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Selected Physicochemical Properties of Basaltic Rocks, Liquids, and Glasses

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SELECTED PHYSICOCHEMICAL PROPERTIES OF BASALTIC
ROCKS, LIQUIDS, AND GLASSES

by

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ABSTRACT

Fundamental data on properties of rocks are required for the engineering development of rock-melting systems (Subterrenes). Selected physicochemical properties of basaltic rocks, liquids, and glasses are presented including viscosity, thermal diffusivity, thermal conductivity, specific heat, density, thermal expansion coefficient, and average chemical composition.

I. INTRODUCTION

Rock-melting systems are under development at the Los Alamos Scientific Laboratory.¹ Based on the concept of progressive localized melting of the rock encountered in forward motion and subsequent chilling of the melt to a glass, these systems, when fully developed, have the potential of contributing significant improvements to the general field of excavation technology.

Basic engineering design and refractory material requirements, heat-transfer considerations, chemical aspects of the rock-melting process, and potential applications have been discussed previously.^{2,3} A common theme in these discussions is the intrinsic properties of the materials used for the rock-melting system (Subterrene) and those characterizing the specific rocks themselves. General properties of materials (metals, alloys, ceramics, and gases) of interest to the overall development program are being accumulated as the program progresses and will ultimately be catalogued in a handbook. Selected physicochemical rock properties deemed necessary for basic hydrodynamic, heat-transfer, general engineering studies, and design work will be included.

This report initiates a compilation of pertinent rock properties of interest to the Subterrene program.

II. SELECTED PROPERTIES OF BASALTIC ROCKS

In view of the wide variation in rock types, this initial effort in compilation is restricted to the class of rock known generally as basalt, and to the liquid (melt) and glasses formed therefrom. Essential mineralogical constituents of a basalt are a calcic plagioclase feldspar, an augite clinopyroxene, and magnetite. Small quantities of other minerals, e.g., olivine, free silica, and ilmenite, may or may not be present. Sufficient variation exists in basalts that other types of nomenclature and petrological classification are often used. Thus the names tholeiite, alkali tholeiite, and olivine tholeiite basalts are mentioned as well as dolerites, gabbros, diabases, norites, and andesites. The latter group may still be classified as basalts although their higher total SiO₂ content (as determined by chemical analyses) identifies them rather as acidic granitic rock types. For purposes of this report, basaltic rocks are those that consist of 45-55 wt% SiO₂. It also seemed desirable to select a specific type of basalt as an "internal" standard whose specific data can be used for calculation purposes. Available data suggest that the Columbia River, Dresser, or olivine tholeiite types of basalt are appropriate candidates.

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Not all properties of the given basalts have been listed. Additional properties will be considered during future developmental needs. Specific properties of basalt rocks that have been included are:

- Viscosity - Tables I, II, and Figs. 1-8.
- Thermal diffusivity - Table III and Figs. 9-11
- Thermal conductivity - Table IV and Figs. 12-15
- Specific heat - Table V and Fig. 16
- Density - Table VI and Fig. 17
- Thermal expansion coefficient - Table VII and Fig. 18
- Chemical composition - Tables VIII and IX.

The reliability and precision of the data presented in the tables and graphs have not been assessed, because the intrinsic variability in chemical composition, sample location, physical integrity, and possible metamorphic changes of the rocks is too wide. In addition, variations in experimental measurement techniques add to the uncertainty. Consequently, rather wide ranges in numerical values are to be expected.

Various works contributing to the compilation are referenced, and the reader is referred to the vast geochemical literature for further information on rock classification.

TABLE I
VISCOSITY DATA

Type-Location	Value	Reference
<u>Liquid-Solid</u>		
1. Local-Los Alamos, NM	$\partial\eta/\partial T$ (see Fig. 1)	8
2. Tholeiite-Westfield, MA	$\partial\eta/\partial T$ (see Fig. 2)	14
3. Hawaiian Tholeiite-Makaopuhi lava lake	$\partial\eta/\partial T$ (see Fig. 3)	15
4. Various lava flows	$\partial\eta/\partial T$ (see Table 2)	9
5. Lava, Oshuma (1950) ^a Japan	$\partial\eta/\partial T$ and effect of water (see Fig. 4)	7, 20
6. Columbia River basalt and andesitic basalt, Mt. Hood, WA	$\partial\eta/\partial T$ (see Fig. 5)	24
7. Dresser, WI	$\partial\eta/\partial T$ (see Fig. 6)	25
8. Gabbro, Duluth, MI	$\partial\eta/\partial T$ (see Fig. 7)	25
9. Tholeiite	$\partial\eta/\partial T$ (see Fig. 8)	25

