reviews are welcome. The Title, Abstract and Key words in Slovene will be included by the author(s) or will be provided by the referee or the Editorial Office.

**** Additional information and remarks for Slovenian authors:***
Only Professional papers, Publications notes, Events notes, Discussion of papers and In memoriam, will be exceptionally published in the Slovenian language.

Authorship and originality of the contributions. Authors are responsible for originality of presented data, ideas and conclusions as well as for correct citation of data adopted from other sources. The publication in RMZ-M&G obligate authors that the article will not be published anywhere else in the same form.

Specification of Contributions

RMZ-M&G will publish papers of the following categories:

<u>Full papers</u> (optimal number of pages is 7 to 15, longer articles should be discussed with Editor prior to submission). An abstract is required.

- **Original scientific papers** represent unpublished results of original research.
- **Review papers** summarize previously published scientific, research and/or expertise articles on the new scientific level and can contain also other cited sources, which are not mainly result of author(s).

- **Preliminary notes** represent preliminary research findings, which should be published rapidly.
- **Professional paper**s are the result of technological research achievements, application research results and information about achievements in practice and industry.

Short papers (the number of pages is limited to 1 for Discussion of papers and 2 pages for Publication note, Event note and In Memoriam). No abstract is required for short papers.

- **Publication notes** contain author's opinion on new published books, monographs, textbooks, or other published material. A figure of cover page is expected.
- **Event notes** in which descriptions of a scientific or professional event are given.
- **Discussion of papers (Comments)** where only professional disagreements can be discussed. Normally the source author(s) reply the remarks in the same issue.
- **In memoriam** (a photo is expected).

Supervision and review of manuscripts. All manuscripts will be supervised. The referees evaluate manuscripts and can ask authors to change particular segments, and propose to the Editor the acceptability of submitted articles. Authors can suggest the referee but Editor has a right to choose another. **The name of the referee remains anonymous.** The technical corrections will be done too and authors can be asked to correct missing items. The final decision whether the manuscript will be published is made by the Editor in Chief.

The Form of the Manuscript

The manuscript should be submitted as a complete hard copy including figures and tables. The figures should also be enclosed separately, both charts and photos in the original version. In addition, all material should also be provided in electronic form on a diskette or a CD. The necessary information can conveniently also be delivered by E-mail.

Composition of manuscript is defined in the attached Template

The original file of Template is available on RMZ-Materials and Geoenvironment Home page address:

http://www.rmz-mg.com

References - can be arranged in two ways:
- first possibility: alphabetic arrangement of first authors - in text: (Borgne, 1955), or
- second possibility: [1] numerated in the same order as cited in the text: example[1]

Format of papers in journals:

Le Borgne, E. (1955): Susceptibilite magnetic anomale du sol superficiel. *Annales de Geophysique*, 11, pp. 399–419.

Format of books:

Roberts, J. L. (1989): Geological structures, *MacMillan*, *London*, 250 p.

Text on the hard print copy can be prepared with any text-processor. The electronic version on the diskette, CD or E-mail transfer should be in MS Word or ASCII format.
Captions of figures and tables should be enclosed separately.
Figures (graphs and photos) and tables should be original and sent separately in addition to text. They can be prepared on paper or computer designed (MSExcel, Corel, Acad).
Format. Electronic figures are recommended to be in CDR, Al, EPS, TIF or JPG formats. Resolution of bitmap graphics (TIF, JPG) should be at least 300 dpi. Text in vector graphics (CDR, Al, EPS) must be in MSWord Times typography or converted in curves.
Color prints. Authors will be charged for color prints of figures and photos.
Labeling of the additionally provided material for the manuscript should be very clear and must contain at least the lead author's name, address, the beginning of the title and the date of delivery of the manuscript. In case of an E-mail transfer the exact message with above asked data must accompany the attachment with the file containing the manuscript.

