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In-situ Mine Measurement of Rock Conductivity and Diffusivity Properties

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The flow of heat through rock into mine openings is strongly affected by the rock thermal property values of diffusivity, α and conductivity, k. *In situ* tests to determine these properties are desirable. Laboratory measurements have shortcomings due to the small size of specimen tested and lack of allowance for effects such as jointing, rock stress, saturation and moisture or gas migration.

A new approach for *in situ* measurement, REKA (rapid evaluation of k and α), which measures quickly and accurately thermal properties for a significant volume of rock is described. Measurements on various rock types have been undertaken at three Australian underground mines. The investigations and results are discussed and comparisons made with laboratory measurements on similar rock types. The REKA technique has been shown to be an efficient method of measuring two important input parameters for underground mine climate simulation computer programs used in the planning of cooling and ventilation in hot mines.

INTRODUCTION

Thermal diffusivity, α and thermal conductivity, k vary with rock types and are required in calculations of the rate of heat flow from rock into a mine opening. Rock as a source of heat has been reported by Enderlin[1], Johnson Bossard and Walli[2], Gillies and Alexander[3] and Gillies[4] to be 50% or more of total heat added to mine ventilation air. Whillier[5] reported that variation of heat flow to mine air from different rock types may be at a level of 250%. The importance of correct values of diffusivity and conductivity can be readily appreciated.

The simplest method of measurement of these parameters is to use a rock disc in the laboratory. However, as the thermal conductivity of a rock is a function of the conductivity of its constituent minerals, the value of k may be affected by different relative proportions of those minerals. The coarser the grain size in the specimen, the greater the likelihood of a scatter of values. For example, in a drill hole core from the Snowy Mountains, Australia, 65 specimens were tested from 134 m of granite, to yield a mean value of conductivity of 3.46 W/mK with a range of values from 2.93–4.48 W/mK (Beck and Beck[6]). In addition, laboratory tests do not allow for variation in fractures, rock stress and rock temperature. In order to overcome the inherent inaccuracy of laboratory tests it has long been recognised that *in situ* tests should be undertaken if at all possible. The problems with previous *in situ* measurements were that they were slow and frequently measured a number of interdependent variables.

A project to evaluate the *in situ* measurement system REKA (rapid evaluation of k and α) from tests in three Australian mines is described. Comparison with laboratory measurements on similar rock types gives some indication of the effectiveness of the approach.

LITERATURE REVIEW ON TECHNIQUES FOR MEASURING THERMAL CONDUCTIVITY AND DIFFUSIVITY OF ROCK

Laboratory Measurements

Measured thermal conductivity values for many common uniform materials are available in scientific reference manuals. For rock, however, there is a considerable variation due to the relative amounts of different rock-forming minerals. Over the last 50 years there has been considerable effort expended in different parts of the world to establish a methodology for accurate determination of this parameter.

The first determinations of thermal conductivity in rock used laboratory techniques. Birch and Clark[7] developed a 'divided bar' method based on apparatus which used rock discs of 38.1 mm diameter and 6.35 mm thickness. Suitable specimens for testing could be obtained from drill core. Studies were undertaken in different directions with respect to bedding planes or other elements of symmetry of the material. A range of test temperatures between 0° and 500°C was examined in these early studies. Experimental measurements showed a considerable variation of thermal conductivity with temperature. For example, a sandstone showed a decrease of conductivity of about 23% between 0° and 100°C. Gneiss over the same temperature range showed a decrease of about 8% and granite greater than 14%. Conductivity for basic rocks appeared independent of temperature.

Birch[8] carried out an extensive study of heat flow in the Front Range, Colorado. The apparatus he used for the measurement of thermal conductivity was the divided bar, remodelled from that used earlier by Birch and Clark[7]. He used the same sized rock disc as in earlier studies.

Beck[9] modified the divided bar method of Birch and Clark[7] to reduce the time taken for the apparatus to reach thermal equilibrium from about one hour to about ten minutes. This not only speeded up measurements but reduced changes in thermal conductivity due to evaporation of water, and other factors.