TABLE II
VISCOSITY DATA^a

Temp K	Viscosity	
	Poises	N·s/m ²
Tachylite 1924 Mauna Iki flow, Kilauea, Hawaii	1347 4350 1420 800 1521 150 1587 76	495 80 15 7.6
Olivine basalt, Gembudo, Japan	1423 37300 1473 3180 1573 296 1673 137	3790 318 29.6 13.7
Olivine basalt, Kcnoura, Japan	1473 732 1573 173 1673 120	73.2 17.3 12
Andesitic basalt, Motomura, Japan	1423 80000 1473 31200 1573 260 1673 140	8000 3120 26 14
Nepheline basalt, Nagahama, Japan	1473 130 1573 37 1673 80	13 3.7 8
Lava, Mt. Vesuvius, Italy	1373 28300 1473 2760 1573 730 1673 256	2830 276 73 25.6

^aThe solubility of water in basalt increases with increasing pressure, whereas the effect of pressure alone is an increase in viscosity.

^aData from Ref. 9.

TABLE III
THERMAL DIFFUSIVITY DATA

Type-Location	Value	Reference
<u>Liquid-Solid</u>		
1. Dresser, WI	$\partial D / \partial T$ (see Fig. 9)	5
2. Columbia River (Yakima Type) WA	$\partial D / \partial T$ (see Figs. 10 & 11)	5
<u>Solid^{a, b}</u>		
	$10^{-7} \text{ m}^2/\text{s}$	
1. Gabbro	5.2	22
2. Diabase, fine-grained	5.8	22
3. Diabase, silicified	8.1	22
4. Basalt, Prov. Tambe, Japan	7.0	26
5. Gabbro, Prov. Awadi, Japan	8.0	26

^a Sources include eastern Kazakhstan, eastern Sayan, west Siberian lowland, Kamchatkan peninsula, and Yuzhno-Minusinskaya depression for items 1-3. Remainder are from Japan, items 4-5.

^b Temperature range 290-300 K unless otherwise stated.

Fig. 1. Viscosity data of local Los Alamos basalt.

Fig. 2. Viscosity data of a tholeiitic basalt from Westfield, MA. (Data from Corning Glass Works).

Fig. 3. Viscosity data of a Hawaiian tholeiitic basalt in the melting range.

TABLE IV

Type-Location	Value W/m·K	Reference	Type-Location	Value W/m·K	Reference
<u>Liquid-Solid^a</u>					
1. Average or general basalt	4.18	13	16. Basalt, Prov. Tanba, Japan	1.4	26
2. Columbia River, WA	λ/λ_T (see Fig. 12)	4,23	17. Gabbro, Ulen-Tuim, Siberia	2.27	22
3. Columbia River, WA	λ/λ_T (see Fig. 13)	17,20,23	18. Diabase, fine-grained, Tigertyshiskiy, Siberia	1.97	22
4. Gabbro, Norite, Diabase (273-373 K)	1.7-2.6	7	19. Diabase, silicified, Shindinskiy, Siberia	2.35	22
5. Various	λ/λ_T (see Fig. 14)	7	<u>Liquid</u>		
6. Lava, Ventersdorp, Transvaal, S.A.	2.7-3.3	9	1. Hawaiian Tholeiite, Makaopuhi Lava Lake, Hawaii (1403 K)	2.1	15
7. Lava, Ventersdorp, Orange Free State, S.A.	2.6-3.6	9	<u>Glass</u>		
8. Norite, Sudbury, Ontario, Canada	2.3-3.1	9	1. Local-Los Alamos, NM	0.67	8
9. Diabase	2.6-3.4	9	2. Artificial Diabase-Type		9
10. Nevada Test Site (NTS)	λ/λ_T (see Fig. 15)	5,21	a. 273 K	1.15	
11. Diabase		9	b. 373 K	1.26	
a. 303 K	1.69		c. 473 K	1.37	
b. 348 K	1.73		d. 573 K	1.48	
12. Columbia River, WA Yakima Type		5	<u>Effect of Pressure</u>		
a. 373 K	1.53		The effect of pressure ^b upon thermal conductivity may be represented by the following equation:		
b. 773 K	1.41		$\lambda_p = \lambda_o (1 + \beta P),$		
c. 1173 K	1.45		where λ_o is the thermal conductivity at ambient pressure; β is a coefficient, and P is the higher pressure (Ref. 9). Pressure, P, has been represented in kg/cm ² . However, 1 kg/cm ² is about 1 bar; 1 atm.; or 1 x 10 ⁵ N/m ² (0.1 MPa).		
13. Dresser, WI			<u>Pressure Coefficient, β</u>		
a. 373 F	3.0	5	<u>Reference</u>		
b. 773 K	2.3		1. Average or general basalt		
c. 1173 K	1.5		a. 303 K	4.7 x 10 ⁻⁶	9
14. Gabbro, Prov. Chikuzen, Japan	3.0	26			
15. Gabbro, Prov. Awadi, Japan	1.8	26			

