18"' International Mining Congress and Exhibition ol Turkey-IMCET 2003, id *2003. ISBN 975-395-605-3*

Determination of Thermal Conductivity of Building Stones from P-Wave Velocity

H. T. Özkahraman & E.C.Işık
Departman of Mining Engineering, Süleyman Deınirel University, İsparta, Turkey

ABSTRACT: One aspect of energy efficiency is the improved insulation of buildings by using stones of a low thermal conductivity. In cold climates this results in reduced heating requirements, whilst in equatorial regions air conditioning energy consumption is decreased. Determination of the thermal conductivity of a natural stone plays an important role when considering its suitability for energy saving insulation. Thermal conductivity of rocks changes with rock type since rocks have variable and different mineral constituents. Secondly the porosity, natural water content and density is also very important property, which affects the thermal conductivity. In the study its found that laboratory determined P-wavc velocity of the rock samples which is a function of total porosity affects the thermal conductivity. So thermal conductivity values of natural stones found to be directly proportional to their P-wave velocities and there exists a good correlated relationship between them. So by measuring sonic velocity of a rock one can guess its thermal conductivity with a close approximation.

I INTRODUCTION

Encıgy efficiency is a subject that needs to be considered in building industry. To an increasing extent, energy usage, and more particularly, energy wastage is receiving close examination at present (Hasan 1999). By using natural stones of a low thermal conductivity improves insulation of buildings by giving energy efficient solution. The hot plate method (BSI 1986) is typical of the steady state method of thermal conductivity measurement. The thermal conductivity is determined from measurements of the temperature gradient in the stone and the heat input (ASTM 1990).

Guarding or correcting for heat losses is essential, as well as accurate measurements of the heat flux. With low conductivity stones, the necessary steady stale conditions take a long time to achieve. Heat conduction obeys to Fourier's law. Equation (I) derived from Fourier's law, which is used for heat conduction (Incropera & Dewitl 1990).

$$k = -\frac{q_x}{(dT/dx)} \qquad (1)$$

In the formula (I), q_x is the heat flux (W/m^2) and its the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer. It is proportional to the temperature gradient, dT/dx. dx is the thickness of the wall in x direction. The proportionality constant k is known as the thermal conductivity (W/mK) and is a characteristic of the wall material. The minus sign shows that heat is transferred in the direction of decreasing temperature. It follows that, for a prescribed temperature gradient, the conduction heat flux increases with increasing thermal conductivity. Considering the physical mechanism associated with conduction in general, the thermal conductivity of a solid is larger than that of a liquid, which is larger than that of a gas. For example (Incropera & Dewilt 1990);

- fireclay brick has a thermal conductivity of 1.7 W/mK,
- water at 30()°K has a thermal conductivity of 0.613 W/mK.
- ice at 273°K has a thermal conductivity of 1.8« W/mK.
- air at 3()0°K has a thermal conductivity of 0.026 W/mK,

As shown above when water becomes ice its thermal conductivity increases three times. This trend is due largely to differences in intcrmolccular spacing for the two slates. The thermal conductivity briefly is a transport properly, provides an indication of the rate at which energy is transferred by the diffusion process. So it depends on the physical structure of matter, atomic and molecular, which is related to the state of the matter.

/./ Insulation systems

Thermal insulations are comprised of low thermal conductivity materials combined to achieve an even lower system thermal conductivity. In fiber, powder, and Hake type insulations, the solid material is finely dispersed throughout an air space. Such systems are characterized by an effective thermal conductivity, which depends on the thermal conductivity and surface radiative properties of the solid material, as well as the nature and volumetric fraction of the air or void space. A special parameter of the system is its bulk density (solid mass/total volume), which depends strongly on the manner in which the solid material is interconnected and the percentage of pores in the solid. Therefore porosity is a determinative parameter of the thermal conductivity.

If bonding or fusing portions of the solid material forms small voids or hollow spaces, a rigid matrix is created. When these spaces are sealed from each other, the system is referred to as a cellular insulation. Most of the lymra limestones are an example of such rigid insulations. Evacuation of the air in the void space will reduce the effective thermal conductivity of the system. On the other hand the presence of water in the pores will increase the effective thermal conductivity.

