RI 7571

Bureau of Mines Report of Investigations/1971

Hardness, Tensile Strength, and Impact Toughness of Reservoir Sandstone at Extreme Temperatures

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7571

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UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF MINES
Elburt F. Osborn, Director

This publication has been cataloged as follows:

Komar, Charles A
Hardness, tensile strength, and impact toughness of reservoir sandstone at extreme temperatures. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1971]

8 p. tables. (U.S. Bureau of Mines. Report of investigations 7571)

Includes bibliography.

1. Sandstone. I. Title. (Series)

TN23.U7 no. 7571 622.06173

U.S. Dept. of the Int. Library

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HARDNESS, TENSILE STRENGTH, AND IMPACT TOUGHNESS OF RESERVOIR SANDSTONE AT EXTREME TEMPERATURES

by

C. A. Komar[1]

ABSTRACT

Hardness, tensile strength, and impact toughness of dry and brine-saturated sandstone specimens were measured at ambient, cryogenic, and elevated temperatures as a measure of the relative stability of reservoir rocks for subsurface disposal of liquid wastes. Hardness measurements were inconclusive. Tensile strength and impact toughness were significantly higher at -320° F than at ambient temperature, but were relatively unaffected at 700° F. Impact toughness was reduced by subjecting the specimens to three cycles of rapid temperature changes (thermal shock) over a 1,000° F range. Tensile strength of brine-saturated sandstone was less than that of dry sandstone. Based on results of the tests, reservoir sandstone likely would be stable if exposed to extreme temperatures of liquid wastes, although rapid changes in waste temperatures should be avoided.

INTRODUCTION

Dry and brine-saturated sandstone specimens were examined for hardness, tensile strength, and impact toughness after exposure to cryogenic, ambient, and elevated temperatures. Quantitative information on the effect of extreme temperatures on reservoir rocks is interesting because increased attention is being given to pressurized pumping into subsurface reservoirs as a method of disposing of sewage and industrial wastes (2).[2] Wastes can be hot or cold and the resulting thermal stresses and chemical reactions could fracture the formation (7) and allow the waste to seep into valuable underground natural resource deposits. Rock properties and their relationship to geologic features of proposed subsurface disposal areas need to be known so that disposal can be carried out effectively and without threat to other natural resources.

Pressures required to rupture rock formations vary considerably and are usually influenced by the principal natural stress in the region. When horizontal stresses around a wellbore are small or approximately equal,

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[1] Research physicist.

[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

properties of the rock become the primary resistance to rupture. Hardness, impact toughness, and tensile strength of rock formations can vary significantly and are important to the stability of formations. Measurement of the properties of reservoir sandstone at extreme temperatures was initiated by the Bureau of Mines to provide useful information for evaluating reservoir formations as potential sites for waste disposal or storage.

LITERATURE REVIEW

Breaking and bending strengths of basalt, granite, and limestone have been observed to increase at lower temperatures (4-5). The elastic moduli of igneous rocks decrease with increases in temperature up to a certain point and then become insensitive to further heating (8). Thermal spalling of high-quartz rock appears to depend on its thermal expansion and shear-strain characteristics (6). The strength of Berea Sandstone rock is reduced by increasing the pore pressure or by decreasing the extent of pore compression by filling the voids with fluid (3), but under such conditions the effect of temperature is small. Little information is known to be available on the effect of temperature extremes on sandstone properties that are important to fracturing. Considering that sandstone formations are extensive and likely to predominate in reservoir areas of interest as disposal sites, their investigation at extreme temperatures was warranted.

PROCEDURE

Reservoir sandstone specimens were obtained from the quarried Berea Formation near Cleveland, Ohio. Specimens for tensile strength and hardness tests measured 2 inches in diameter by 1 inch thick, and for impact toughness tests measured 2 inches in diameter by 2 inches thick. The specimens were allowed to dry in the air for about 2 weeks before the tests. Specimens to be tested for the effect of saturation were evacuated for 6 hours, saturated in brine, and allowed to soak for 16 hours before testing.

Hardness measurements were made with a scleroscope, which indicates hardness by the height of rebound of a diamond-pointed hammer dropped vertically onto the test surface. The surface of the hammer was cleaned before each measurement, and the test area was repeatedly changed to assure random data accumulation.

