The Contribution of Cemented Backfill to Heat Loads in Mines

E De Souza[1] and A Hewitt[1]

ABSTRACT

Portland cement is the chief binding ingredient in mine backfill. In the presence of water, the chemical compounds within portland cement hydrate causing hardening and strength gain. During hydration, heat is generated. In certain cases, hydration heat may be produced significantly faster than it can be dissipated, which can create high temperatures in the underground environment. This paper presents the results of a series of investigations aimed at quantifying the heat generated by cemented backfill during hydration. Scaled stope models, instrumented with thermistors, were used in the investigation. Heat transfer to the hanging wall, orebody, footwall and cross-cut and production drifts was assessed during the backfill curing process and relationships between cement content, cure time, and heat generation were developed. The results of this work will assist mine operators in predicting the heat generated by cemented backfill and provide the necessary information to implement effective engineering control of heat in the underground environment.

INTRODUCTION

In hot and deep underground mines, prediction of climate conditions is essential for planning air requirements and the cooling capacity necessary to provide adequate working conditions. Although the dominant method of heat removal in mines is by ventilation air, the heat emitted in deep hard rock mines may become intensive enough to require the installation of a refrigeration system.

The selection and design of a mine climate control system is very complex. Identification and quantification of each source of heat emitted into the mine atmosphere is required in order to evaluate the quantity of airflow needed to remove the heat or to size a refrigeration plant.

Many researchers have devoted extensive time and effort to identify the sources of heat in underground mines, and a number of models have been developed to estimate the total heat load into the mine air. Elaborate mine climate simulation programs have also been developed to help evaluate such complex models.

The primary sources of heat in underground mines are:

- exposed strata,
- auto-compression, and
- machinery.

Other important sources of heat include fissure water, transported rock, personnel, explosives, ore oxidation, compressed air pipes, electric cables and lighting equipment.

Although cemented backfill is an important source of heat, no studies concerning its contribution and effect have been produced. Under certain circumstances, cemented backfill may become a critical source of heat. Mines operating in the high Arctic, for example, operate in permafrost ground conditions. Although frozen rock exhibits superior strength and demonstrates low susceptibility to ground disturbance, mining development may result in thawing of the rock mass due to heat transfer, with subsequent reduction in rock strength. A number of such mines use frozen backfill as a means of ground support, whilst some have employed cemented backfill when secondary filling is required. Under such circumstances, heat produced from cemented backfill, if not controlled, may adversely affect the integrity of such mines. As the thaw front advances into joints and fractures in the rock mass, reduction in rock strength would result, thus compromising the stability of the workings.

In highly productive, hot and deep mines utilising bulk mining methods and employing large quantities of cemented backfill, the backfill mass may also become a major contributor of heat, significantly affecting the underground climate. Workers exposed to high temperatures are known to have reduced work output and higher accident rates.

This paper presents the first known effort in quantifying the contribution of cemented backfill to the heat load in mines. The study presents the results of a series of investigations aimed at measuring the heat generated by cemented backfill during hydration. Scaled stope models, instrumented with thermocouples, were used in the investigation. Heat transfer to the hanging wall, orebody, footwall and cross-cut and production drifts were measured during the backfill curing process and relationships between cement content, cure time and heat generation were developed. The results of this work will assist mine operators in predicting the heat generated by cemented backfill and provide the necessary information to implement effective engineering control of heat in the underground environment.

SOURCES OF HEAT IN MINES

The major sources of heat in mines include heat from (Bossard *et al*, 1983; Burrows *et al*, 1989; Hartman, Mutmansky and Wang, 1982; McPherson, 1993; Misra, 1986; Rabia, 1988; Vutukuri and Lama, 1986):

- exposed strata,
- auto-compression,
- machinery,
- fissure water,
- transported rock,
- personnel,
- explosives,
- oxidation,
- compressed air pipes,
- electric cables, and
- lighting equipment.

Although the contribution of each source to the heat load of a mine is site dependent, a typical per cent range in heat contribution is provided:

- strata 40 - 50 per cent,
- auto-compression 10 - 15 per cent,
- equipment 20 - 25 per cent,
- water 15 - 20 per cent, and
- all other sources 2 - 5 per cent.

Strata heat is considered one of the most important sources of heat transfer to ventilating air; in deep mines it may account for more than 50 per cent of the total heat gained by the ventilation air. A source of heat that has not been quantified to date is backfill, and no studies concerning its effect have been found in the literature.

1. Department of Mining Engineering, Queen's University, 25 Union Street, Kingston Ontario K7L 3N6, Canada.

CEMENT HYDRATION AND HEAT

Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. The principal chemical components of portland cement are calcium, silicon, aluminium and iron and the main chemical compound constituents are tricalcium silicate, dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite and gypsum. In the presence of water, these chemical compounds hydrate causing hardening and strength gain. The reaction is time dependent; the product normally sets in a few hours and hardens over a period of weeks.