The internal structure of a natural stone having open and closed pores in its texture effects to its heat transfer. The heat transfer inside such a stone may have several mode of heat conduction such as: conduction through the solid materials: conduction or convection through the air in the void spaces: and. if the temperature is sufficiently high, radiation exchange between the surfaces of the solid matrix. The effective thermal conductivity accounts for all of these processes. The values for selected insulation systems are summarized in Table 1.

Table 1 Theimophy.sical properties of building and insulating materials and nicks ai 300 Kdnciopera &Dewm 1990)

	Density, p (kü/m'l	Thermal conduetivity. UW/mK)
Coneietei stone mix 1	2300	1.40
Cement mortal	1S60	0.72
Perine	105	0 053
Wood (pine)	540	0.17
Plvwood	545	0 12
Rock		
Oiamre (Barre)	2630	2.79
Limestone. (Salem)	2320	2 15
Maible(llalstiin)	26X0	2 SO
Quarmte. Sioux	2640	5 3«
Sandstone. Berea	2150	2 90

1.2 Other relevant properties

In heat transfer, it is necessary to use many properties of matter. These properties are generally referred to as thermo physical properties and include two distinct categories, transport and thermodynamic properties. The transport properties include the diffusion rate coefficients such as k. the thermal conductivity (for heat transfer), and v, the kinematic viscosity (for momentum transfer). Thermodynamic properties on the other hand pertain to the equilibrium .state *of* a system. Density (p) and specific heat (C„) are two such properties used extensively in thermodynamic analysis. The product pC_p (J/m'K), commonly termed the volumetric heat capacity, measures the ability of a material to store thermal energy. Because substances of large density are typically characterized by small specific heats, many solids and liquids, which are very good energy storage media, have comparable heat capacities (pCp > I MJ/nr K). Many natural stones are also very good energy storage media, in this aspect. Because of their very small densities, however gases are poorly suited for thermal energy storage (pCp = 1 kJ/nı K)

In heat transfer analysis, the ratio of the thermal conductivity to the heat capacity is an important property termed the thermal diffusivityce, which has units of m^2/s:

$$\alpha = \frac{k}{\rho C_p} \qquad (2)$$

It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. Materials of large a will respond quickly to changes in their thermal environment, while materials of small a will respond more sluggishly, taking longer to reach a new equilibrium condition (Incropera&Dewiti 1990).

2 THE PROPERTIES OF NATURAL STONES

The mineralogy, grain size and porosity are the intrinsic properties controlling rock strength. The rocks containing quartz as the binding material are the strongest followed by calcite, ferrous minerals; rocks with clayey binding material are the weakest (Clauser and Huenges 1995). In general, the higher the quartz content, the greater is the strength (Price 1960). The strength of rocks is greater for finer grained rocks (Brace 1961). Compressive strength decreases with increase in porosity (Price 1960), (Smorodinov et al. 1970) . Solidified volcanic ashes such as tuff stones, and briquettes made from pumice, are used in Turkey in buildings as an insulating material. These kinds of building stones have large percentage of porosity. On the other hand porous materials arc good insulators of heat and sound. The thermal properties of a natural stone depend primarily on;

- Its mineral composition and constitution

- Its structural and textural features. These include mineral size fine grained or coarse grained, mineral shape and the presence of pores. Also the presence of micro cracks.
- The amount of pore water present.
- The condition it is in, when tested (e.g.. temperature, water content).

In bulk specimens of intact rock the mechanical properties depend not only on the properties of the individual minerals, but also upon the way in which the minerals are assembled. The relevant information is given by a full pétrographie description, which includes the mineral composition of crystals, grains, pores and cracks. The degree of isotropy or anisotropy is also important and varies with the size of the body of rock under consideration. For example, in schist, gneiss, and other foliated rocks, the constitutive properties vary with direction even at the microscopic scale, and to the extent that the mechanical properties even of a small specimen are affected. However, in sedimentary rocks, which are generally laminated, the rock within a lamina may be relatively isotropic, where as at a scale that includes the separation between lamina, the same rock may be relatively anisotropic. On the other hand, other rocks may be strongly anisotropic even within very thin sheets. Primary anisotropy, brought about by preferential orientation during crystallisation, or by recrystallisation during sedimentation or melamorphic processes, may be distinguished from secondary anisotropy, brought about by geologic deformation of the rock.

