Physical and Engineering Properties of Some Selected Jordanian Basalt

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Abstract

This study is oriented towards studying the physical and engineering properties of some selected basalt rocks in the northern parts of Jordan. For that purpose, about 150 rock core specimens were extracted from five different locations in northern Jordan. These locations are identified as: Irbid, Ramtha, Al-Mafraq, Um-Qais, and Al-Azraq area. Several experimental tests were conducted on these specimens. The results were analyzed, compared, and classified according to several internationally known classification systems. Based on previous work by others and the extensive investigation made in this study several conclusions, recommendations and practical applications are drawn and are presented in this work.

Key terms: Basalt Rock, Rock Classification.

1. Introduction

Basalt is a dark-colored, fine grained heavy extrusive volcanic igneous rock which was derived from magma and spread over different localities in Jordan. It is the most abundant lava formed rock, and is composed mainly of pyroxene, plagioclase, with or without olivine. Basalt may be quite dense, or filled with many gas bubbles, depending upon the conditions prevailing at the time of extrusion.

During Neogene and Quaternary times, huge masses of alkali basalt erupted along the western margin of the Arabian plate and covered large areas in Syria, Jordan and Saudi Arabia [1].

During the last decade, many studies were carried out on the basalts of northern Jordan. The area which is covered by basalt ranges in width from 50 to 170 km, and extends for more than 80 kilometers from the Syrian border to the south-southeast. The Lava flows extend east and southeast of the Al-Azraq Depression another 210 kilometers along the eastern side of the Wadi Sirhan Depression Figure 1.

Six phases of major eruption could be distinguished. The basaltic flows of the lower three phases, in Jordan, are only known from drilling wells. The total thickness of these flows is 150 meters, overlying middle and upper Eocene limestone. They are separated from each other by approximately 5 meters' fossil soils, red clays and weathered surfaces. The uppermost unit of these three phases is overlain by 6 to 20 meters' thick soil, which is in turn, is locally covered by a fourth flow of a thickness of 60 meters [2].

The fourth flow covers a flattish relief, which forms the surface of older flows, or that of the middle and upper Eocene limestone. It is locally covered by sandstones, calcareous sandstones and sandy marls of Miocene age.

The fifth flow forms the major part of the basalts exposed in the North –East Jordan. It attains a thickness of up to 25 meters. In some places, it might be considerably thicker. The work in [2] placed the lava flow of the fifth phase within the Miocene – Pleistocene time interval.

