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INFLUENCE OF THERMAL PROPERTIES OF ROCKS ON THE ENVIRONMENTAL COMFORT IN UNDERGROUND MINING – A CASE STUDY IN PERU

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ABSTRACT

The effect of temperature in underground environments is related to the thermal properties of rocks, which at certain depths may exceed the minimum standards of comfort to human work, thus causing thermal and other environmental risks.

To evaluate this influence a mathematical model was developed upon the concept of heat transfer from the rock mass to the ventilation air flowing in the underground space.

The model was applied to the underground mine of San Rafael located in the eastern mountain range of southern Peru, at an altitude of 5 299 m above sea level, with underground works located 1,000 m deep, where water temperatures are around 40ºC, thus generating high air thermal values (up to 34ºC).

The study allowed to determine the geothermal degree of the mine field (89.46 m/ºC), the thermal conductivity of local rocks (2.25 W/m.ºC) and led to evaluate the required corrective procedures by means of injecting 26.3 to 35.0 m^3/s of cool air, in order to attenuate those values to the recommended ones of 29ºC to 26.5ºC, respectively.

1. DEVELOPMENT OF A MATHEMATICAL MODEL

1.1. Geothermal degree

At a certain depth from the surface (15 m according to Hartman, 1992, 20 to 40 m as indicated Vutukuri, 1986), the temperature of rock masses varies during the year in function of the changes of surface air temperature, and that depth defines what is called thermal neutral layer (Fig. 1). At greater depths rock temperatures increase gradually, due to the ever present geothermal degree, many relations have been proposed, such as the one by Vutukuri:

$$g_g = f_r/C_t \quad (1)$$

where g_g is the geothermal degree (ºC/m), f_r the flow of rock mass heat, which is approximately 0,05 W/m^2 and C_t the thermal conductivity of the rock mass (W/m.ºC).

1.2. Transference of heat in underground openings

The temperature of any rock mass at a certain depth can be calculated by the following equation:

$$t_{hr} = t_{cn} + (h.\ h_{tcn})/g_g \qquad (2)$$

$$\Delta t_{gg} = (h_1.\ h_{tcn} \pm L.\ \mathrm{sen}\alpha)/g_g \qquad (3)$$

where t_{hr} is the rock temperature at depth h (ºC), t_{cn} is the temperature of the rock layer above the thermal neutral zone (ºC), h_{tcn} is the depth of the thermal neutral zone (m) and g_g geothermal degree of the rock (m/ºC). The value of Δt_{gg} represents the temperature increase in the rock mass due to the geothermal degree (ºC), h_1 is the initial depth of the tunnel measured from the surface (m), L is the length of the underground opening (m), and α the inclination of the opening (º), $+\alpha$ when the gradient is descending and $-\alpha$ when it is ascending (Fig. 1).

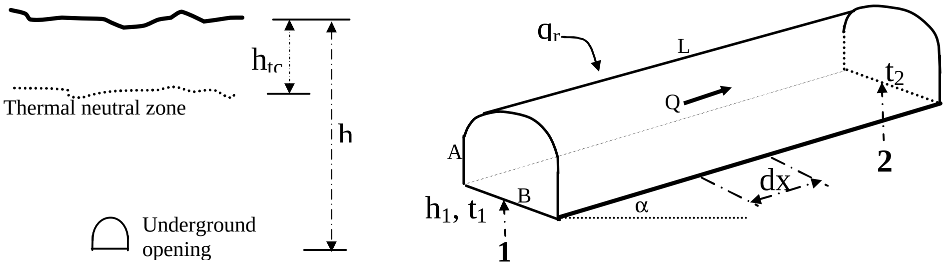

Figure 1: Layer of rock influenced by external temperature and elementary parameters of an underground opening

In order to obtain the mathematical model for the calculation of Δt_r , use of the heat transfer formulation of gas flow in pipes can be applied to underground openings.

Heat spreads from one point to another one in three distinct ways: conduction, radiation and convection. In most cases, the three processes occur simultaneously (E. Gomes de Azevedo, 1995) and therefore the amount of heat "q" supplied to a body of mass "m" and specific heat $C_{e,}$ when the temperature increases from t_1 to t_2 is given by the general equation:

$$q = m.C_e\,(t_2 - t_1) = m.\ C_e.\ \Delta t \qquad (4)$$

For the air flowing in the underground openings this equation can be expressed in function of the circulating air volume Q through:

$$q_r = 1000.\rho_a.\ C_e.Q.\ \Delta t_r = 1000.\rho_a.\ C_e.Q.(\,t_2 - t_1) \qquad (5)$$