The number of specimens to be tested should be large enough to obtain an absolute value. But to limit the testing costs without sacrificing the reliability of results, it is necessary to ascertain the minimum number of specimens to be tested. In determining the number of specimens to be tested, account must be taken of the variability of test results and the desired accuracy and reliability of the mean value. (Yamaguchi 1970) analysed this problem by using a statistical technique "Decision of the sample number" after carrying out experiments for compressive and tensile strengths on three kinds of rock, granite, andésite and sandy tuff. He concluded that testing ten specimens could give 90% confidence level in determining the strength of rock. Therefore to lest about ten samples would be enough to accept the result with high confidence.

2. / *Mechanical significance of porosity and density data*

The presence of pores in the fabric of a rock material decreases its strength, and increases its deformabilily. A small volume fraction of pores can produce an appreciable mechanical effect.

Information on the porous nature of rock materials is frequently omitted from petrological descriptions, but is required if these descriptions are to be used as a guide to mechanical performance. Sandstones and carbonate rocks in particular occur with a wide range of porosities and hence of mechanical character; igneous rocks that have been weakened by weathering processes also have typically high porosities.

Most rocks have similar grain densities and therefore have porosity and dry density values that are highly correlated. A low-density rock is usually highly porous. It is often sufficient, therefore, to quote values for porosity alone. But a complete description requires values for both porosity and density.

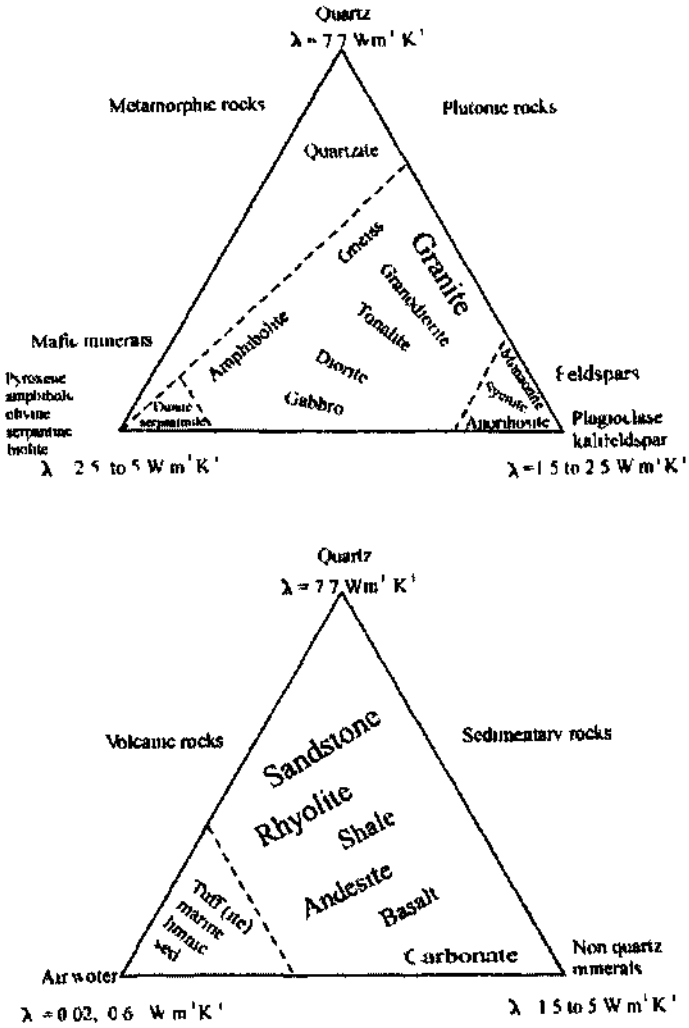
Samples were cut into cubes from several rock lumps. The lump sizes are chosen to be large to minimize the effect of experimental error.

Bulk density determination is carried out according to ISRM Committee or Laboratory Tests, suggested methods for determining physical properties such as porosity or density (ISRM 1972). Grain density is taken as density of solid component of the sample. Buoyancy method is used to determine bulk volume using Archimedes principle, from the difference between saturated-surface dry and saturated-submerged sample weights. Grain mass or the mass of solid part of the sample is obtained by oven drying at a temperature of 105 °C.

Porosity calculated from bulk volume and grain volume using the pulverization method. This gave total porosity. Therefore pore volume obtained includes that of closed pores as well as open pores. The ratio of volume of interconnected pores called open pores to bulk volume of the sample only gives effective porosity value, which can be determined from water absorption quantity.