Tensile strength was measured with a machine that applied a compressive line load to the edge of the test specimen, across the diameter, until failure occurred. The load was applied perpendicular to the bedding plane throughout the tests. In this manner, the tensile strength was measured parallel to the bedding plane and was determined by the equation

$$S_T = \frac{2L}{\pi D t}, \tag{1}$$

where S_T = tensile strength, psi,

L = load at failure, lb,

D = diameter of disk, in,

and t = thickness of disk, in.

Impact toughness was determined according to the ASTM (1) procedure of dropping a weight from successive heights, onto a plunger in contact with the rock specimen, until the specimen fractured. Toughness was calculated by dividing the height required to produce fracture by the cross-sectional area and is expressed as inches per square inch.

Air-dried and brine-saturated specimens were tested first at room temperature. Some of these specimens were then cooled to -320° F for about 30 minutes and removed for testing. Other specimens were oven heated to 700° F for several hours, removed, and the values determined. Hardness, tensile-strength, and impact-toughness tests were conducted within 2 minutes after removal from the extreme temperature. (Temperature of the specimens changed only 15° F per minute after they were removed from the hot and cold media.) A factorially designed experiment was carried out, that included 12 replications in the hardness tests, six replications of tensile strength, and 10 replications of impact toughness. These replications were sufficient for a reliable analysis of variance.

Tensile-strength and impact-toughness measurements were also conducted on specimens that were heated to 700° F, immersed in liquid nitrogen, and vice versa, to measure the effect of a rapid thermal change or shock. For comparison, measurements were made on specimens that were first immersed in liquid nitrogen and then subjected to heat at 700° F. In an attempt to observe the effect of thermal cycling, tensile-strength and impact-toughness measurements were made on specimens that were thermally stressed by immersion in liquid nitrogen and then placed into a preheated oven at 700° F. After heating for approximately 4 hours, the specimens were allowed to cool to room temperature before the tests were conducted. Similarly, measurements were made on specimens for which the cycle was reversed, that is, they were heated, cooled, and then allowed to rise to ambient temperature. Measurements were made following one, two, and three such thermal cycles.

RESULTS

Tests concerned with the effects of saturation and temperature were studied by means of a statistical analysis of variance. The experiment was designed so that the main and interaction effects could be investigated simultaneously. The analysis included statistical testing to evaluate the significance of the results.

Temperature Effects

Table 1 lists the factors that relate the fracture properties of the specimens to temperature. As designated by the footnotes, measurements of scleroscope hardness were significantly affected by temperature and the interaction of temperature with saturation. Hardness measurements (table 2) were lower than those of ambient temperature for both the cryogenic and elevated environments, but only for the air-dried specimens. Little difference was evident among the measurements at different temperature levels whenever the specimens were saturated with brine. The lowest values of hardness occurred in saturated rocks at cryogenic temperatures.

TABLE 1. - Analysis of variance for factorial experiment

	Hardness		Tensile strength		Impact toughness	
	Degree of freedom	F-ratio	Degree of freedom	F-ratio	Degree of freedom	F-ratio
Temperature.................	2	[1]13.9	2	[1]55.4	2	[1]49.98
Saturation..................	1	.9	1	[1]9.34	1	.0
Temperature, saturation.....	2	[1]11.9	2	[1]17.28	2	[1]5.98
Experiment error............	66	([2])	30	-	48	-
Direction...................	-	-	-	-	1	[1]238.6
Temperature, direction......	-	-	-	-	2	[1]1.14
Saturation, direction.......	-	-	-	-	1	[1]17.8
Temperature, saturation, direction................	-	-	-	-	2	2.8

[1] Statistically significant at the 99-percent level.

[2] Does not apply.

TABLE 2. - Effect of temperature on hardness of dry and brine-saturated specimens

Hardness (scleroscope units)					
Cryogenic		Ambient		Elevated	
Dry	BS[1]	Dry	BS[1]	Dry	BS[1]
22	17	22	22	18	17
18	19	30	19	23	22
23	21	27	21	18	18
22	17	27	18	19	26
18	23	30	22	23	22
20	17	29	27	20	29
17	22	30	18	19	31
23	20	29	30	21	30
21	19	27	25	23	27
19	19	23	19	23	23
21	17	26	23	24	31
20	19	23	19	26	29
[2]20	[2]19	[2]27	[2]22	[2]21	[2]25

[1] Brine saturated. [2] Average.