^aTemperature range 290-300 K unless otherwise stated.

^b Over the pressure range 0.1 MPa to 1200 MPa
(1-12,000 atm.)

TABLE V
SPECIFIC HEAT DATA

Type-Location	Value, kJ/kg·K	Reference
<u>Solid</u> ^a		
1. Average or general basalt	1.00	6, 12
2. Average or general basalt	0.71-0.84	7
3. Average or general basalt (298-898 K)	0.988	12
4. Recrystallized	0.84	10
5. Average or general basalt	1.25	13
6. Average or general basalt	1.00	4
7. Diabase	0.946	12
8. Basalt, Dresser, WI	$\alpha_{cp}/\Delta T$ (see Fig. 16)	27
<u>Liquid</u>		
1. Hawaiian Tholeiite-Makaopuhi Lava Lake, H-waii	1.05	15

^aTemperature range 290-300 K unless otherwise stated.

TABLE VI
DENSITY DATA

Type-Location	Value, Mg/m ³	Reference
<u>Solid</u>		
1. Average or general basalt	2.8	4
2. Nepheline basalt, Lind, WA	2.94	26
3. Dresser, WI	2.97	5
4. Gabbro, Duluth, MN	2.79	26
5. Average or general basalt	2.8-2.9	6
6. Diabase, Taylor Falls, MN	3.00	26
7. Gabbro, diabase, norite	2.95-3.10	7
8. Gabbro, York Haven, PA	3.04	26
9. Nevada Test Station (NTS)	2.68	21
<u>Liquid</u> ^a		
1. Average or general basalt	2.58-2.72	7
2. Transcaucasia	2.63	9
3. Columbia River, WA	$\rho_p/\Delta T$ (see Fig. 17)	16
<u>Glass</u> ^a		
1. Average or general basalt	2.68-2.90	7
2. Local - Los Alamos, NM	2.76	8
3. Average or general basalt	2.70-2.85	9

^aDensities of liquid and glasses tend to be 5-10% less than of solid.

TABLE VII
AVERAGE LINEAR THERMAL EXPANSION COEFFICIENT DATA

Type-Location	Value, $\bar{\alpha} \times 10^{-6}/K$	Reference
<u>Solid</u>		
1. Average or general basalt (273-373 K)	5.4	9
2. Average or general basalt (300 K)	4.3-6.5	7
3. Recrystallized (273-373 K)	7.8	10
4. Recrystallized (Glass-ceramic) (273-573 K)	7.0-8.5	11
<u>Liquid</u>		
1. Transcaucasia (1523 K) ^a	82	9
<u>Glass</u>		
1. Local-Los Alamos, NM (293-873 K)	6.9 (see Fig. 18)	8
2. Tholeiite and Alkali type (300 K)	5.9-6.2	11

^aVolume expansion coefficient.

Fig. 4. Viscosity for the Oshima 1950 basaltic lava and effect of water upon viscosity. Curves are theoretically deduced.