3 THERMAL CONDUCTIVITY OF ROCKS AND MINERALS

Clauser & Huenges (1995) illustrated the various factors that influence thermal conductivity in rocks and minerals in two ternary diagrams as shown in Figure I. The diagrams relate different types of rocks with those factors that have the most pronounced effect on their thermal conductivity. Figure la is for melamorphic and plutonic rocks. Figure lb is for volcanic and sedimentary rocks. The différent rocks are representative for various classes of rocks within each group, thus representing the total spectrum of thermal conductivity in each group. Feldspars having low thermal conductivity and low variability are not further classified. The position of a rock's name in the compositional triangle indicates in a qualitative way its thermal conductivity.



h»uie I Theinnil conduct.vit> ot basic lock-loiming mmeials and compositional lelal.o.islup with locks (A) Meiamorphic and plûtonıc locks (B) Volcanic and sedimentary locks Foi Volcanic and sedimenlaiy locks the th.ıd mineral P j · ª ^ ^ ' ^ " ſ ^ due to tht gieat importance ot poiosity toi the theimal conductivity ol these locks (Clausei & Huenges I99*i)

Meiamorphic and plntonic rocks are made up ot quart? teldspais and mafic minerals, and the content ol mmeials horn these thtee groups basically determines a lock's theimal conductivity since these locks display a much smallei porosity Quaitz content determines conductivity since low conductivity associated with low quaitz-contcnt in metamoiphic tocks In volcanic and sedimentary locks the thud mineral component is leplaced by air and water as the high vaiiabiiity ot poiosity in these locks is a major factor controlling their theimal conductivity Especially tor sedimentary locks the controlling lactors on thermal conductivity aie poiosity and ongin ot particular sediment As tat as origin is concerned chemical sediments, mainly formed by precipitation of dissolved minerals or by compaction of organic material, and low porosity (< about 30%) physical sediments formed by compaction and cementation of clastic material have relatively high thermal conductivities. In contrast, high porosity (> about 80%) mainly marine physical sediments display a distribution which is biased towards low conductivities (Clauser & Huenges 1995).