Beck and Beck[6] noted variations in thermal conductivity measured with Beck's[9] technique. In a granite of very uniform composition 48 discs were cut from 137 m of core. Conductivities measured ranged from 2.76–4.48 W/mK. In order to obtain the most accurate result, they recommended using a standard contact resistance of 4.9 mm of brass (the discs were held between cylinders of brass) in calculating the results. Thermal conductivity of a weathered shale was shown to vary according to its moisture content. With a fully dry disc the value was 2.55 W/mK, while at 13.2% moisture the value was 3.43 W/mK.

Doubts were cast on the reliability of these types of tests in determining *in situ* thermal conductivity, particularly because of the modifications to pre-existing stress due to the core removal. Beck and Beck's[6] recommendations were to compare laboratory methods with *in situ* determinations over a wide variety of rock types. It was noted that for many coarse-grained rocks the normal laboratory specimens are so small that they give a value of thermal conductivity significantly higher than the thermal conductivity of a large mass of the rock.

Jaeger and Sass[10] claimed that the divided bar method suffers many disadvantages.

1. It was usually tedious to operate but too involved to leave to any but the most skilled technicians.
2. It was comparative and not absolute.
3. It required accurate machining of the discs whose surfaces had to be flat to better than 0.02 mm.
4. It was difficult or impossible to prepare suitable discs of friable or weathered rock.
5. The method was unreliable for coarse-grained rocks since single crystals may easily traverse the entire thickness of the disk.
6. The apparatus was difficult to operate at other than room temperature although it was highly desirable to measure conductivities at other temperatures.

Jaeger and Sass[10] proposed a line source method of measurement, whereby two longitudinal slots were cut in a piece of drill core, with a heater wire cemented in one, and a thermocouple in the other. The thermal conductivity was measured normal to the long axis of the core.

Walsh and Decker[11] studied the effect of pressure and saturating fluid on the thermal conductivity of compact rock. It was pointed out that the thermal conductivity of dry rock (in a laboratory) might differ by about 15% from its *in situ* value. Opening up of fractures caused by a reduction of hydrostatic pressure, and the elimination of fluid in cracks and pores would both tend to reduce the apparent conductivity of a particular rock.

In Situ Measurements

Beck, Jaeger and Newstead[12] used an *in situ* measurement technique whereby a long metal probe, with a heater and temperature-measuring element was inserted in a water-filled drillhole. Loss of heat was a function of thermal conductivity and diffusivity, the thermal contact resistance between the probes and the rock, and the thermal capacity of the water between the probe and the rock.

Hitchcock and Jones[13] used a technique whereby a new heading in hot ground was monitored as it cooled, temperature readings being taken in drill holes up to 3 m deep. Heat flow was measured at the rock surface. Inaccuracies in the determination of surface temperatures affected the measured temperature gradient giving a degree of scatter in the results. The effect of water on the floor was not quantified, and this may have affected the results.

Sherratt and Hinsley[14] used a method whereby a section of underground roadway was sealed and heated for 50 days, recording temperature in the air and in six radiating boreholes up to 6 m into the rock. Thermal conductivities of rocks in that section of roadway were calculated from the borehole readings.

Sclater, Corry and Vacquier[15] developed a probe for the *in situ* measurement of the thermal conductivity of ocean-floor sediments. Heat was dissipated along the length of the probe at a constant rate by passing a known current through uniform resistance wire. The temperature was measured by a thermistor halfway down the length of the probe. This method of *in situ* measurement was only applied to unconsolidated sediments, and the authors claimed a reliability at the 95% confidence limit of 9%. The apparent lack of precision was justified by the speed of measurement, it no longer being necessary to take a core of the material. No attempt was made by the authors to adapt this technique to consolidated materials such as rock.

Vost[16] reviewed previous methods of in situ measurement of thermal diffusivity. He concluded that the method employed by Beck, Jaeger and Newstead[12] was difficult to interpret, gave acceptable values of thermal conductivity, but was unsuitable for the determination of diffusivity. The method used by Sherratt and Hinsley[14] assumed uniform rock type, which was not likely, and required greater precision in temperature measurement than was currently available. In addition it was a complicated (and thus expensive) procedure.

Vost proposed a method to measure rock temperatures continuously at various distances from the surface of a ventilated driveway. Natural changes in temperature (e.g. random, diurnal and seasonal) were measured on a continuous basis to allow corrections, but essentially he measured change of temperature due to ventilation of a previously closed drive. This technique was used to measure thermal diffusivity independently of conductivity and achieved an experimental error of 18% which compared favourably with existing *in situ* methods.