where q_r is the heat received by the air from the rock mass (W), ρ_a the air density (kg/m^3), C_e the specific heat of air (kJ/m.ºC), Q the flow of air (m^3/s) and Δt_r the variation of temperature from t_1 to t_2 (Fig. 1). The heat coming out of the rock mass and received by the air of the underground environment can also be given in terms of coefficient of heat transference λ (J.P. Holman, 1983) according to the equation:

$$dq = \lambda.P.dx.(T_p - T_m) \qquad (6)$$

where T_p and T_m are the temperatures of rock wall and air mixture in the particular position x (ºC), λ the coefficient of transference of heat of the rock mass the air mixture (W/m^2.ºC) and P the perimeter of the opening of the section of the underground opening (m). The total heat q_r transferred (W) can be calculated through:

$$q_r = \lambda.P.L.(T_p - T_m)_{average} \qquad (7)$$

With the equation (7) the average temperature of the rock mass may be given by:

$$T_p = \{ t_1 + [t_1 + (h_1 - h_{tcn} \pm \text{Lsen}\alpha)/g_g]\}/2$$

and $T_m = (t_1 + t_2)/2$

By relating equations (5) and (7) it conducts to:

$$(\lambda.P.L)/2 \,.\, [(h_1 - h_{tcn} \pm \text{Lsen}\alpha)/g_g + t_1 - t_2] = 1000.\rho_a.\, C_e.Q.(t_2 - t_1)$$

Finally the variation of temperature from t_1 to t_2 becomes:

$$\Delta t_r = t_2 - t_1 = \lambda.P.L.\, (h_1 - h_{tcn} \pm \text{Lsen}\alpha)/[g_g.(\lambda.P.L + 2000.\rho_a.\, C_e.Q)] \qquad (8)$$

In raises or any vertical underground openings, $h_1 = 0$, and the length which influences the geothermic degree is $\text{Lsen}\alpha - h_{tcn}$ and α +, thus giving:

$$\Delta t_r = t_2 - t_1 = \lambda.P.(\text{Lsen}\alpha - h_{tcn})^2/g_g \,.\, [\lambda.P.(\text{Lsen}\alpha - h_{tcn}) + 2000.\rho_a.\, C_e.Q] \qquad (9)$$

The coefficient of heat transfer λ is calculated in function of the thermal conductivity K (W/m.ºC), the adimensional coefficient of Dittus and Boelter Nu_d and the diameter of section d (m); for horizontal and inclined underground openings d = (B + A)/2, where B is the width of the section (m) and A its height (m):

$$\lambda = K.\, Nu_d/d \qquad (10)$$

The relation of Dittus and Boelter $Nu_{d.}$ (J.P. Holman, 1983) was studied in detail by Petukohov for gases (air) who arrived to the following equation:

$$Nu_d = [(f/8).Re_d.Pr]/[1.07 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)] \qquad (11)$$

where Re_d is the Reynolds number (adimensional), given by:

$$Re_d = V.d/\mu$$

in which V is the average velocity of air (m/s), d the underground opening diameter (m) and μ the kinematic viscosity of air (Kg/m.s). In addition, f is the friction coefficient of the underground opening walls (Kg/m^3), P_r is the Prandtl number (adimensional) calculated by:

$$P_r = C_e \mu . / K$$

The total variation temperature in the underground environment (Δt_{total}), including the variation of temperature from air auto-compression (Δt_{ha}), thermal properties of rock (Δt_r), machines or equipment running with diesel engines (Δt_{ed}), excavation of rocks with explosives (Δt_{ex}), human metabolism (Δt_{ex}) and thermal water (Δt_{at}), is given by:

$$\Delta t_r = \Delta t_{total} - \Delta t_{ha} - \Delta t_{ed} - \Delta t_{ex} - \Delta t_{at} \qquad (12)$$

and this can be applied to look for alternatives of attenuating the thermal and environment risks and obtaining good conditions of comfort for human underground work.

2. CASE STUDY IN PERU

2.1. Rock mass and the underground environment

The San Rafael mine belongs to the Peruvian company MINSUR S.A. and is located Southwest of the San Bartolomé de Quenamari mountain (altitude 5,299 m), in the Department of Puno in the Eastern Mountains of Southern Peru. Geographically located in the coordinates 70°19' longitude West and 14°14' latitude South . This mine is the only producer of tin in Peru, with an ore production of 2 500 tons per day, with 5.23% of Sn.