During hydration, heat is generated. The heat of hydration is most influenced by the proportion of tricalcium silicate and tricalcium aluminate in the cement, but is also influenced by fineness, water-cement ratio, cement content, curing temperature, the presence of admixtures, and the dimensions of the structural element.

The heat of hydration evolves over time as the cement constituents react and the cement sets. The hydration reaction can be measured by the rate of heat generation. Rapid heat generation occurs very early in the mix process. Hydration eventually reaches a steady state process, in which temperature has little effect on hydration. It is noted, however, that the development of the internal structure of hydrated cement continues to occur after the material has set and continues for months, even years, after placement. The rate of heat generation is greatest during the first few days.

Eight different types of portland cement are manufactured to meet different physical and chemical requirements for specific purposes (ASTM):

- type I is a general purpose cement suitable for all uses;
- type II is used where precaution against moderate sulfate attack is important;
- type III is a high-early-strength cement;
- type IV is a low heat of hydration cement for use where the rate and amount of heat generated must be minimised; and
- type V is a sulfate-resisting cement.

Types IA, IIA and IIIA are air-entraining cements, where concrete air content control is required. The average heat of hydration at seven days for the different cement types are (Portland Cement Association, 1997): Type I, 83.4 cal/gram; Type II, 82.3 cal/gram; Type III, 88.5 cal/gram; Type IV, 55.7 cal/gram, and Type V, 74.2 cal/gram.

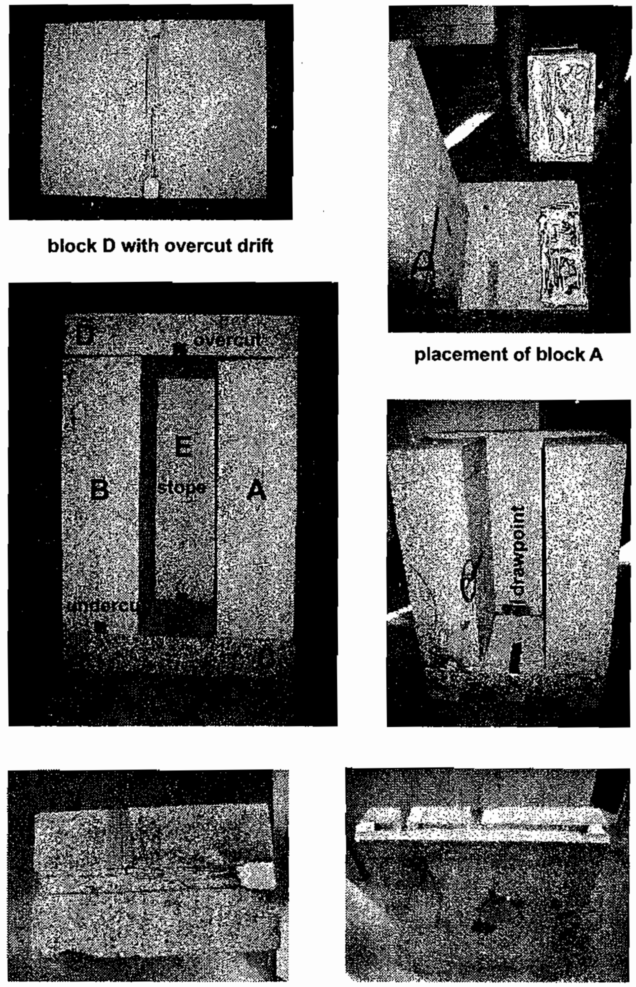
It is noted that cement performs differently when used in backfill. In certain cases, hydration heat may be produced significantly faster than it can be dissipated, possibly creating extreme temperature conditions in the underground environment.

THE TESTING PROGRAM FOR DETERMINING BACKFILL HEAT LOAD

Physical model development

Cemented backfill may contribute to the heat load in mines in different ways. This could be through exposed fill face in empty stopes; exposed fill in overcut drifts; exposed fill in drawpoints; and from heat transfer to adjacent rock. A scaled physical model of a backfilled stope was constructed to determine the different contribution processes of fill to the heat load, as presented in Figure 1.