Mousset-Jones and McPherson[17,18] carried out measurements of the *in situ* values of α and k in two underground mines. In both cases a modification and simplification of the Sherratt and Hinsley[14] and Vost[16] methods were used. The results indicated that the *in situ* values were higher than the laboratory measured values and this was consistent with the *in situ* stress and water content at the measurement sites. While the methods developed were quite viable, they required a number of conditions to be present at the measurement sites in the mines.

Lee[19] used an *in situ* method for measuring both thermal conductivity and diffusivity at Mount Isa. The technique used was to place two or three rings of boreholes along the airways to be studied. Boreholes were 15 m long and had rock temperature sensors spaced along them. Rock thermal properties were calculated by comparing air temperature increases along each study airway with rock heat flux as indicated by temperature variation along the boreholes. For this approach to be accurate, there must be no other heat source or thermodynamic influence along the airway length. In particular, the airway must be dry with no potential for water evaporation into the mine air.

The significant differences between values determined in this study and those obtained in another study by Hyndman and Sass[20] were attributed by Lee[19] to the earlier study using homogeneous laboratory samples of a single rock type. Some of Lee's airways were wet and for the study it was found impossible to find airways totally within one rock type, so an area was studied rather than determining parameters for each rock type in the mine. Later examination of the airways used by Lee showed them to be either wet or damp. If the conditions in 1979 were similar, doubt would be cast on these results.

Danko and Mousset-Jones[21] used the former's Thermal System Identification (TSI) device as a means of measuring thermal conductivity *in situ*. The method required that a small portion of the rock surface be made flat and smooth. Further research was said to be needed to verify this technique. While not advancing the case for this technique, they pointed out the necessity of determining the isotropy of rocks surrounding a mine opening.

Danko, and Cifka[22] described an *in situ* method employing a point source heater of constant heat flux in a drill hole, thus creating a spherical temperature field which is monitored at several points along the length of the drill hole. They stated that the device and method made it possible to obtain highly precise values of thermal conductivity and diffusivity from a single drill hole within an eight hour period. The method was further developed by Danko, Mousset-Jones and McPherson[23]. It was claimed that this was a rapid method of measuring the two thermal parameters and that its results were quite reliable, comparing favourably with other methods.

Danko[24] pointed out the advantages of in situ measurements of rock thermophysical measurements over laboratory measurements because they take into account the influence of rock fractures, stress field and the possibility of cross effects (for example, moisture or vapour migration in the pores or fractures of the rock).

The measurement method called REKA, proposed by Danko and Mousset-Jones[25] had the additional advantages.

1. A measurement can be completed in an eight hour period, and a relatively large volume of rock of approximately one cubic metre, can be characterized by the measurement.
2. Thermal conductivity, k and thermal diffusivity, α are both obtained from the measurement.
3. A single borehole is needed for the measurement, although a second hole is used for cold junction comparison.
4. The geometry of the surface and the conditions above the rock surface do not influence the measurement.
5. In addition to averaged values for k and α the variation of these properties is also obtained during measurement.
6. The apparatus is relatively compact and portable.

The REKA method modified the assumption of a spherical temperature field, as described by Danko, Mousset-Jones and McPherson[23] as the heater was not a point source. Instead an elliptical temperature field was proposed. The results of this change gave greater accuracy but had the disadvantage of losing the simplicity of the original evaluation.

Danko and Mousset-Jones[25] used the REKA technique in a porous and completely saturated sandstone. It was observed that moisture evaporation significantly disturbed the measurements if boiling occurred at the heater, but it was possible to obtain values of the thermophysical properties by controlling the heater temperature below the boiling point of water.

IN SITU MEASUREMENT OF THERMAL CONDUCTIVITY AND DIFFUSIVITY OF ROCK

Experimental Equipment

The latest version of the REKA equipment used in this project was constructed by Danko[24] in 1989. It consisted of a probe which is inserted into a 600 mm long, 13 mm diameter drill hole in rock. At the furthest end of the probe is a heater and along the body of the probe are six temperature sensors. In operation, the heater and sensors are expanded against the side of the hole. During the measuring process the sensors record temperature changes in the rock over 40 equal periods taking a total of about four hours. The first 10 periods do not heat the rock, but check that rock temperature is stable. At the end of the tenth period or cycle the heater is turned on to a temperature at or below 100°C.