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- **Reception** of the Faculty of Natural Science and Engineering (for RMZ-M&G)
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- E-mail - addresses of Editor and Secretary
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These instructions are valid from August 2009

NAVODILA AVTORJEM

RMZ-MATERIALS AND GEOENVIRONMENT (RMZ- Materiali in geookolje) – kratica RMZ-M&G - je revija (ustanovljena kot zbornik 1952 in preimenovana v revijo RMZ-M&G 1998), ki izhaja vsako leto v štirih zvezkih. V reviji objavljamo prispevke s področja rudarstva, geotehnologije, materialov, metalurgije, geologije in geookolja.

RMZ- M&G objavlja izvirne znanstvene, pregledne in strokovne članke ter predhodne objave samo v angleškem jeziku. Strokovni članki so lahko izjemoma napisani v slovenskem jeziku. Kot dodatek so zaželene recenzije drugih publikacij (knjig, monografij …), nekrologi In Memoriam, predstavitve znanstvenih in strokovnih dogodkov, kratke objave in strokovne replike na članke objavljene v RMZ-M&G v slovenskem ali angleškem jeziku. Prispevki naj bodo kratki in jasni.

Avtorstvo in izvirnost prispevkov. Avtorji so odgovorni za izvirnost podatkov, idej in sklepov v predloženem prispevku oziroma za pravilno citiranje privzetih podatkov. Z objavo v RMZ-M&G se tudi obvežejo, da ne bodo nikjer drugje objavili enakega prispevka.

Vrste prispevkov

Optimalno število strani je 7 do 15, za daljše članke je potrebno soglasje glavnega urednika.
Izvirni znanstveni članki opisujejo še neobjavljene rezultate lastnih raziskav.
Pregledni članki povzemajo že objavljene znanstvene, raziskovalne ali strokovne dosežke na novem znanstvenem nivoju in lahko vsebujejo tudi druge (citirane) vire, ki niso večinsko rezultat dela avtorjev.
Predhodna objava povzema izsledke raziskave, ki je v teku in zahteva hitro objavo.
Strokovni članki vsebujejo rezultate tehnoloških dosežkov, razvojnih projektov in druge informacije iz prakse.
Recenzije publikacij zajemajo ocene novih knjig, monografij, učbenikov, razstav …(do dve strani; zaželena slika naslovnice in kratka navedba osnovnih podatkov - izkaznica).

In memoriam (do dve strani, zaželena slika).
Strokovne pripombe na objavljene članke ne smejo presegati ene strani in opozarjajo izključno na strokovne nedoslednosti objavljenih člankov v prejšnjih številkah RMZ-M&G. Praviloma že v isti številki avtorji prvotnega članka napišejo odgovor na pripombe.
Poljudni članki, ki povzemajo znanstvene in strokovne dogodke (do dve strani).

Recenzije. Vsi prispevki bodo predloženi v recenzijo. Recenzent oceni primernost prispevka za objavo in lahko predlaga kot pogoj za objavo dopolnilo k prispevku. Recenzenta izbere Uredništvo med strokovnjaki, ki so dejavni na sorodnih področjih, kot jih obravnava prispevek. Avtorji lahko sami predlagajo recenzenta, vendar si uredništvo pridržuje pravico, da izbere drugega recenzenta. **Recenzent ostane anonimen**. Prispevki bodo tudi tehnično ocenjeni in avtorji so dolžni popraviti pomanjkljivosti. Končno odločitev za objavo da glavni in odgovorni urednik.

Oblika prispevka

Prispevek predložite v tiskanem oštevilčenem izvodu (po možnosti z vključenimi slikami in tabelami) ter na disketi ali CD, lahko pa ga pošljete tudi prek E-maila. Slike in grafe je možno poslati tudi risane na papirju, fotografije naj bodo originalne.

Razčlenitev prispevka:

Predloga za pisanje članka se nahaja na spletni strani:

http://www.rmz-mg.com/predloga.htm

Seznam literature je lahko urejen na dva načina:
-po abecednem zaporedju prvih avtorjev ali
-po [1]vrstnem zaporedju citiranosti v prispevku.