Tensile strength (table 3) and impact toughness (table 4) of both dry and brine-saturated specimens increased with a decrease in temperature, with values of the saturated specimens being somewhat higher. No significant change in these properties was evident between ambient temperature and 700° F. Without regard to temperature, the effect of saturation alone was only evident in measurements of tensile strength that exhibited a 14-percent reduction in magnitude whenever the specimens tested were saturated with brine.

In addition, the direction of loading relative to the bedding plane was tested. Impact strength parallel to the bedding plane was always lower than that perpendicular to the bedding plane. Results were consistent for the levels of temperature and saturation that were investigated as well.

Thermal Shock and Cycling Effects

Tensile strength and impact toughness increased whenever the specimens were rapidly cooled from elevated to cryogenic temperature and then tested. Whenever specimens were heated from cryogenic to elevated temperatures and tested, impact toughness was reduced by about 15 percent, whereas tensile strength was not significantly altered beyond experimental variation.

Thermal cycling of the specimens before testing had no significant effect on the magnitudes of tensile strength that were measured. Impact toughness, however, was observed to be about 15 percent lower than usual owing to successive cycling above 1,000° F.

TABLE 3. - Effect of temperature on tensile strength of dry and brine-saturated specimens

Specimen	Tensile strength, psi		
	Cryogenic	Ambient	Elevated
Dry......................	893	695	605
	872	577	627
	923	619	587
	1,064	601	644
	877	592	506
	995	620	651
Average............	937	617	603
Brine saturated.........	1,671	594	588
	2,173	482	525
	1,315	551	605
	1,766	511	533
	1,010	567	449
	2,209	511	534
Average...........	1,691	536	539

TABLE 4. - Effect of temperature and direction of loading on impact toughness of dry and brine-saturated specimens

Loading direction and specimen	Impact toughness, in/in^2		
	Cryogenic	Ambient	Elevated
PERPENDICULAR TO BEDDING PLANE			
Dry	5.0	5.0	4.3
	6.0	4.4	5.3
	6.9	4.3	4.6
	6.5	4.3	5.9
	6.3	4.5	3.9
Average	6.1	4.5	4.8
Brine saturated	6.2	4.1	4.1
	6.3	4.0	4.8
	6.4	3.8	4.5
	5.1	3.4	3.4
	4.6	3.6	3.0
Average	5.7	3.8	3.9
PARALLEL TO BEDDING PLANE			
Dry	2.1	2.0	1.9
	2.3	2.4	1.6
	2.3	2.4	1.6
	4.0	1.9	1.6
	2.0	1.5	1.9
Average	2.5	2.0	1.7
Brine saturated	4.1	2.0	2.3
	4.6	2.0	1.9
	3.9	1.9	1.6
	5.9	2.3	1.3
	3.8	2.1	1.5
Average	4.5	2.1	1.7

CONCLUSIONS

Sandstone reservoir rocks were found to be stable at extreme temperatures. Tensile strength and impact toughness of both dry and brine-saturated reservoir sandstone specimens were significantly higher at cryogenic temperature, particularly the saturated specimens. Reservoir formations infused with cold fluids would probably not disintegrate or weaken. Hardness measurements at cryogenic temperature were inconclusive. Contrary to theory, specimens exposed to cryogenic temperature were not as hard as at ambient temperatures. This suggests that measurements were influenced by frost from the cryogenic fluid.

Exposure to elevated temperature (700° F) did not significantly affect the hardness, tensile strength, or impact toughness of reservoir specimens. Formations exposed to elevated temperatures are likely to be stable. Thermal shock or thermal cycling over 1,000° F decreased the impact toughness. Reservoir rock subjected to successive thermal shocks should be monitored closely to avoid formation rupture.

Tensile strength of brine-saturated sandstone rock was lower than that of dry specimens. A brine-saturated reservoir sandstone might rupture sooner and at a lower injection pressure than dry reservoir sandstone.

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