The model consisted of five granite blocks to simulate the orebody and stope walls. Blocks A and B, used to represent unmined stopes, were 0.56 m high × 0.15 m wide × 0.27 m deep. Block B had an undercut drift 2.54 × 2.54 cm in cross-section. Between blocks A and B was the backfilled stope, 0.56 m high × 0.15 m wide × 0.27 m deep. Blocks C and D, 0.08 m thick × 0.5 m wide × 0.36 m deep, were used to represent the rock mass below and above the mining area, respectively. Block D had an overcut drift 2.54 × 2.54 cm in cross-section. Block E, used to represent the footwall, was 0.56 m high × 0.47 m wide × 0.11 m deep. Block E had a haulage drift and two cross-cuts, each 2.54 × 2.54 cm in cross-section. One cross-cut connected the haulage drift to the block B undercut and the other cross-cut connected the haulage drift to the backfilled stope bulkhead.



block D with overcut drift

placement of block A

block B with undercut drift

block E with haulage drift and cross-cuts

FIG 1 - Scaled physical model.

Twelve thermocouple probes were installed in the model to monitor the temperature profile within the mine area. The thermocouple probes were Type T flexible insulated wire probes, 0.254 mm in diameter (30 gauge) and 1.5 m long. A 12 channel Digi-Sense scanner was used for monitoring of temperatures. The scanner had such features as user-defined scan and log rates, individually programmable channels and alarm output. The scanner was connected to a computer via bidirectional RS-232 for data transmission, storage, and real-time data graphing.

Data acquisition was set at one sample every ten minutes per channel to provide a detailed temperature profile over the testing period. The ten per cent cement backfill was tested over 28 days, with a total sample size per channel of 4009 data points and 56 126 data points for the 12 thermocouples, date and time. The five per cent cement backfill was tested over 56 days, with a total sample size per channel of 8064 data points and a total of 112 896 data points.

Figure 2 illustrates the temperature probe position configuration in longitudinal and cross-sectional views. Probes one through five were positioned within the backfill and ore to provide the temperature profile along a horizontal line passing from the centre of the backfilled stope to the centre of the orebody. Probes six, nine, ten and 11 were positioned to provide the vertical temperature profile within the fill and in the overcut drift. Probes seven and eight were positioned to provide temperatures within undercut and haulage drifts. Probe 12 was installed to provide temperatures at the footwall. An external thermocouple (Omega precision fine wire teflon type T thermocouple), connected to an Omega Programmable Digital Thermocouple Metre, was also used to monitor the temperature in the control room.

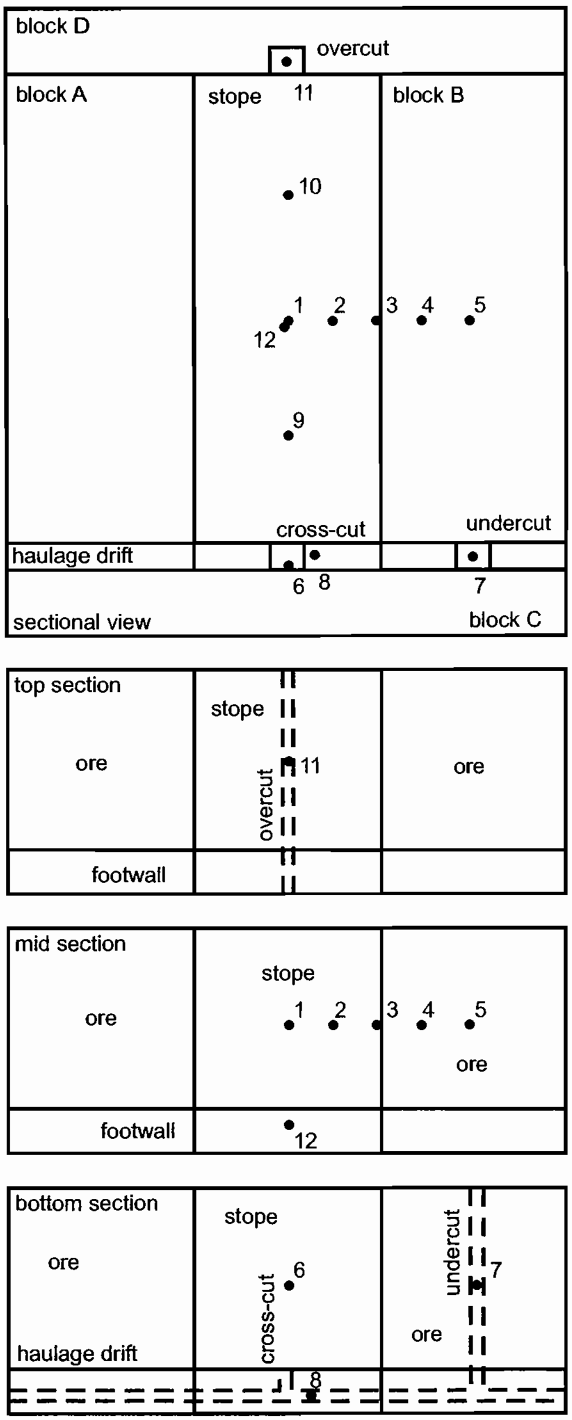


FIG 2 - Temperature probe position configuration.