Oblika je za oba načina enaka:
Članki:

Le Borgne, E. (1955): Susceptibilite magnetic anomale du sol superficiel. *Annales de Geophysique*; Vol. 11, pp. 399–419.

Knjige:

Roberts, J. L. (1989): Geological structures, *MacMillan*, *London*, 250 p.

Tekst izpisanega izvoda je lahko pripravljen v kateremkoli urejevalniku. Na disketi, CD ali v elektronskem prenosu pa mora biti v MS Word ali v ASCII obliki.
Naslovi slik in tabel naj bodo priloženi posebej. Naslove slik, tabel in celotno besedilo, ki se pojavlja na slikah in tabelah, je potrebno navesti v angleškem in slovenskem jeziku.
Slike (ilustracije in fotografije) in tabele morajo biti izvirne in priložene posebej. Njihov položaj v besedilu mora biti jasen iz priloženega kompletnega izvoda. Narejene so lahko na papirju ali pa v računalniški obliki (MS Excel, Corel, Acad).
Format elektronskih slik naj bo v EPS, TIF ali JPG obliki z ločljivostjo okrog 300 dpi. Tekst v grafiki naj bo v Times tipografiji.
Barvne slike. Objavo barvnih slik sofinancirajo avtorji
Označenost poslanega materiala. Izpisan izvod, disketa ali CD morajo biti jasno označeni – vsaj z imenom prvega avtorja, začetkom naslova in datumom izročitve uredništvu RMZ-M&G. Elektronski prenos mora biti pospremljen z jasnim sporočilom in z enakimi podatki kot velja za ostale načine posredovanja.

Informacije o RMZ-M&G: urednik prof. dr. Peter Fajfar, univ. dipl. ing. metal. (tel. ++386 1 4250316) ali tajnica Barbara Bohar Bobnar, univ. dipl. ing. geol. (tel. ++386 1 4704630), Aškerčeva 12, 1000 Ljubljana
ali na E-mail naslovih:
peter.fajfar@ntf.uni-lj.si
barbara.bohar@ntf.uni-lj.si

Pošiljanje prispevkov. Prispevke pošljite priporočeno na naslov **Uredništva:**

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  1000 Ljubljana, Slovenija

oziroma jih oddajte v

- **Recepciji** Naravoslovnotehniške fakultete (pritličje) (za RMZ-M&G)
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- Možna je tudi oddaja pri uredniku oziroma pri tajnici.

Navodila veljajo od avgusta 2009.

TEMPLATE

The title of the manuscript should be written in bold letters (Times New Roman, 14, Center)

Naslov članka (Times New Roman, 14, Center)

NAME SURNAME[1], …. , & NAME SURNAME[X] (TIMES NEW ROMAN, 12, CENTER)

[x] University of ..., Faculty of ..., Address…, Country ... (Times New Roman, 11, Center)

*Corresponding author. E-mail: ... (Times New Roman, 11, Center)

Abstract (Times New Roman, Normal, 11): The abstract should be concise and should present the aim of the work, essential results and conclusion. It should be typed in font size 11, single-spaced. Except for the first line, the text should be indented from the left margin by 10 mm. The length should not exceed fifteen (15) lines (10 are recommended).

Izvleček (Times New Roman, navadno, 11): Kratek izvleček namena članka ter ključnih rezultatov in ugotovitev. Razen prve vrstice naj bo tekst zamaknjen z levega roba za 10 mm. Dolžina naj ne presega petnajst (15) vrstic (10 je priporočeno).

Key words: a list of up to 5 key words (3 to 5) that will be useful for indexing or searching. Use the same styling as for abstract.
Ključne besede: seznam največ 5 ključnih besed (3–5) za pomoč pri indeksiranju ali iskanju. Uporabite enako obliko kot za izvleček.