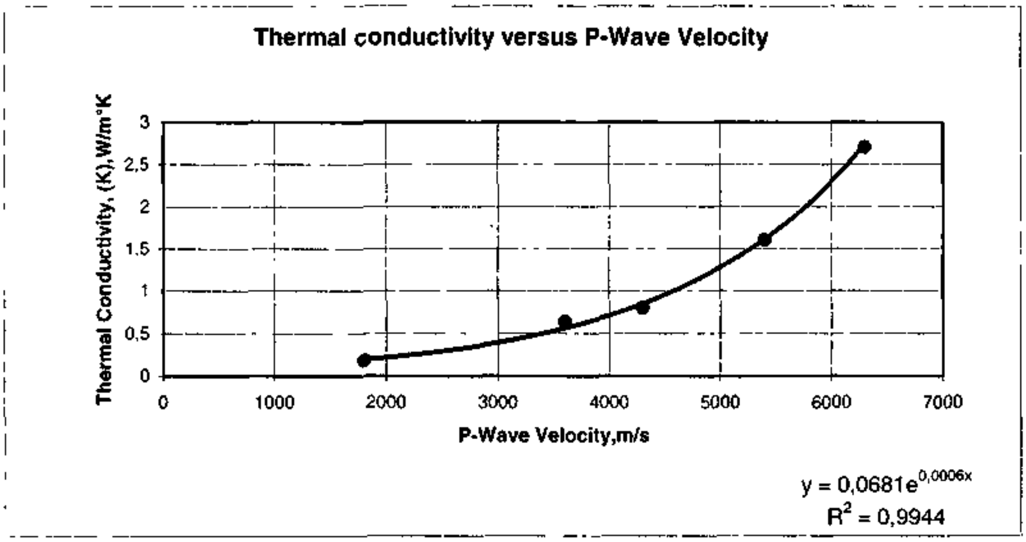
4 TESTS CONDUCTED IN THE LABORATORY

Tests conducted in the laboratory on specially prepared rock samples to determine a relation between thermal conductivity and their physico-mechanical properties. The types of rocks chosen are mainly used in building construction as a structural element or cladding inside and outside walls. Thermal conductivity tests conducted on 50 cm x 50 cm in 3 cm thick plates al a temperature of 300 K. P-wave velocity is measured on oven dried prismatic samples of 5 x 5 x 16 cm in dimension by Pundit apparatus. All the rock specimens were oven dried in all tests. Bulk density is found from bulk volume. The bulk volume of regular specimens is calculated using Archimedes principle, from the difference between dry and submerged sample weights. During the tests a thermostatically controlled, ventilated drying oven capable of maintaining a temperature of 105 °C for a period of at least 24 h is required. After determination of bulk volume and grain mass, the oven-dry sample is pulverized and its grain volume is determined by displacement of an equivalent volume of water in a volumetric flask (picknometer). Porosity calculated from bulk volume and grain volume by this method is termed total porosity, since the pore volume obtained includes that of "closed" pores. Porosity values given in Table I are total porosity values including open and closed pores. Cubic specimens with side length 4 cm. and 10 cm. are tested for compressive strength tests. Tests carried out in accordance with procedures laid out by Standards by l.S.R.M Committee on Laboratory Tests (ISRMI972). The results of tests carried out are given in Table I.

Table *2.* Laboratory determined thermal conductivity, compressive strength, porosity, density and P-wave velocity values of various stone types

Type of stone	Thermal Conductivity, (W/mK) at 300 K	P-Wave Velocity (m/s)	Porosity, (%)	Bulk Density (kg/m^3*)	Uniaxial Compressive Strength, (Mpa)
Burdur beige Limestone	2.7	6300	1.82	2690	84.8
Bucak travertine	1.6	5400	2.3	2550	57.0
Lymra limestone	0.8	4300	13.2	2430	44.0
Andésite	0.64	3600	16	2240	50.6
AAC bloke*	0.186	1800	84	500	3.43

AAC " is autoclaved aerated concrete (Ytong) which is a structural, insulating building material made of a combination of cement, lime, gypsum and a siliceous material.



Fıguıe 2 Thermal conductivity veisus P-wave velocity

5 SAVING ENERGY BY USING STONE PLATES IN BUILDINGS

Energy efficiency is a subject that needs to be considered by all engineering disciplines. To an increasing extent, energy usage, and more particularly, energy wastage is receiving close examination. By using stones of a low thermal conductivity improves insulation of buildings giving energy efficient solution.

The increase in limestone usage depends on supply and demand in natural stone market. The early use of stones at the beginning was just placing one stone on top of another as a massive construction without paying much attention to costs as today. Later to achieve larger spaces people begin to choose the shape, position and installation of stone. So builders sought stable ways to make the pieces stay together, this led to masonry stone workshops. However it wasn't long before, that people recognised that raw materials was getting expensive due to scarcity of finding stones and increased costs. So builders had to optimise the stone and make it thinner, smaller and more even. Therefore natural stones loose its role as a foundation element and other materials like concrete were used for this purpose and stones begin to be used lor cladding interiors and exteriors. Today cement mortar together with chemical additives is still used to attach the stone to the support wall. Now even thinner stone panels and faster building techniques are being used. Also it was vital to save energy after the oil crises. Global insulation of buildings by their outer skins was a boom and today is still the rage. Today stone plates are the most widely used material for this job and its anchored to the walls. Research is still centred on how to reduce weight, save labour and of course costs. So new technology involves either reducing stone to the thinnest possible sizes or use lightweight limestones like lymra limestone, since it has a lower thermal conductivity coefficient secondly its lighter due to low bulk density.

6 CONCLUSION

The graphs of thermal conductivity against P-wave velocity, porosity, density and compressive strength are drawn. It's determined from the graphs that, P-wave velocity, bulk density and compressive strength of the rock specimens are directly proportional to thermal conductivity and porosity is inversely proportional to thermal conductivity.

Among the relationships, thermal conductivity against P-wave velocity has the best correlation R=0.9944 (is nearest to unity). This means thermal conductivity of any rock can readily be calculated from laboratory determined P-wave velocity, from the relationship:

$$Y = 0.0681e^{0.0006x} \quad , \quad R^2 = 0.9944 \qquad (3)$$

Thermal conductivity values of 0.75, 1.37and 2.49 W/(mK) are obtained inserting 4000, 5000 and 6000 m/s values in Equation 3. Prediction from P- wave velocity is easier than measuring thermal conductivity on larger plates of 50 x 50 x 3 cm plates, which takes longer time and requires larger plates to prepare. In conductivity tests to reach steady state conditions takes longer time.