Backfill preparation

Backfill was prepared using unclassified tailings supplied by an underground gold mine's mill operation. The received material had a moisture content approximating 19 per cent. Particle size analysis conducted using a laser particle size analyser indicated a uniformity coefficient (D_{60}/D_{10}) of 1.28 and a coefficient of curvature ($D_{30}^2/D_{10} \times D_{60}$) of 0.96. Approximately 80 per cent of the size distribution is 75 microns (minus 200 mesh). Material characterisation tests indicated the dry tailings material to have a bulk density of 1760 kg/m^3, a porosity of 36 per cent, cohesion averaging 35 kPa and an angle of friction of 36 degrees.

Two backfill recipes were designed at five per cent and ten per cent cement contents and 76 per cent solids. Approximately 58 kg of backfill was required for each batch to fill the model test stope (0.028 m^3). For the five per cent cement backfill, the recipe included 40.35 kg of dry tailings, 2.02 kg of portland cement and 13.38 kg of water. For the ten per cent cement backfill, the recipe included 40.35 kg of dry tailings, 4.04 kg of portland cement and 14.02 kg of water.

Figure 3 presents the different phases of backfill preparation, placement and curing.

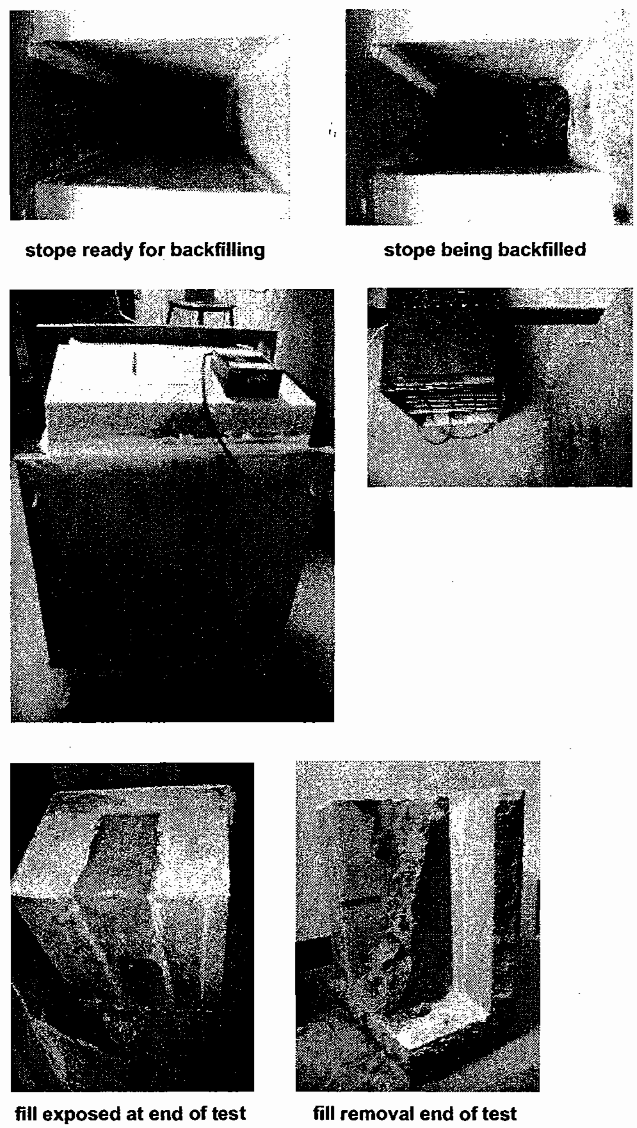


FIG 3 - Backfill preparation, placement and curing.

A SIMPLIFIED MODEL OF BACKFILL HEAT TRANSFER

The heat contribution from backfill is a transient phenomenon. Poured fill will initiate hydration as soon as the mix is prepared; hydration will continue in the first few hours and may last from a few months to years, depending on the type of fill.

The flow of exposed cemented backfill heat into mine airways depends on a number of parameters, including cement type and cement content; tailings material; water to cement ratio; cure time; thermal properties of the backfill; the length and geometry of the opening; and the volume of air flow.

Heat flow from backfill to the surrounding rock

The heat flow from backfill to the surrounding rock is due to conduction:

$$Q_f = KA\Delta T/L \tag{1}$$

where:

Q_f is the heat flow in W

A is the area in m^2

L is the thickness in m

K is the thermal conductivity in W/m.K

T is the temperatures in K

The heat flux (Q_f/A) is given by:

$$H = K\,\Delta T/L \tag{2}$$

where:

H is the heat flux (W/m^2)

Using the above model, the thermal conductivity of the backfill can be determined. Thermal conductivity is a property of materials that expresses the heat flux Q_f that will flow through the material if a certain temperature gradient ΔT exists over the material. It should be noted that thermal conductivity is a property that describes a semi static situation; the temperature gradient is assumed to be constant. As soon as the temperature starts changing, other parameters enter the equation. Since the curing of backfill is a non-steady state process the thermal conductivity can be determined as a time dependent parameter.