INTRODUCTION (TIMES NEW ROMAN, BOLD, 12)

Two lines below the keywords begin the introduction. Use Times New Roman, font size 12, Justify alignment.

There are two (2) admissible methods of citing references in text:

1. by stating the first author and the year of publication of the reference in the parenthesis at the appropriate place in the text and arranging the reference list in the alphabetic order of first authors; e.g.:
   "Detailed information about geohistorical development of this zone can be found in: Antonijević (1957), Grubić (1962), ..."
   "… the method was described previously (Hoefs, 1996)"
2. by consecutive Arabic numerals in square brackets, superscripted at the appropriate place in the text and arranging the reference list at the end of the text in the like manner; e.g.:
   "... while the portal was made in Zope environment. [3]"

Materials and methods (Times New Roman, Bold, 12)

This section describes the available data and procedure of work and therefore provides enough information to allow the interpretation of the results, obtained by the used methods.

Results and discussion (Times New Roman, Bold, 12)

Tables, figures, pictures, and schemes should be incorporated in the text at the appropriate place and should fit on one page. Break larger schemes and tables into smaller parts to prevent extending over more than one page.

Conclusions (Times New Roman, Bold, 12)

This paragraph summarizes the results and draws conclusions.

Acknowledgements (Times New Roman, Bold, 12, Center - optional)

This work was supported by the ****.

References (Times New Roman, Bold, 12)

In regard to the method used in the text, the styling, punctuation and capitalization should conform to the following:

FIRST OPTION - in alphabetical order

Casati, P., Jadoul, F., Nicora, A., Marinelli, M., Fantini-Sestini, N. & Fois, E. (1981): Geologia della Valle del'Anisici e dei gruppi M. Popera - Tre Cime di Lavaredo (Dolomiti Orientali). *Riv. Ital. Paleont.*; Vol. 87, No. 3, pp. 391–400, Milano.

Folk, R. L. (1959): Practical petrographic classification of limestones. *Amer. Ass. Petrol. Geol. Bull.;* Vol. 43, No. 1, pp. 1–38, Tulsa.

SECOND OPTION - in numerical order

[1] Trček, B. (2001): *Solute transport monitoring in the unsaturated zone of the karst aquifer by natural tracers.* Ph. D. Thesis. Ljubljana: University of Ljubljana 2001; 125 p.

[2] Higashitani, K., Iseri, H., Okuhara, K., Hatade, S. (1995): Magnetic Effects on Zeta Potential and Diffusivity of Nonmagnetic Particles. *Journal of Colloid and Interface Science, 172*, pp. 383–388.

Citing the Internet site:

CASREACT-Chemical reactions database [online]. Chemical Abstracts Service, 2000, updated 2. 2. 2000 [cited 3. 2. 2000]. Accessible on Internet: http://www.cas.org/CASFILES/casreact.html.

Texts in Slovene (title, abstract and key words) can be written by the author(s) or will be provided by the referee or by the Editorial Board.

PREDLOGA ZA SLOVENSKE ČLANKE

Naslov članka (Times New Roman, 14, Na sredino)

The title of the manuscript should be written in bold letters (Times New Roman, 14, Center)

IME PRIIMEK[1], …, IME PRIIMEK[X] (TIMES NEW ROMAN, 12, NA SREDINO)

[X]Univerza…, Fakulteta…, Naslov…, Država… (Times New Roman, 11, Center)

*Korespondenčni avtor. E-mail: ... (Times New Roman, 11, Center)

Izvleček (Times New Roman, Navadno, 11): Kratek izvleček namena članka ter ključnih rezultatov in ugotovitev. Razen prve j bo tekst zamaknjen z levega roba za 10 mm. Dolžina naj ne presega petnajst (15) vrstic (10 je priporočeno).

Abstract (Times New Roman, Normal, 11): The abstract should be concise and should present the aim of the work, essential results and conclusion. It should be typed in font size 11, single-spaced. Except for the first line, the text should be indented from the left margin by 10 mm. The length should not exceed fifteen (15) lines (10 are recommended).