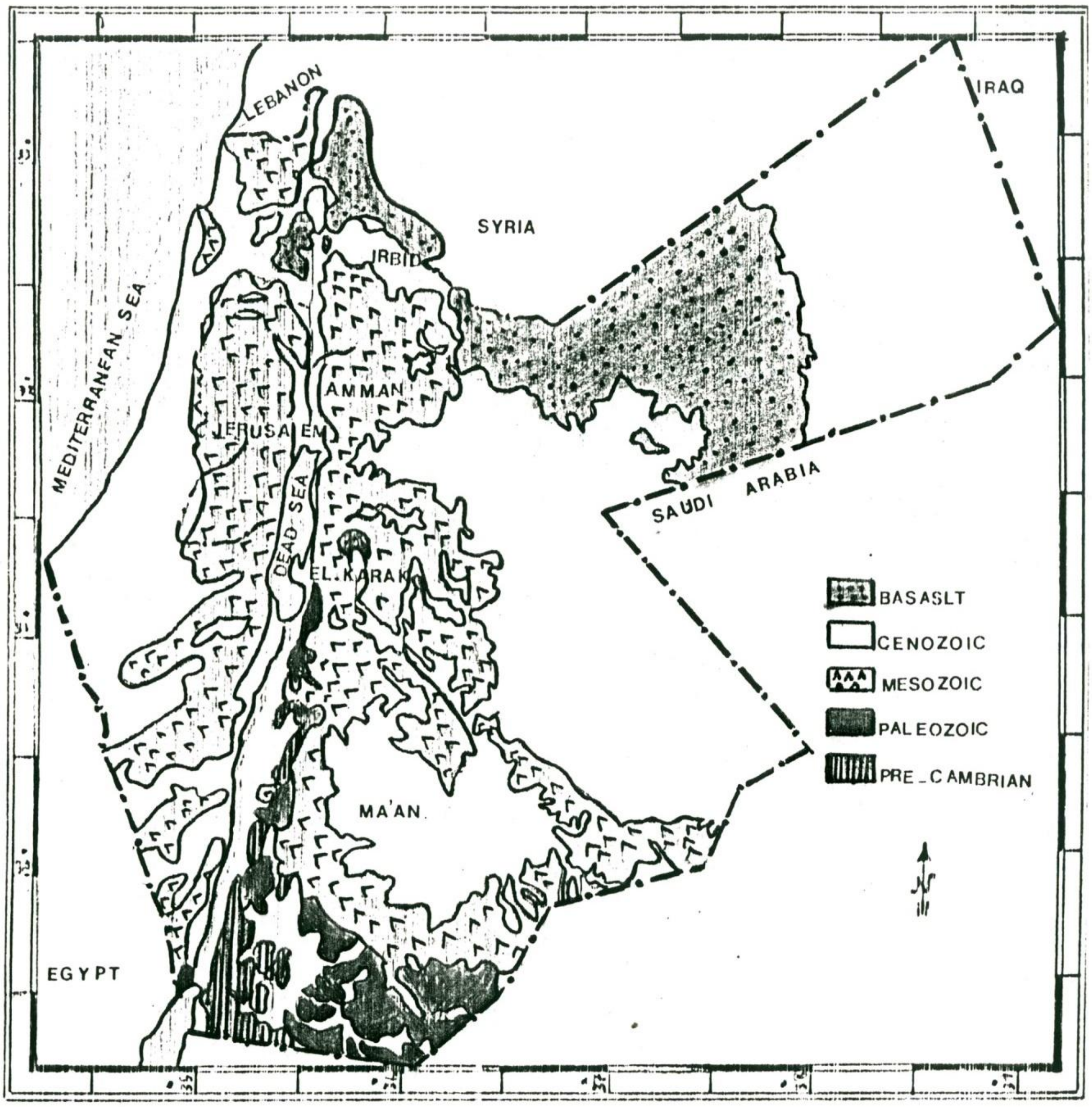

Figure 1. Geological Map of Jordan

The main tuff eruptions commenced after the fifth phase of extrusion. Fine and coarse tuffs with lapillis overlie the older basalts including those of the fifth phase, either as small occurrences of thin sheets, or as tuff volcanoes.

The final (sixth) phase of eruption produced basalt flows extending for several kilometers; the surface of these basalts are un-weathered. They partially covered the older basalts, or their weathered products. These lava flows of the sixth phase, which are more than 10 km wide and up to 30 kilometers long cross the Al-Mafraq- Baghdad highway. The age of the sixth phase was determined to be the middle Pleistocene [2]. The most important locations are in the north eastern part of Jordan at Harat Al Sham which is a volcanic field subgroup that covers an area of some 4,000 square kilometers (15,000 square miles). This wide extended basaltic province contains more than 800 volcanic cones and around 140 dikes [3]. This volcanic field extends from southern Syria across Jordan and into the north western part of Saudi Arabia. Basalt also occurs in central Jordan (Mujib and Shihan area), south western Jordan along the Rift and southern part of the country as basaltic flow and volcanic centers in Tel Burma and Jabel Uneiza (Maan Area) ([2], [4] Ibrahim). Basalt also occurs in the Um-Qais plateau which is situated in north Jordan, south of Yarmouk river. It is estimated that basalt in north east Jordan covers an area of 11,000 square kilometers or roughly about 12% of the total area of Jordan.

Historically basalt stone was intensively used by man. In Jordan, since Nabataeans, the Byzantine through the Islamic period basalt stone was used in construction as noted by many archaeological amphitheaters, castles, mosques and ancient cities such Um- Qais city located to the north of Jordan, Qaser Al Mashta, Um- Al Jimal (east of Al-mafraq), and Qaser Al Hallabat and Qastal (south of Jordan), and Qasr Al-Azraq, which dates back to the Roman period [5].

Basalt stone was used as basic construction materials. Roman engineers paved a lot of roads with basalt and engineers still use a lot of ground up basalt to make asphalt to pave roads. Basalt is used as aggregates, dimension stones, armor rock for sea walls, curb stones, paving stones, airfield, flooring tiles, railroad ballast and in many industrial applications such as rock wool, pipes, textile fiber, roofing felt and grinding stones for grinding grains like corn and barely.