Geology of San Rafael mine involves silts and quartzite rocks of the tertiary Sandia formation with the intrusion of two granites. In the neighborhood there are rocks of the superior Paleozoic. In the Sandia formation silts have dark gray colors with muscovite in the cleavage plans and the quartzites are intercalated with silts.

The mineralized veins and ore bodies are located in the intrusive orebody of San Rafael along the NE – SW direction, with a length of 1000 m to 800 m, a width of 300 m and depth of up to 2000 m. (Alvarez J. 2001) (Fig.2). These volumes have widths of 4 m to 30 m, by lengths of 30 m to 180 m and heights of 60 m to 610 m, and in general have prismatic forms. The main existing minerals are cassiterite, stanhite and calcopyrite.

Currently the main access from surface is through ramp 4 523, that communicates to level 3825, constituting the principal infrastructure of underground transport, as well as the ventilation circuit (Fig. 3).

2.2. Thermal characterization

By analyzing the meteorological data for 2000 in Rafael Mine it was possible to notice maximum temperatures of 26.3ºC in the month of November and a minimum of -9.2ºC in the month of July. The place annual average temperature is 6.61ºC.

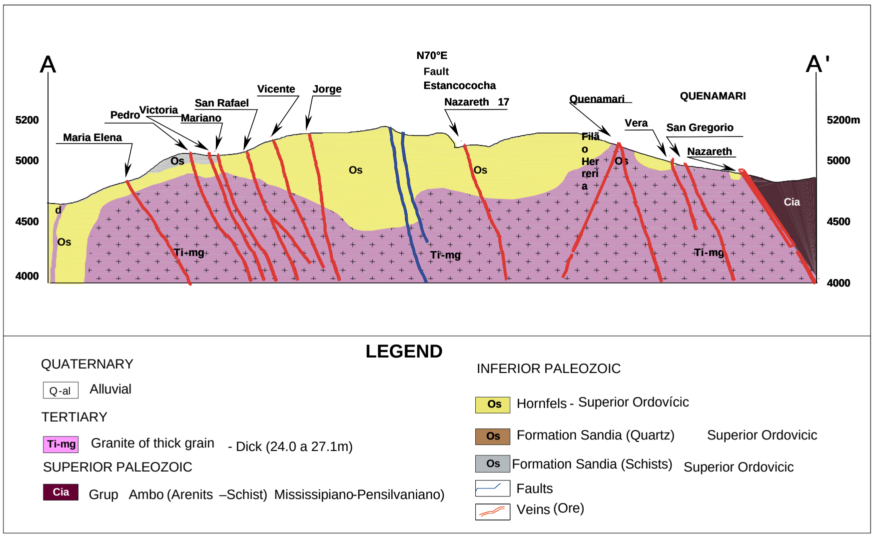

Figure 2: Geologic section with zones of mining in San Rafael along the direction N 70º E (Alvarez J, 2001)

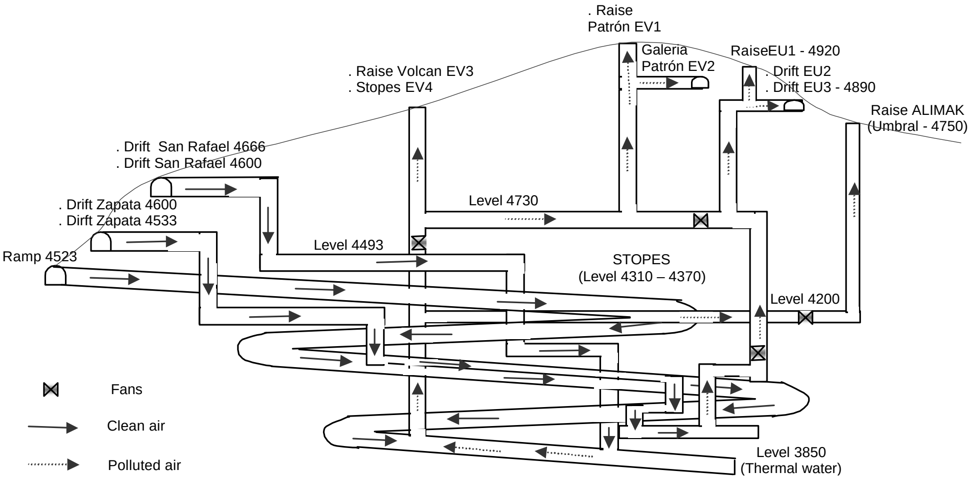

Figure 3: General project of the underground environment of the mine of San Rafael (V. Navarro Torres, 2001)

2.3. Temperature trends in the underground environment and influence for thermal water in level 3850

In general terms and considering as reference the entrance of clean air for the drifts 4666, 4600 and ramp 523, with the mine deepest level at 3 835 m, there is a 831 m difference where temperature raises 21.5ºC, or about 1ºC for each 40 depth m (Fig.4 left). The decrease of temperature in the direction of mine exit, or air exhaust, is from 30ºC to 14ºC making a difference of 16ºC for a total depth of 1 150 m (between levels 3850 and 5000), with an average of 1 ºC for each 72 m.