Consider three temperature measurement points: point one within the fill, point two at the interface between the fill and the stope wall and point three within the rock mass. The distance between points one and two is L_1 and the distance between points two and three is L_2.

From Equation 2, for backfill:

$$H_{fill} = K_{fill}\,(T_1 - T_2)/L_1$$

For rock:

$$H_{rock} = K_{rock}\,(T_2 - T_3)/L_2$$

Assuming the heat flux to be the same though each layer:

$$K_{fill}\,(T_1 - T_2) / L_1 = K_{rock}\,(T_2 - T_3) / L_2$$

$$K_{fill} = (T_1 - T_2) / L_1 = K_{rock}\,(T_2 - T_3)\,L_1 / (T_1 - T_2)\,L_2$$

If $L_1 = L_2$, then the thermal conductivity of the backfill can be determined as:

$$K_{fill} = K_{rock}\,(T_2 - T_3) / (T_1 - T_2) \tag{3}$$

Heat flow from backfill to the mine air

The heat flow process to the mine air is due to convection:

$$Q_f = h_c\,A\,(T_s - T_a) \tag{4}$$

where:

Q_f is the heat flow in W

h_c is the heat transfer coefficient in W/m^2K

A is the rock surface area in m^2

T_s is the surface backfill temperature in K

T_a is the air drybulb (db) temperature in K

The heat pick-up by the air can be calculated from:

$$Q_f = M_f\,\Delta h \tag{5}$$

where:

M_f is the mass flow of dry air in kg/s

h is the specific enthalpies in kJ/kg

The heat pick-up by the air can also be calculated from:

$$Q_f = M_f\,C_p\,\Delta t \tag{6}$$

where:

C_p is the specific heat of air in J/kg°C

t is the backfill and air temperatures in °C

EVALUATION OF BACKFILL HEAT LOAD

Heat load assessment for the ten per cent cement backfill

The temperature in the control room over the testing period of 28 days remained relatively constant, at an average temperature of 25.3°C. The ambient temperature thus did not affect model temperatures.

Figure 4 presents measured temperatures for the 12 probes over the 28 days in the cure process. Prior to fill placement the average model temperature was 24.5°C. In general, model temperatures reached a maximum 16 to 24 hours after fill placement followed by a steady decrease over the first week of curing. Temperatures then increased steadily reaching a maximum at 22 days after placement, followed by a decreasing trend in a converging mode. This correlates well with the hydration of cement. Rapid heat generation occurs very early in the mix process followed by a decrease in temperature due to the presence of excess water in the fill. As the reaction process continues and water is absorbed, the heat of hydration increases to a point coinciding with fill highly developed strengths.

As expected, temperatures were higher within the upper section of the fill (probe ten) and in the overcut drift (probe 11). The temperature within the fill reached a maximum of 27.5°C; this occurred 28 hours after backfill placement. The temperature in the overcut drift reached a maximum temperature of 27.6°C, 23 days after fill placement. The lowest temperatures were recorded in the haulage (probe eight) and undercut (probe seven) drifts. Both haulage and undercut drifts reached a maximum temperature of 25.6°C, 23 days after fill placement.

When considering the temperature profile along a horizontal line passing from the centre of the backfilled stope to the centre of the orebody (probes one through five), for the first four days the temperature decreased from the centre of the fill to the centre of the orebody and heat transfer occurred from the fill to the rock mass. After four days all probe temperatures were approximately similar. Minimum and maximum temperatures within the unmined stope were 23.5°C and 26.6°C. Using Equation 3, the variation in thermal conductivity of the backfill during the curing process was determined as presented in Figure 5. The minimum and maximum values of thermal conductivity were 0.73 and 6.6 W/m.K, with an average value of 2.3 W/m.K. The graph may be used to assess the flow pattern between fill and surrounding rock; curve sections where no data points are presented indicate time periods in which either no heat flux occurred or the heat flow reversed, ie from the rock to the fill. Based on variations in temperature within the fill, the backfill heat flux was estimated at 38 kW/m^2.