Many studies were conducted to explore the possible utilization of basalt in aggregate and concrete mixes due to the availability of this resource in many parts of Jordan where the basalts stone constitutes more than 15% of the economic industrial rock potential in Jordan [3], [6]-[10]. Cellular basalts are used in the manufacture of light weight building blocks. Because of their cellular nature, these light weight blocks have excellent insulating properties against heat, cold and sound. Basalt is also used in the manufacturing of rock wool which has an increasing importance in the building industry in connection with the energy saving measures. Due to the high compressive strength and high abrasion resistance, it is considered as an economic commodity for industrial application. Due to its high insulation capacity, rock wool is replacing almost all the application of asbestos.

2. Mineralogical Composition of Jordanian Basalt

The northeastern Jordanian basalt is an aphanitic (fine grained) volcanic igneous rock characterized by a preponderance of Calcic Plagioclase Feldspar and Pyroxene. Olivine can also be a significant constituents of other Jordanian basalt with minor amounts of iron oxides in the form of Magnetite and other minor minerals such as Zeolite, Nepheline in addition to some opaque minerals which may fill the vesicles. The black color of basalt is attributed to the Pyroxene and Magnetite while the pale grey color of other types of basalts is attributed to the existence of high volumetric percentage of Plagioclase.

Field Sampling

Few, if any, of a complete physical and engineering properties studies of the Jordanian basalts are available. This work is a part of ongoing studies aimed at evaluating the physical and engineering properties of selected Jordanian rocks [11] – [12]. Laboratory testing was carried out on intact core specimens extracted from basalt boulders which were collected from five locations in the northern and northeastern parts of Jordan. These locations are Irbid city, Um Qais, Ramtha, Al-Mafraq and Al-Azraq Area.

A total of about 150 core specimens were extracted from the field samples. These specimens were subjected to various tests including air dry and wet cases as well as two sets of bedding orientation (parallel and perpendicular to bedding).

In order to establish as much information regarding a complete mineralogical analysis, X-Ray diffraction (XRD) and X-RAY fluorescence (XRF) tests of the specimens were conducted at the Natural Resources Authority (NRA) Laboratories in Amman – Jordan. The results of XRD and XRF are presented in Table 1 and Table 2.

Table 1. X-RAY Diffraction Analysis for the specimens of basalt selected from different locations in Northeast Jordan.

<table>
<tr><th>Location</th><th colspan="2">Results</th></tr>
<tr><td rowspan="3">Irbid</td><td>Major:</td><td>Calcite</td></tr>
<tr><td>Minor:</td><td>Albite</td></tr>
<tr><td>Trace:</td><td>Quartz</td></tr>
<tr><td rowspan="2">Ramtha</td><td>Major:</td><td>Albite</td></tr>
<tr><td>Trace:</td><td>Calcite</td></tr>
<tr><td rowspan="2">Al-Mafraq</td><td>Major:</td><td>Albite</td></tr>
<tr><td>Trace:</td><td>Calcite</td></tr>
<tr><td rowspan="2">Al-Azraq</td><td>Major:</td><td>Albite</td></tr>
<tr><td>Trace:</td><td>Dolomite and Calcite</td></tr>
<tr><td rowspan="2">Um-Qais</td><td>Major:</td><td>Albite</td></tr>
<tr><td>Minor:</td><td>Dolomite and Quartz</td></tr>
</table>

Table 2. X-RAY Fluorescence analysis for the specimens of basalt selected from different locations in Northeast Jordan.

X-RAY Fluorescence Analysis (%)										
Location	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
Irbid	1.31	7.53	13.58	42.24	0.11	0.75	11.85	1.84	0.17	11.84
Ramtha	1.61	7.56	14.27	43.76	0.12	0.89	10.31	1.81	0.17	11.77
Al-Mafraq	1.1	8.22	14.77	43.96	0.11	0.55	9.88	1.96	0.19	12.33
Al-Azraq	1.23	8.26	14.99	41.36	0.09	0.49	10.62	1.85	0.17	11.88
Um-Qais	1.84	6.75	14.98	41.08	0.18	0.6	10.81	1.68	0.16	11.16

Laboratory Testing

To measure or evaluate any property of basalt, suitable specimens needed to be prepared. The suggested test procedure by many authorities worldwide, such as the American Society for Testing and Materials (ASTM) or the International Society of Rock Mechanics (ISRM), call for cylindrical or cubic specimens extracted either in-situ or in the laboratory. For this study, rock specimens were prepared by means of laboratory equipment, such as the laboratory rock coring drill, the commercial diamond impregnated rock saw, a universal specimen grinding machine, and other necessary accessories.