In Fig. 4 (right) the clean air temperatures one notices that a normal trend exists until the depth of 3 950 m (17ºC), but in level 3850, with a variation of only 100 m, temperature increases to 32ºC, thus showing the effect of thermal water. A forecast for air temperature in the 3850 level without the influence of hot water leads to 20ºC, with an airflow of 8 m^3/s.

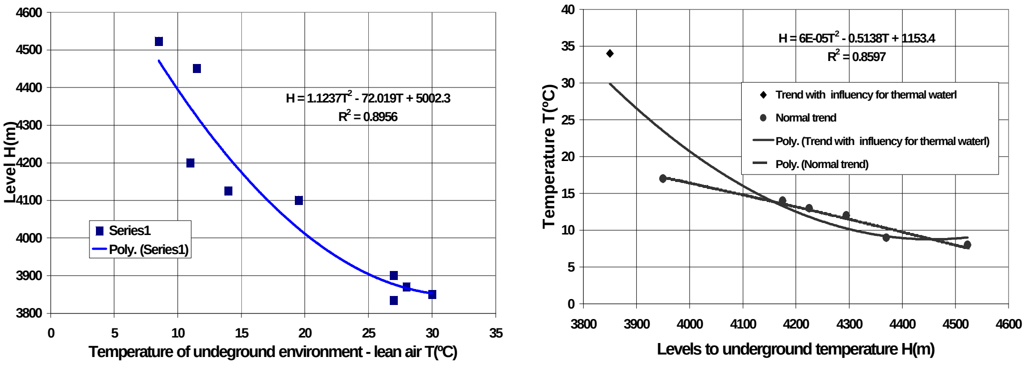

Figure 4: Trend of the temperature of the underground environment in the entrance process and influence of thermal water (elaborated based in the measurements of September to 20001)

The thermal water temperature of about 40ºC causes an increase to 34 ºC in the air temperature of the underground opening (with a 15 m^2 section), increasing in 12 ºC respect to normal air temperatures, thus representing about 60% increase.

2.4. Determination of the geothermal properties of rock

Applying equation (8) it is possible to obtain the geothermal degree in the Mine (g_g) by the expression:

$$g_g = \lambda.P.L.\ (h_1 - h_{tcn} \pm Lsen\alpha)/[\Delta t_r(\lambda.P.L + 2000.\rho_a.\ C_e.Q)]$$

For using the equation (10) calculated λ, the parameter N_{ud}. by equation (11) and the Reynolds number by its well known expression. To determine the g_g it is necessary to know the additional temperature generated by the virgin rock ((Δt_r), which is possible by means of balanced contributions from different sources of heat (following Table) and applying equation (12).

Increment of temperature values in the underground environment of San Rafael Mine (Navarro Torres V, 2001)

Increment the temperature	Δt_{total}	Δt_r	Δt_{ed}	Δt_{ex}	Δt_{at}
Calculated values (ºC)	26	16.66	0.85	0.52	12

Addition of Δt_{ed} , Δt_{ex} and Δt_{at} values gives a partial total (without considering Δt_r) of 13.34 ºC; but as the Δt_{total} is 26ºC (34ºC - 8ºC), therefore the value of Δt_r is 12.66 ºC. For properties of air at the atmospheric pressure using to the US National Bureau of Standards and Heat Transfer (J.P. Holman, 1983), and measured in the Mine are: K=0.0248056 W/m.ºC, d = 4.5m, f=0.0046 kg/m3, V=0.39 m/s, m=14.07x10-6 m^2/s, Pr=0.710, P=18m, L=7000m, h1=30m, htcn = 30m, a=7º, Q=8.11m^3/s, r = the 1.26614 kg/m^3 and C_e=1.0056 KJ/kg.ºC.