The vertical temperature profile from the bottom of the fill to the overcut drift, represented by probes six, nine, one, ten and 11, showed a consistent increase in temperature over the backfill height. This temperature profile was observed throughout the curing time of 28 days. The temperature in the overcut drift increased from a minimum 22.6°C of to a maximum of 27.6°C. Using Equation 2, the maximum static heat transfer from the fill to the overcut drift air was estimated at 5.3 kJ per kg of dry air. The temperature in both haulage and undercut drifts increased from a minimum of 23.3°C to a maximum of 25.6°C. The maximum static heat transfer from the fill to the undercut and haulage drift air was estimated at 2.3 kJ per kg of dry air.

As expected, footwall rock temperatures (probe 12) were similar to temperatures within the orebody (probes four and five). The temperature in the footwall rock increased from a minimum 23.7°C of to a maximum of 26.2°C. The heat flux into the footwall was estimated at 10.8 kW/m^2.

Heat load assessment for the five per cent cement backfill

The temperature in the control room over the testing period of 56 days remained relatively constant, at an average temperature of 23.8°C; the ambient temperature did not affect model temperatures.

Figure 6 presents measured temperatures for the 12 probes over the 56 day cure process. Prior to fill placement the average model temperature was 23.9°C. In general, model temperatures reached a maximum between the second and forth day after fill placement. Cycles of steady decrease followed by steady increases in temperature were observed throughout the 56 day curing period. A sharp decrease in temperature was observed on the 28th day of curing, followed by a sharp increase in temperature, and to a steadier trend.

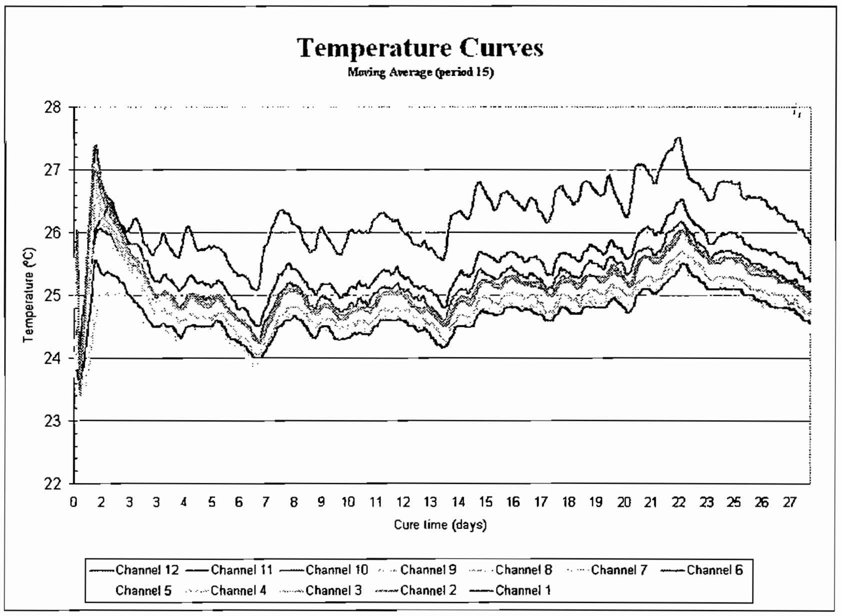


FIG 4 - Model temperature profile for the ten per cent cement backfill.

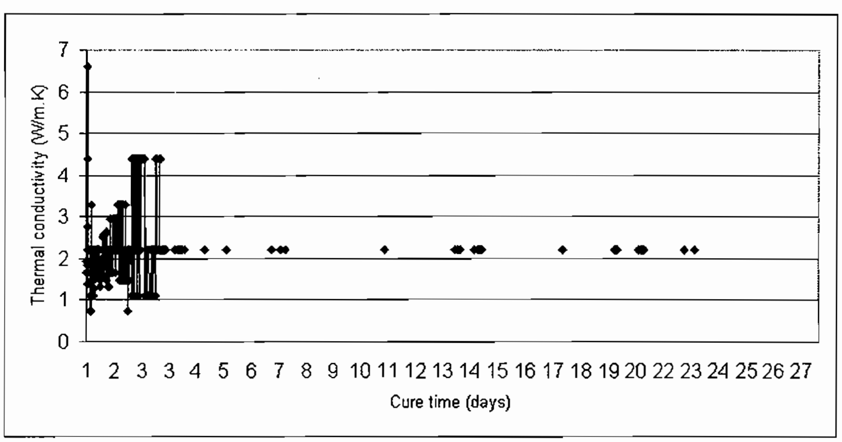


FIG 5 - Thermal conductivity for the ten per cent cement backfill.

Temperatures were higher within the upper section of the fill (probe ten) and in the overcut drift (probe 11). The temperature within the fill reached a maximum of 25.1°C; this occurred 16 hours after backfill placement. The temperature in the overcut drift reached a maximum temperature of 25.8°C, four days after fill placement. The lowest temperatures were recorded in the haulage (probe eight) and undercut (probe seven) drifts. Both haulage and undercut drifts reached a maximum temperature of 24.3°C, four days after fill placement.