Laboratory Methods and Results

Tests to measure the index properties are normally conducted for classification purposes. These properties include specific gravity, density, water content, void ratio, absorption, degree of saturation, Los Angeles Abrasion, slake durability indices, point load index and ultrasonic velocity. Following is a brief description of some of these properties tested in this study.

Apparent Specific Gravity, Apparent Porosity, Degree of saturation, water content and Grain Density

Rock, in general, is considered as three- phase material since it consists of solid mineral matter, water (or other liquid), and air (or other gases). The determination of how much water and air occupy the rock specimen is very important since they give indication on the strength of the rock core, and how strongly the grains are bonded. Rock cores with vesicular nature have low densities, low strength and high porosity. As stated earlier, all these parameters are determined following the ISRM [13]-[16] and ASTM [17] standards. The procedure is rather simple. Five core specimens from each location were tested. The initial weight to the nearest 0.1 gm and the external dimensions using micrometer caliper were determined. The specimens were then immersed in distilled water for a period of two weeks or until weights stabilize to within 0.1 gm. The final saturated stabilized weights are recorded after blotting the specimen with a moist towel before weighting. Next, the specimen was placed in an oven at 105 ^{o}C until they reached to a stabilized weight to within 0.1 gm. The dried weights are then recorded. Using the following formulae:

1. Apparent Porosity: $$n = \frac{100(w_s - w_0)}{V.\rho_w} \quad (1)$$
2. Apparent Specific Gravity: $$G_s = \frac{w_0}{V.\rho_w} \quad (2)$$
3. Water Content : $$W\% = \frac{100(w_n - w_0)}{w_0} \quad (3)$$
4. Degree of Saturation : $$S_r = \frac{100(w_n - w_0)}{(w_s - w_0)} \quad (4)$$
5. Dry Density: $$\rho_d = G_S \rho_w (1-n) \quad (5)$$
6. Void Ratio: $$e = \frac{n}{(1-n)} \quad (6)$$

Where:

w_0 : Oven dry weight of the core specimen.

w_s : Saturated weight of the core specimen.

w_n : Initial natural weight of the core specimen.

V : Volume of the core specimen.

ρ_w : Density weight of the water.

Tables 3(a) and 3(b) present the results of all these tests of the core specimens.

Table 3 (a). Basic physical properties of the tested Northeast Jordanian Basalts

Basic Physical Properties (Average values)						
Location	**Apparent Porosity (n %)**	**Apparent Specific Gravity (G_s)**	**Void Ratio (e)**	**Dry Density (ρ_d)**	**Water Content ($W\%$)**	**Degree of Saturation ($S_r\%$)**
Irbid	1.95	2.72	0.02	2.669	0.98	46.6
Ramtha	3.1	2.629	0.32	2.547	0.37	34.5
Al-Mafraq	2.32	2.582	0.024	2.519	0.41	43.3
Al-Azraq	2.4	2.67	0.525	2.604	0.36	39.3
Um-Qais	1	2.731	0.017	2.731	0.36	56.6

Table 3 (b). Test on the core specimens

Standard Followed in Testing	Number of samples tested
Apparent Specific Gravity (ASG)	ASTM (C127) 17
Apparent Porosity (n)	ASTM (C2073) 17
Bulk Dry Density (ρ_d)	ASTM (C2073) 17
Void Ratio (e)	American Petroleum Institute(API)
Absorption %	ASTM (C127, C128) 17
Water Content ($W\%$)	ASTM (7079) 17
Degree of Saturation ($S_r\%$)	ASTM (C131) 17
% wear from Abrasion and Impact Test in the Los Angeles Machine	ASTM (C131-69) ASTM (C533-69) 17
Slake Durability Index (Id_1)	ISRM 16
Slake Durability Index (Id_2)	ISRM 16

Ultrasonic Wave Velocity Test

The ultrasonic wave velocity method used in this study consists of measuring the travel time of an ultrasonic pulse passing through the basalt rock specimen having a length to diameter ratio (L/D) greater than 3. The velocity is determined from the known relation of time, distance and velocity. The technique uses two transducers that are connected to the greased ends of the core specimen to eliminate any air voids that may result due to deviation in the flatness of end faces. The transducers are, in turn, connected to a battery- operated, digitized unit called PUNDIT (which stands for Portable Ultrasonic Non-destructive Digital Indicating Tester). The pulses are transmitted through one transducer and picked up by the other. The travel time is displayed on the tester in microseconds. The velocity is then calculated by dividing the length of the specimen by the travel time. The average results of this test are shown in Table 4.