The result is : g_g =65 m/ºC or g_g = 0.0154ºC/m

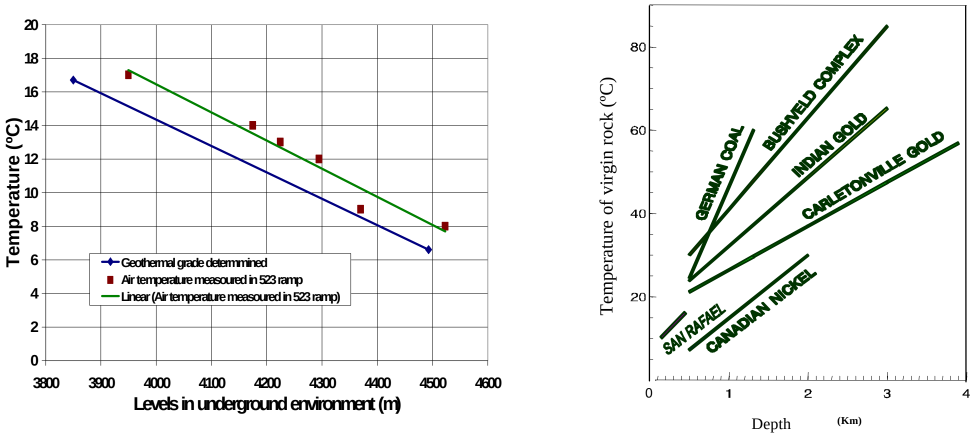

Figure 5: Comparison of geothermal degree in San Rafael Mine without hot water influence (left), compared with other mines in the world (right).

This result indicate, with an annual average external temperature of 6.61 ºC and at level 3 850 would reach 16.70 ºC (Fig. 5 left), which is compatible with the trend of temperatures measured in ramp 523. By applying the equation (1) the thermal conductivity of the rock mass of the San Rafael mine is estimated as 3.25 W/mºC.

2.5. Environmental comfort in underground mine

The increment of temperature generated by any diesel engine equipment Δt_{ed} can be calculated by the equation (13), where $f_m.f_t$ are factors of mechanical energy conversion for equipment use (0.032), q_d is the released energy equivalent for diesel oil (2,9 kW/kW) and p_d the engine power (kW).

$$\Delta t_{ed} = f_m.f_t \,.\, q_d \,.\, p_d / \rho_a .\, C_e.Q \qquad (13)$$

As far as temperature increases due to explosive detonations Δt_{ex} they are calculated by the equation(14), where C_e is the heat liberated by the explosive (kJ/kg) – for example 3,900 ANFO, 4,650 to 4,030 for dynamite 60% - and e_u the amount of used explosive (kg/day).

$$\Delta t_{ex} = c_e \,.\, e_u/86400.\, \rho_a .\, C_e.Q \qquad (14)$$

With these expressions and the equation (8) and other sources of heat as of hot water, for the conditions an average external air temperature of 6.61ºC it results as equation (15), where T_c is the underground air temperature in ºC (including effects of auto-compression, virgin rock, diesel equipment, explosive, thermal water) and Q_t is the clean airflow in m^3/s.

$$T_c = 25.31 + 1/(0.053 + 0.00384\, Q_t) + 27.80/\, Q_t \qquad (15)$$

The graphic representation of the equation (15) shows that the temperature of comfort (20ºC to 29ºC – according to J.K. Kreider, 2001), will be attained with clean airflows from 10 m^3/s to 35 m^3/s, respectively (Fig.6). Near the 3850 level it is not necessary to install a system of refrigeration due to the presence of hot water. That an increase of airflow in the faces of Level 3850 does not lead proportionally to the temperature reduction in the underground environment.

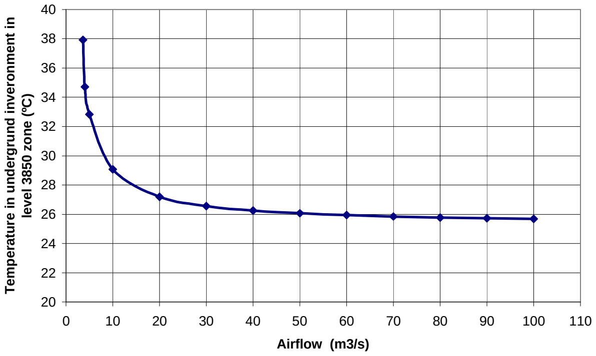

Figure 6: Variation of comfort conditions at depth in the 523 ramp and level 3850 of the San Rafael Mine

3. CONCLUSIONS

A mathematical model aimed to determining the geothermal properties of rock masses (geothermal degree and thermal conductivity) was developed on the basis of evaluating the thermal conditions of air flow in the underground environment.

Based on the influence of the thermal properties of rocks and other sources of heat (equipment use with diesel engines, explosive detonations, hot water flow, human metabolism, etc.), as well as local conditions such as the external temperature and physical dimensions of the underground openings, it is possible to determine air quantities for obtaining conditions of human comfort.

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