Ključne besede: seznam največ 5 ključnih besed (3–5) za pomoč pri indeksiranju ali iskanju. Uporabite enako obliko kot za izvleček.
Key words: a list of up to 5 key words (3 to 5) that will be useful for indexing or searching. Use the same styling as for abstract.

UVOD (TIMES NEW ROMAN, KREPKO, 12)

Dve vrstici pod ključnimi besedami se začne Uvod. Uporabite pisavo Times New Roman, velikost črk 12, z obojestransko poravnavo. Naslovi slik in tabel (vključno z besedilom v slikah) morajo biti v slovenskem jeziku.

Slika (Tabela) X. Pripadajoče besedilo k sliki (tabeli)

Obstajata dve sprejemljivi metodi navajanja referenc:

1. z navedbo prvega avtorja in letnice objave reference v oklepaju na ustreznem mestu v tekstu in z ureditvijo seznama referenc po abecednem zaporedju prvih avtorjev; npr.:

"Detailed information about geohistorical development of this zone can be found in: ANTONIJEVIĆ (1957), GRUBIĆ (1962), ..."

"… the method was described previously (HOEFS, 1996)"

ali

2. z zaporednimi arabskimi številkami v oglatih oklepajih na ustreznem mestu v tekstu in z ureditvijo seznama referenc v številčnem zaporedju navajanja; npr.;

"... while the portal was made in Zope[3] environment."

MATERIALI IN METODE (TIMES NEW ROMAN, KREPKO, 12)

Ta del opisuje razpoložljive podatke, metode in način dela ter omogoča zadostno količino informacij, da lahko z opisanimi metodami delo ponovimo.

REZULTATI IN RAZPRAVA (TIMES NEW ROMAN, KREPKO, 12)

Tabele, sheme in slike je treba vnesti (z ukazom Insert, ne Paste) v tekst na ustreznem mestu. Večje sheme in tabele je po treba ločiti na manjše dele, da ne presegajo ene strani.

SKLEPI (TIMES NEW ROMAN, KREPKO, 12)

Povzetek rezultatov in sklepi.

Zahvale (Times New Roman, Krepko, 12, Na sredino - opcija)

Izvedbo tega dela je omogočilo ………

Viri (Times New Roman, Krepko, 12)

Glede na uporabljeno metodo citiranja referenc v tekstu upoštevajte eno od naslednjih oblik:

PRVA MOŽNOST (priporočena) - v abecednem zaporedju

Casati, P., Jadoul, F., Nicora, A., Marinelli, M., Fantini-Sestini, N. & Fois, E. (1981): Geologia della Valle del'Anisici e dei gruppi M. Popera – Tre Cime di Lavaredo (Dolomiti Orientali). *Riv. Ital. Paleont.*; Vol. 87, No. 3, pp. 391–400, Milano.

Folk, R. L. (1959): Practical petrographic classification of limestones. *Amer. Ass. Petrol. Geol. Bull.;* Vol. 43, No. 1, pp. 1–38, Tulsa.

DRUGA MOŽNOST - v numeričnem zaporedju

[1] Trček, B. (2001): *Solute transport monitoring in the unsaturated zone of the karst aquifer by natural tracers.* Ph. D. Thesis. Ljubljana: University of Ljubljana 2001; 125 p.

[2] Higashitani, K., Iseri, H., Okuhara, K., Hatade, S. (1995): Magnetic Effects on Zeta Potential and Diffusivity of Nonmagnetic Particles. *Journal of Colloid and Interface Science, 172*, pp. 383–388.

Citiranje spletne strani:

CASREACT-Chemical reactions database [online]. Chemical Abstracts Service, 2000, obnovljeno 2. 2. 2000 [citirano 3. 2. 2000]. Dostopno na svetovnem spletu: http://www.cas.org/CASFILES/casreact.html.

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