Table 4. Results of Ultrasonic Wave Velocities (UWV) for the tested specimens of basalt extracted from different locations North east Jordan.

Ultrasonic wave velocity (UWV) V_p (m/sec) ASTM (D2845 -69)				
Location	**1**	**2**	**3**	**Average**
Irbid	5500	5568	5369	5480
Ramtha	5567	4977	5363	5302
Al-Mafraq	5525	5606	5266	5465
Al-Azraq	5378	5487	5623	5496
Um-Qais	5371	5088	5461	5306

Engineering Index Properties

Hardness using Schmidt Impact Hammer

Hardness is a concept of material behavior and it depends on the type a quantity of the various mineral constituents and the bond in the mineral skelton. However, the results are also affected by the method of testing. In this study, the rebound test was adopted using Schmidt Impact Hammer Type L. This test can well be correlated with the compressive strength of the tested basalt rock. According to Schmidt Hammer Rebound Manual, which relates the rebound reading of the hammer to the compressive strength of a concrete cylinder

Five cores of basalt from each location were tested using a special calibration anvil. Ten readings from each core sample were recoded with a total of 50 readings for each location. Raw average was first calculated for the 50 readings then the extreme higher and lower five readings from the raw average were excluded. The average was recalculated for the remaining 40 data points. Also, calculation of the standard deviation and the coefficient of variation were made using the following equations:

$$S_x = \sqrt{\frac{\sum (x_I - \hat{x})^2}{(n-1)}} \qquad (7)$$

$$C_v = \frac{S_x}{\hat{x}} \qquad (8)$$

Where:

S_x : Standard deviation.

C_v : Coefficient of Variation

x_I : Individual rebound reading

$\hat{x}$: Average rebound number for the remaining readings.

n : Number of readings.

The average test results are presented in Table 5.

Table 5. Average Schmidt Hammer Test Rebounded (SHR) for the selected Basalt locations Northeast Jordan

Schmidt Hammer Rebound Hardness Test				
Location	**Raw Average**	**Average**	**Standard Deviation**	**Coefficient of Variation**
Irbid	51.0	51.2	3.73	7.28
Ramtha	46.26	46.2	6.0	13.01
Al-Mafraq	48.6	48.7	10.2	20.95
Al-Azraq	43.78	43.78	3.06	6.99
Um-Qais	46.06	46.03	6.53	14.18

Abrasiveness Test (ASTM C131-69, ASTM C535-69) [17]

The abrasiveness property, like the hardness property, depends mainly on the bond strength that exists between the mineral grain and on the type and quality of the various rock constituents and cementing materials. This test is used mainly to determine the suitability of certain types of crushed rock to be used as an aggregate in concrete and in road construction.

The Los Angeles machine described by (AASHTO, T96) was used in this study to test the resistance of basalt to abrasion. Several basalt rock from each location were crushed to different aggregate sizes. Table 6 shows the sieves used for grade (A) which corresponds to the highest abrasive charge (12 spheres).

Table 6. Grade (A) Basalt Aggregate Size Specifications used for the abrasion test in Los Angeles Machine.

Weight (gm)	Passing sieve size (in)	Retaining sieve size (in)
1250	1 ½	1
1250	1	¾
1250	¾	½
1250	½	⅜

A total weight of 5000 ± 10 gm of oven dried samples were placed in the drum of the Los Angeles machine after dropping the twelve spheres. The cylinder was allowed to rotate 500 revolutions at a speed of 30 to 33 rounds per minute (rpm). The sample was then discharged and separated on sieve No. 12 and the material retained on sieve No. 12 was washed, oven dried at 105^{0}C then re- sieved and its weight was recorded. Finally, the abrasion was calculated, as a percentage, using the following relationship:

$$\%A = \frac{(I_w - R_w)}{I_w} \qquad (9)$$

Where:

$\%A$: Percent Abrasion

I_w: The initial weight of the sample

R_w: The retained weight on sieve No. 12.

The results of this test are presented on Table 7.

Table 7. Percent wear from Abrasion and Impact Test on the Los Angeles Machine for selected Northeast Jordanian Basalt.