The thermal conductivity and diffusivity measurement routine is controlled by a Hewlett Packard HP71B computer, a Hewlett Packard HP3421A 20 channel measurement unit and a heater controller unit. A 12 volt regulated power supply is required for the heater. At the end of the 40 cycles the data in the HP71B is uploaded to a Personal Computer and the results processed and evaluated statistically.

Experimental Procedure

Mine heat conductivity and diffusivity measurements were undertaken at three Australian mines during the first half of 1990.

1. Four sets of measurements taken in separate locations in Urquhart shale in a development zone in the vicinity of the T62 Decline of the Mount Isa Mine.
2. Four sets of measurements again were taken in separate locations, mostly close to the orebody, on the 36 Level at the North Mine, Broken Hill. Three sites were in gneiss and the other in quartz lode rock.
3. Three sets of measurements were taken in separate locations in moderately weathered rhyolite and strongly foliated phyllite on the 140 Level of the University of Queensland Experimental Mine. In order to test the effects of foliation on thermal characteristics, in tests in the phyllite one pair of holes was drilled parallel to and the other pair normal to the foliation.

Experimental Results

Experimental results are summarized in Table 1. This table is divided into two parts. The left hand side sets down average values of thermal conductivity and diffusivity measured by the University of Queensland team at sites at the three mines. The right hand side references published literature values for thermal conductivity values for rock types at the Mount Isa and North Mine, Broken Hill mines. With no published values for University of Queensland Experimental Mine rock types available, reference is made to values for phyllite and lava from South Africa. Most published values referenced were obtained by laboratory techniques. There is a paucity of rock diffusivity values in the published literature.

Discussion of the Results

A comparison has been made of the thermal conductivity results obtained from *in situ* tests with previously published laboratory tests.

Broken Hill

For a total of 92 published laboratory values in gneiss at Broken Hill and the Front Range, Colorado (Birch[8]) distributed log-normally, the following results have been calculated.

Table 1
Rock Thermal Diffusivity and Conductivity

IN SITU MINE MEASUREMENTS					OTHER MEASUREMENTS					
MINE	SITE	ROCK TYPE	α $x10^{-6}m^2/s$	k W/mK	ROCK TYPE	k W/mK	RANGE	NO. OF SAMPLES	METHOD	REFERENCE
Mt Isa	Q62	Pyritic Shale	1.27	4.60	Silica Dolomite	4.14		12	Laboratory}	Hyndman and Sass[20]
	T62	Recrystallized Shale	1.28	4.41	Dolomitic Shale	4.06		36	Laboratory}	
	U64	Pyritic Shale	1.13	3.74	Pyritic Shale	6.57		6	Laboratory}	
	R61	Pyritic Shale (weakly recrystallized)	1.13	3.77	Shale	3.98	3.22–4.6	12	Laboratory	Howard and Sass[26]
					Pyritic Sh./Silica Dol./Spear Slst.	5.88			In situ}	
					Dolomitic Shale	2.19			In situ}	Lee[19]
					Silica Dol./Pyritic Sh./Dol.Breccia	7.59			In situ}	
North Broken Hill	CRM	Intermediate Quartzitic Gneiss	0.56	6.89	Various Gneisses	3.73*	2.18–6.11	46	Laboratory}	Sass and Le Marne[27]
	ORE	Quartz lode rock	1.24	4.17	Amphibolite	3.19*	2.34–4.1	11	Laboratory}	
	QTZ	Intermediate Quartzitic Gneiss	1.21	3.72						
	4DD	Quartzitic Gneiss	1.31	4.37						
U Q Experimental Mine	RHY	Rhyolite (moderately weathered)	1.1	3.46						
	PH1	Phylite (moderately weathered) parallel to foliation	1.21	3.14						
	PH2	Phylite (moderately weathered) normal to foliation	0.72	3.63						
Rajasthan, India					Phyllite	3.27*	2.78–4.1	20	Laboratory	Gupta *et al*[28]
South Africa					'Lava'	3.29**	2.31–5.09	22	Laboratory	Jones[29]

* mean, log-normally distributed
** mean, log-normally distributed, of unweighted averages

Number of values	=	92
Mean	=	3.56 W/mK
Limits at 1 σ	=	2.92–4.34 W/mK
Limits at 2 σ	=	2.39–5.29 W/mK
Range	=	2.18–6.11 W/mK

For Broken Hill alone, a total of 53 laboratory values, again distributed log normally, had the following results.