When considering the temperature profile along a horizontal line passing from the centre of the backfilled stope to the centre of the orebody (probes one through five), for the first three days the temperature decreased from the centre of the fill to the centre of the orebody and heat transfer occurred from the fill to the rock mass. After three days all probe temperatures were relatively similar. On the 28th day, further heat transfer occurred followed by equalisation of temperatures. Minimum and maximum temperatures within the unmined stope were 20.8°C and 24.8°C. Using Equation 3, the variation in thermal conductivity of the backfill during the curing process was determined as presented in Figure 7. The minimum and maximum values of thermal conductivity were 0.73 and 6.6 W/m.K, with an average value of 2.47 W/m.K. Based on variations in temperature within the fill, the backfill heat flux was estimated at 33 kW/m^2.

The vertical temperature profile from the bottom of the fill to the overcut drift, represented by probes six, nine, one, ten and 11, showed a consistent increase in temperature over the backfill height. This temperature profile was observed throughout the curing time of 56 days. The temperature in the overcut drift increased from a minimum 21.3°C of to a maximum of 25.8°C. Using Equation 2, the maximum static heat transfer from the fill to the overcut drift air was estimated at 4.5 kJ per kg of dry air. The temperature in both haulage and undercut drifts increased from a minimum of 20.3°C to a maximum of 24.3°C. The maximum static heat transfer from the fill to the undercut and haulage drift air was estimated at 4 kJ per kg of dry air.

Footwall rock temperatures (probe 12) were similar to temperatures within the orebody (probes four and five). The temperature in the footwall rock increased from a minimum 20.7°C of to a maximum of 24.8°C. The heat flux into the footwall was estimated at 13 kW/m^2.

DISCUSSION

A summary of the observations and calculations of backfill heat load properties is given in Table 1.

The testing program indicated that the ten per cent and five per cent cement backfill materials experienced a change in

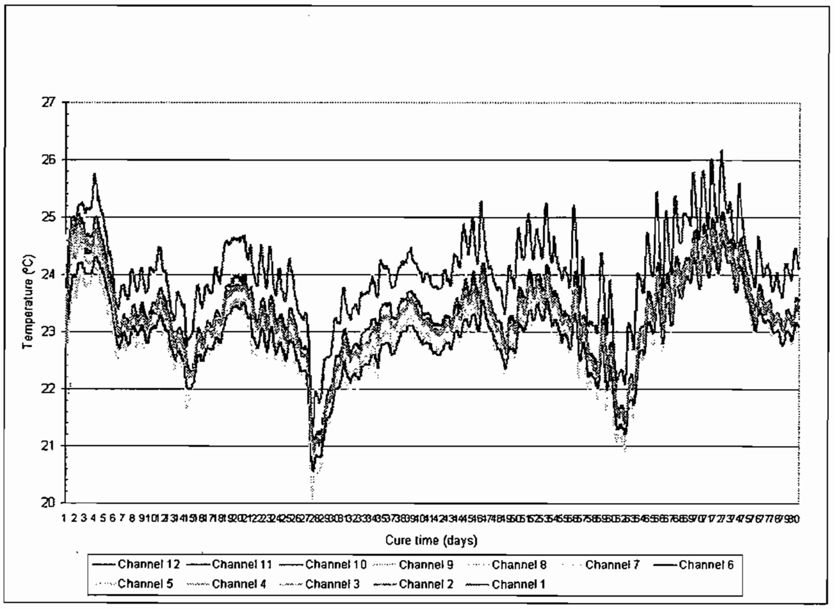


FIG 6 - Model temperature profile for the five per cent cement backfill.

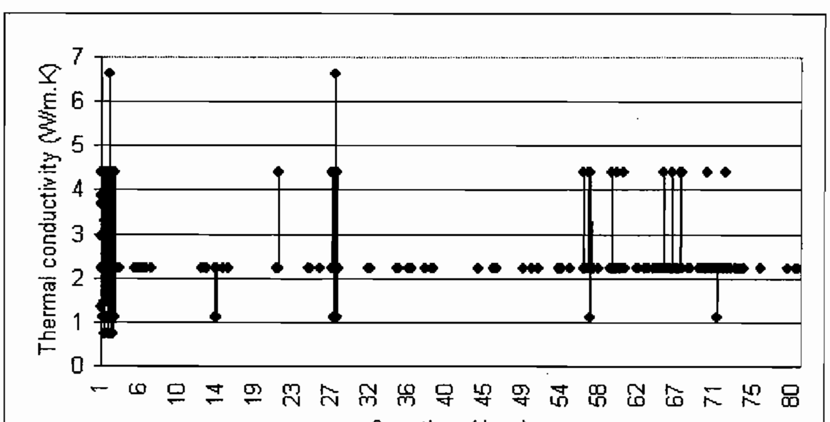


FIG 7 - Thermal conductivity for the five per cent cement backfill.