Location	Percent Abrasion for 100 Rev	Percent Abrasion for 500 Rev	Uniformity of wear ratio (100/500)
Irbid	4.4	23.3	0.19
Ramtha	5.3	23.4	0.23
Al-Mafraq	4.0	19.3	0.20
Al-Azraq	4.5	20.1	0.22
Um-Qais	4.3	21.0	0.20

Slake Durability Test

The slaking characteristics of rocks is of vital importance in civil engineering practices. The weather ability problem of rocks due to their exposure to moisture include excavation stability with time, design of fills, riprap and others. The slake durability test as suggested by the ISRM in [16] is intended to assess the resistance offered by rock samples to weathering and disintegration when subject to specific standard cycles of drying and wetting.

In this study, a slake durability testing machine was used for assessing the selected basalt slaking. Ten rock lumps weighing (40-60) gm each were used from each location. Lumps were roughly spherical in shape and had rounded corners. The sample was first oven dried at a temperature of 105°C for about 12 hours. The mass (A) of the drum and the sample after cooling was determined. Tap water at 20°C was used to fill the trough of the slake durability equipment to the level specified which is 20 mm below the axis of the drum. The machine was turned on and the drum was rotated at a rate of 200 revolution for 10 minutes. The mass (B) of the drum and the dried sample was then determined. The same procedure was carried out for a second sample and the mass (C), which corresponds to the mass (B) in the first cycle, was determined. Finally, the drum was brushed clean and its mass (D) was weighed out. The slake durability index for the two cycles were calculated using the following relationship [18]:

$$I_{d1} = \frac{(B-D)}{(A-D)} \times 100 \qquad (10)$$

$$I_{d2} = \frac{(C-D)}{(A-D)} \times 100 \qquad (11)$$

Where:

I_{d1}: Slake durability index corresponding to the first cycle.

I_{d2}: Slake durability index corresponding to the second cycle.

A: The initial weight of the sample and drum.

B: The weight of the sample and the drum after the first cycle.

C: The weight of the sample and the drum after the second cycle.

D: The weight of the clean drum.

Usually, the second cycle slake durability index (I_{d2}) is taken as a reference for classification purposes. Furthermore, (I_{d2}) values approach zero for samples that are highly susceptible to slaking, and approach 100% for rocks of low slaking susceptibility. The results of this test are presented in Table 8.

Table 8. Slake Durability Index values for basalt specimens selected from different locations Northeast Jordan.

Index values (%) [16]		
Location	I_{d1}	I_{d2}
Irbid	99.5	99.3
Ramtha	99.3	98.9
Al-Mafraq	99.6	99.4
Al-Azraq	99.3	99.1
Um-Qais	99.3	99.1

Indirect Tensile Strength Test

This test is referred to as splitting tensile and belongs to the family of the "indirect tensile" strength test or the Brazilian Test. It is based on the fact that most rocks in the biaxial stress field fail in tension when the

principal stress is in compression. In this study, ten rock specimens from each location were selected for this purpose. In order to apply a line load on the rock specimen, two pieces of straight metals were placed above and below the rock specimen between the platens of the compression machine.
The diameter to length ratio (d/L) was approximately 2:1, while the rate of loading was set at 500 Newton/sec as recommended in [15]. All of the rock specimens were tested at their natural water content to simulate the true rock conditions in the field. The indirect tensile strength is calculated using the following relationship [19] :

$$\sigma_1 = \frac{2P}{\pi LD} \qquad (12)$$

Where:

σ_1: Indirect Tensile Strength (kg/ cm^2)

P: Maximum Load Applied (kg).
L: Length or thickness of the specimen (cm).
D: Diameter of the specimen (cm).

The results of this test are presented in Table 9.

Table 9. Results of the indirect tensile strength (Brazilian Test) for the basalt specimens selected from different locations Northeast Jordan.