Number of values	=	53
Mean	=	3.92 W/mK
Limits at 1 σ	=	3.26–4.72 W/mK
Limits at 2 σ	=	2.71–5.66 W/mK
Range	=	2.18–6.11 W/mK

To obtain this number of readings all types of gneiss have been included.

The average values from the *in situ* tests at Broken Hill were 6.89, 4.17, 3.72 and 4.37 W/mK. The average for three sites (excluding the CRM site) is 4.09 W/mK. This compares well with the log mean value of 3.92 W/mK for the 53 samples tested in the laboratory. The value of 6.89 W/mK for the CRM test is more than two standard deviations from the mean, which suggests that this is not a reliable value. This area of the mine is extensively rock bolted due to the fractured nature of the ground. It is possible that a rock bolt was within the zone of influence of the probe. The high conductivity of a steel rock bolt may thus explain this high value.

Looking at the spread of values of the laboratory samples, the limits at one standard deviation are 18% below and 22% above the mean, while at two standard deviations the limits are 33% below and 49% above the mean.

Another rock type in the Broken Hill area is quartzite. Published laboratory measurements on quartzite are distributed log-normally, and the following results have been calculated. Indian results refer to those published by Gupta *et al.*[28]

	Broken Hill	Broken Hill + India
Number of values	45	75
Mean	4.32 W/mK	3.99 W/mK
Limits at 1 σ	3.42–5.46 W/mK	3.19–5.0 W/mK
Limits at 2 σ	2.71–6.89W/mK	2.55–6.26W/mK
Range	2.01–6.4W/mK	2.01–6.4 W/mK

Looking at the spread of values, the limits at one standard deviation are 20% below and 25% above the mean, while the limits at two standard deviations are 36% below and 57% above the mean.

Mount Isa

The individual laboratory tests were not available, but the average of 120 values was 4.07 W/mK. No quantitative idea of the spread of values can be obtained from the published figures.

The *in situ* tests conducted in this project yielded average values of 4.6, 4.41, 3.74 and 3.77 W/mK. The average of these four is 4.13 W/mK, which compares very well with the figure of 4.07 W/mK.

For accurate determinations of heat flow it is not enough to use average values of either conductivity or diffusivity for a particular rock type. Nor is it enough to use a single measurement of a rock type in a mine as representative of that rock. Further work will be necessary within a mine environment to determine the acceptable spacing of test sites (i.e. sampling frequency) necessary to calculate average values of conductivity and diffusivity.

CONCLUSIONS

The aim of this project was to evaluate the in situ method of measurement of thermal conductivity and diffusivity REKA (Rapid Evaluation of k and α). In addition, representative values of thermal conductivity and diffusivity were to be obtained at the participating mines.

Satisfactory values of k and α were measured at Mount Isa, Broken Hill and The University of Queensland Experimental Mine. No major experimental procedure problems were experienced.

It has been demonstrated that the REKA method is quick, economical and reliable. Laboratory measurements of k reported in the literature have shown a considerable scatter in values. The far greater sample size used in the REKA method has significance in this respect.

The simplicity of operation of this method and its minimal interference with mining operations, has been shown at all mines visited. Other *in situ* methods inevitably interfere with operations, and the greater number of variables necessary for computation render their results less reliable. Laboratory measurements do not allow for *in situ* factors such as moisture content, stress, rock temperature and fractures. In addition they only measure values within a small borehole sample.

Variation in values of k and α is principally a function of geology. Mineralogy is rarely consistent within one mine, and even within one area of the mine. For this reason it is necessary for a series of measurements in any area to be taken if an accurate heat balance is required. The REKA system and equipment has proved satisfactory for the accurate and practical measurement of two of the most important parameters in any mine heat evaluation.

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