Also, thermal conductivity versus porosity curve (Figure 3) has a correlation coefficient very close to unity (R^2=0.97), indicating a meaningful relationship.

$$Y = 3.4934x^{-0.6369} \quad , \quad R^2 = 0.97 \qquad (4)$$

Thermal conductivity versus density relationship is not as good as porosity and P-wavc relations, since the bulk densities of natural rocks doesn't differ much, (2240-2690) as shown in Figure 4. The minerais constituting solid part of these rocks have very close much, (2240-2690) as shown in Figure 4. The minerals constituting solid part of these rocks have very close specific gravity values. The data fitted to an exponential curve as given below.

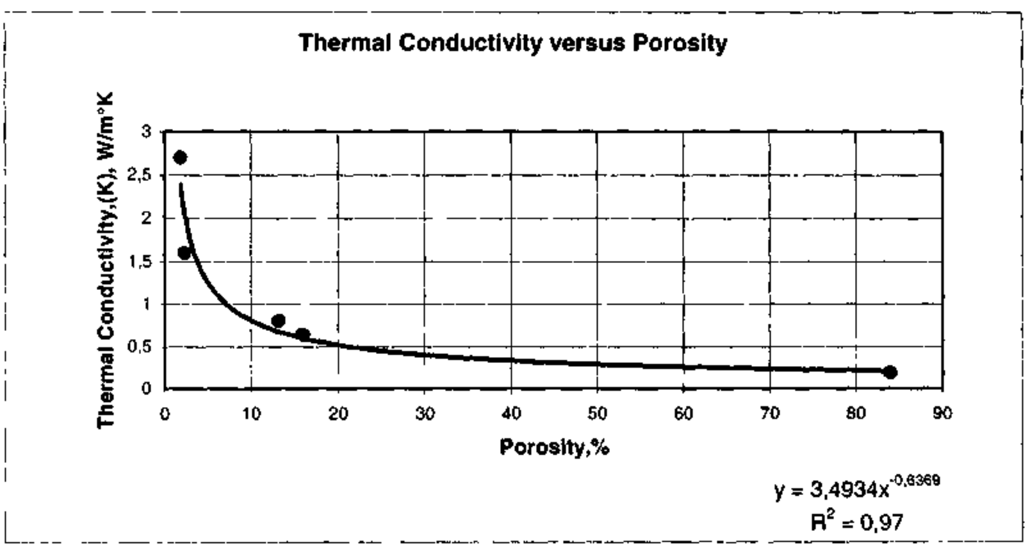
$$Y = 0.0003e^{0.0033x} \quad , \quad R^2 = 0.9236 \qquad (5)$$

Thermal conductivity versus compressive strength curve was also an exponential curve given by;

$$Y = 0.1677e^{0.0135x} \quad , \quad R^2 = 0.9375 \qquad (6)$$

In Equation R^2 is close to unity, this is due to the strength of the rocks shows distinct variation.Energy conservation is an important part of any national energy strategy. Energy conservation in underdeveloped countries with inadequate resources is even more important. Energy conservation in buildings, by using natural rocks that have low thermal conductivity will reduce energy requirement and reduce fossil fuel combustion and its polluting products.

The limestone usage will increase due to its high demand in natural stone market.