TABLE VIII
AVERAGE VALUES OF WEIGHT% FOR ANALYSES
OF DIFFERENT BASALTIC ROCK TYPES (Ref. 7)

Rock Type ^a	1	2	3	4	5	6	7	8	9	10	11	12
Number of analyses	1996	1558	417	127	715	283	998	182	48	230	288	247
SiO ₂	49.5	49.3	50.6	48.4	51.6	51.6	51.6	48.6	49.4	48.8	48.6	48.5
TiO ₂	1.9	2.0	1.5	1.6	1.6	1.5	1.6	1.7	1.3	1.6	2.1	2.2
Al ₂ O ₃	15.9	16.0	15.3	16.2	16.4	15.1	16.0	15.5	15.4	15.5	16.3	16.3
Fe ₂ O ₃	3.0	3.2	2.4	2.6	3.2	2.3	3.0	2.6	2.0	2.5	3.1	3.1
FeO	8.0	7.8	8.9	7.9	7.4	8.9	7.8	8.7	9.6	8.8	8.1	8.0
MnO	.17	.17	.18	.19	.17	.19	.18	.17	.19	.17	.17	.17
MgO	6.6	6.6	6.4	7.3	5.6	6.1	5.8	8.4	7.8	8.3	6.5	6.6
CaO	10.0	9.9	10.1	10.8	9.8	10.1	9.8	10.3	9.8	10.2	9.9	9.9
Na ₂ O	2.7	2.8	2.4	2.6	2.5	2.2	2.4	2.3	2.3	2.3	3.0	3.0
K ₂ O	1.0	1.0	0.9	0.7	0.8	0.9	0.8	0.6	0.9	0.7	1.0	1.0
P ₂ O ₅	.35	.32	.26	.26	.21	.20	.21	.23	.21	.23	.34	.36
H ₂ O ⁺	0.9	0.9	1.0	1.0	0.7	0.9	0.8	0.9	1.1	0.9	0.9	0.9

- ^a
1. Total sample
 2. All basalts
 3. All dolerites^b
 4. All gabbros
 5. q-basalts^b
 6. q-dolerites
 7. q-basalts + dolerites
 8. ol tholeiitic basalts
 9. ol tholeiitic dolerites
 10. ol tholeiitic basalts + dolerites
 11. ol alkalic basalts + dolerites
 12. ol alkalic basalts

^b Dolerites, q-basalts, etc.. are petrographic classifications.

Fig. 5. Viscosity data of Columbia River basalt (CRB) and andesitic basalt (MHA) from Mount Hood, WA.

TABLE IX

CHEMICAL COMPOSITION OF NEW MEXICO BASALT ROCKS

Constituents	Type wt %		
	Basalt ^a	Olivine Basalt ^a	Local ^b
SiO ₂	50.06	45.81	49.90
Al ₂ O ₃	14.51	14.08	19.00
Fe ₂ O ₃	4.33	5.21	2.78
FeO	4.46	7.41	7.40
MgO	6.36	8.79	3.98
CaO	9.17	9.45	8.30
Na ₂ O	3.24	2.49	3.82
K ₂ O	2.04	0.86	1.08
CO ₂	—	0.88	0.04
TiO ₂	1.50	1.63	1.54
P ₂ O ₅	1.05	0.28	0.36
MnO	0.15	0.19	0.16
Cr ₂ O ₃	—	—	—
H ₂ O ⁺	2.18	2.43	—
H ₂ O ⁻	0.52	0.43	—
H ₂ O (drying only - @ 380 K)	—	—	0.10

^a Cienega area, Santa Fe County, NM - Ref. 18.
^b Los Alamos County, NM - Ref. 19.

Fig. 7. Viscosity data of Duluth gabbro.

Fig. 6. Viscosity data of Dresser basalt.

Fig. 8. Viscosity data of Tholeiitic basalt.

Fig. 9. Thermal diffusivity of Dresser basalt.

Fig. 12. Thermal conductivity of Columbia River basalt.

Fig. 10. Thermal diffusivity of Columbia River basalt, Yakima Type.

Fig. 13. Thermal conductivity of Columbia River basalt.

Fig. 11. Additional thermal diffusivity data on Columbia River basalt, other samples.

Fig. 14. Thermal conductivity of various basaltic compositions and basalt-type glasses.

Fig. 15. Thermal conductivity of Nevada Test Site basalt.

Fig. 18. Average thermal expansion of Los Alamos basalt glass.

Fig. 16. Specific heat data for Dresser basalt.

Fig. 17. Density of Columbia River basalt. Solid lines indicate a calculated range to account for variations in oxidation of iron.

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