TABLE 1
Summary of backfill heat contributions.

Property	10% cement backfill		5% cement backfill	
Backfill temperatures (°C)	max	27.5	max	25.1
	min	22.3	min	20.5
	diff	5.2	diff	4.6
Ore temperatures (°C)	max	26.6	max	24.8
	min	23.5	min	20.8
	diff	3.1	diff	4
Footwall temperatures (°C)	max	26.2	max	24.8
	min	23.7	min	20.7
	diff	2.5	diff	4.1
Overcut temperatures (°C)	max	27.6	max	25.8
	min	22.6	min	21.3
	diff	5	diff	4.5
Undercut temperatures (°C)	max	25.6	max	24.3
	min	23.3	min	20.3
	diff	2.3	diff	4
Backfill thermal conductivity (W/m.K)	2.3		2.47	
Heat flux from fill to ore (kW/m^2)	38		33	
Heat flux from fill to footwall (kW/m^2)	10.8		13	
Heat transfer to overcut drift (kJ/kg)	5		4.5	
Heat transfer to undercut drift (kJ/kg)	2.3		4	

temperature of 5.2°C and of 4.6°C during the hydration process, respectively. Average thermal conductivities of 2.3 W/m.K and 2.47 W/m.K were determined for the ten per cent and five per cent cement fill material. The heat flux for the ten per cent cement backfill was estimated at 38 kW/m^2 and for the five per cent cement backfill at 33 kW/m^2.

For the ten per cent cement backfill, the overcut drift experienced a maximum temperature of 27.6°C; the static heat transfer from the fill to the air was estimated at 5 kJ per kg of dry air. The undercut drift experienced a maximum temperature of 25.6°C; the static heat transfer from the fill to the air was estimated at 2.3 kJ per kg of dry air. The footwall rock experienced an increase in temperature of 2.5°C, and the heat flux into the footwall was estimated at 10.8 kW/m^2.

For the five per cent cement backfill, the overcut drift experienced a maximum temperature of 25.8°C; the static heat transfer from the fill to the air was estimated at 4.5 kJ per kg of dry air. The undercut drift experienced a maximum temperature of 24.3°C; the static heat transfer from the fill to the air was estimated at 4 kJ per kg of dry air. The footwall rock experienced an increase in temperature of 4.1°C, and the heat flux into the footwall was estimated at 13 kW/m^2.

The above information clearly indicates that backfill can represent a major contributor to the heat load in underground mines; with heat loads equivalent to other major sources of mine heat.

CONCLUSIONS

This paper presented the results of a series of investigations aimed at quantifying the heat generated by cemented backfill during hydration and the heat flux to the hanging wall, orebody, footwall and cross-cut and production drifts of a scaled stope model. Heat transfer was assessed during long term backfill curing processes and relationships between cement content, cure time, and heat generation were developed. For the tested backfills, heat flux to adjacent rock reaching 38 kW/m^2 and heat transfer to mine air reaching 5 kJ per kilogram of air were determined. Such values indicate that backfill materials may represent a major contributor to the heat load in underground mines, and in mines where heat or coldness is critical, backfill heat load should be incorporated in mine climate engineering planning exercises.

REFERENCES

ASTM C-150. Standard specification for portland cement, ASTM Standard developed by subcommittee C01.10 on hydraulic cements for general concrete construction, Volume 04.01.

Bossard, F C, LeFever, J J, LeFever, J B and Stout, K S, 1983. *A Manual of Mine Ventilation Practices*, Second edition (F C Bossard and Associates, Inc).

Burrows, J, Hemp, R, Holding, W and Stroh, R M, 1989. *Environmental Engineering in South African Mines*, p 987 (Mine Ventilation Society of South Africa).

Hartman, H L (ed), Mutmansky, J M and Wang, Y J (co-eds), 1982. *Mine Ventilation and Air Conditioning*, Second edition, p 791 (John Wiley & Sons).

McPherson, M J, 1993. *Subsurface Ventilation and Environmental Engineering*, p 905 (Chapman & Hall).

Misra, G B, 1986. *Mine Environment and Ventilation*, p 619 (Oxford University Press).

Portland Cement Association, 1997. *Portland Cement Today*, 8(2):8.

Rabia, H, 1988. *Mine Environmental Engineering*, p 425 (Entract Software).

Vutukuri, V S and Lama, R D, 1986. *Environmental Engineering in Mines*, p 504 (Cambridge University Press).