Fiğine 1 Theimal conductivity versus potostty

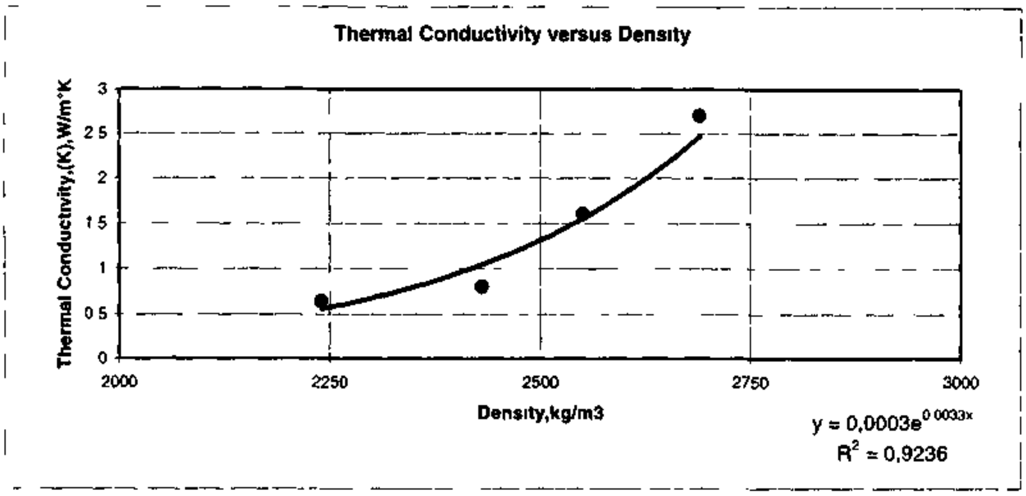
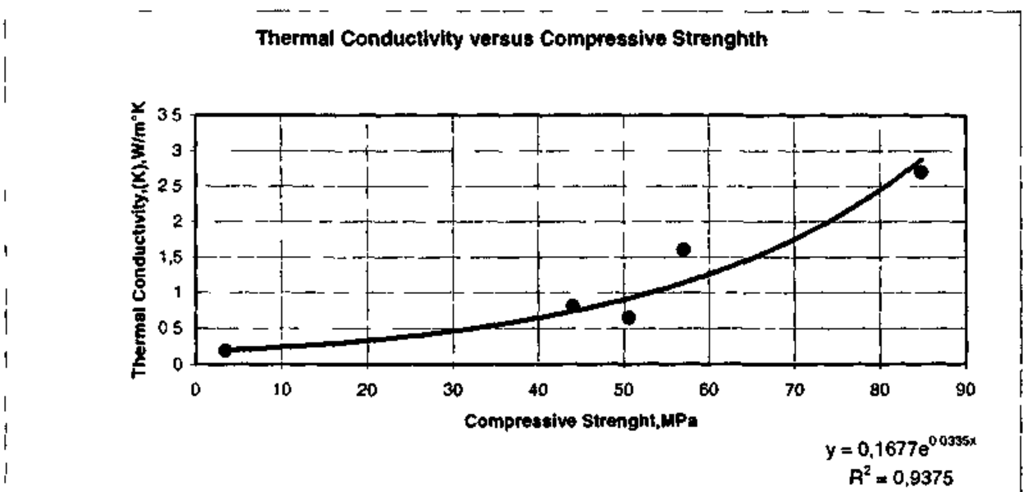


Figure 4 Thermal conductivity versus density



Hguıe S Theini.il conductivity veısus coınpıessıve stiength

REFERENCES

ASTM C 1990 Pıactıce toi the calculation ot tlıeımal tiaiisniission properties liom steady state heat flu\ nıeasuıenıcnts *Amelinin Soıut\ foi le\tm<i dilti Mtihiuth* 104^-90

Biace WF 1961 Dependence ot tıactuıe stiength ot locks on gıaın size *Pim 4 ıh S\mp Rıık Malı* Unıv Park Penn p 99- 101

Clausei C Huenges h 199i Tlıeı inal conductivity ol locks and mıneıals *Anient an (n'ophwtml Union* p I0v126

Bıııish Standaids Institute (BSD Detei mining Tlıeı mal insulating Pıopeıtıes Guaıdcd hot plate method Pan 2 Section 2 1 BS 874

Hasan A 1999 Optimising insulation thickness toi buildings using life cycle cost *Appliul DimR\ (ft* p ll'i-124

Inciopeia FP Dewitl DP 1990 *Iiiiultmienlah of hail and mtiw tminfc* Wiley NevvYoik

I S R M Committee on Laboiatoiy Tests 1972 Suggested Methods loi Detei mining Watei Content Poıosıty Density Absoiplion and related piopeilies p 12

Price NJ I960 The coınpıessıve stiength of coal measuie locks *Coll* Die 17 p 2X1-292

Smoxxlinov Ml Molovilov EA Volkov VA 1970 Deıeı initiations ot conelation lelationships between stiength and some physical cliaiactensiics ot locks *Prot 2"'Conti Im Sot Rotk Malı BLIRIMU 1* p ^-V7

Yamaguchi U 1970 The number ot lest pieces lequiied to detei mine the slieiigth of rock *Inl J Rotk Mali Mm Sa* 7 p 209-227