Indirect Tensile Strength (Brazilian Test) (MPa)						
Location	**1**	**2**	**3**	**4**	**5**	**Average**
Irbid	9.63	10.08	8.77	9.85	11.75	10.02
Ramtha	8.81	12.82	9.76	9.92	10.63	10.39
Al-Mafraq	9.4	10.63	8.38	10.55	11.07	10.01
Al-Azraq	9.25	8.79	11.65	9.79	10.52	10
Um-Qais	5.64	8.82	10.24	10.03	7.59	8.46

Flexural Strength Test (Modulus of Rupture R_o)

Flexural strength, or Modulus of rupture, is a measure of outer fiber strength of rock. This test is carried out by supporting a core specimen at its ends and applying a load at the midpoint of the span to failure. The specifications call for a minimum length of the core strength of 6 inches (15 cm) while the span between the supports should be 5 inches, the rate of loading should be about 35 kg/cm^2/min [20].
As the load is applied on the specimen, a maximum tensile stress is developed on the under surface at the midpoint and hence, only a small part of the specimen is under test. Thus the value obtained by this procedure is higher than that determined in direct tension. This higher value is presumed to result from the fact that only a small area (or point), on the opposite side of the specimen, directly under the point of loading is subject to maximum strain. Hence the probability of a defect (plane of weakness) occurring at or near this point is less than that for an equivalent defect occurring in the length of the tensile specimen [20].
Once the maximum load is obtained, the flexural strength (R_o) can be calculated using the following Relationship:

$$R_0 = \frac{8F_c L}{\pi D^2} \tag{13}$$

Where:

F_c : Maximum Load Applied.

L: Span between the two supports

D: Diameter of the core specimen.

The results of this test are shown in Table 10.

Table 10. Flexural Strength test of the basalt core specimen selected from different locations northeast Jordan

Flexural Strength (Modulus of Rupture, R_0) (MPa)						
Location	**1**	**2**	**3**	**4**	**5**	**Average**
Irbid	33.4	30.2	36.2	37.9	38	35.14
Ramtha	26.7	15.5	26.9	25.4	23.3	23.56
Al-Mafraq	25.2	22.3	33.1	29	26.1	27.14
Al-Azraq	34.4	31.1	33.1	27.1	28.3	30.8
Um-Qais	29.2	24.3	25.4	25.6	24.4	25.78

Uniaxial Compressive Strength

Uniaxial compression of cylindrical specimens prepared from drill core is probably the most widely used test on intact rock. This test is used to determine the uniaxial unconfined compressive strength, (σ_c), and the elastic constants: Young Modulus, E, and the Poisson's ratio, v, of the rock material. It is considered as a basic parameter in rock strength criterion [21].

The maximum applied uniaxial stress that a rock core can withstand without failure is termed as uniaxial

$$\sigma_c = \frac{F_c}{A} \tag{14}$$

Where:

σ_c : Uniaxial compressive strength.

σ_c : Maximum Applied Load.

A : The end area of the specimen.

For the same rock type, several factors can affect the test results significantly, such as the porosity, the degree micro fissuring, and the degree of weathering [18]. Other factors, such as the flatness of the end faces, moisture content, rate of loading, the friction developed between the specimen and the bearing platens, specimen size and shape also have great influence on the test results. For the purpose of eliminating discrepancies in the results emerging from mechanical errors, this test was carried out in accordance with the techniques suggested by the ISRM which recommends:

1. The length to diameter ratio should be in the range of (2.5 -3.0).
2. The flatness of the ends should be to within 0.02 mm, while perpendicularity should not exceed 0.001 radian or 0.05 in 50 mm.
3. Constant rate of loading of (0.5 – 1.0) MPa/sec.
4. Specimens should be tested at their natural water content.
5. The use of capping is not permitted.

However, discrepancies due to physical differences in the rock specimens may occur and cannot be avoided.

Obert and Duvall [20] reported that the compressive strength of the core specimen having (L/D) ratio other than 2:1 should be corrected using the following relationship:

$$C_{2:1} = \frac{C_0}{0.875 + 0.25\left(\frac{D}{L}\right)} \qquad (15)$$

Where:

C_0 : Compressive strength of the actual core specimen.

$C_{2:1}$: Compressive strength of an equivalent specimen having (L/D) of 2:1.

A high capacity compression machine, with a data acquisition system attached to it, was used in this study. This machine is equipped with a spherical compression head to ensure a uniform loading across the end surfaces of the core specimens. Test specimens were loaded until crushing has occurred. Test results for all locations of this study are presented in Tables 11(a) – 11(e)

Table 11(a). Uniaxial Compressive Strength test results for Irbid core specimens.

Specimen No.	Length (cm)	Diameter D_0 (cm)	P_{max} (kN)	C_0 (MPa)	$C_{1:1}$ (MPa)	$C_{2:1}$ (MPa)
1	14.47	7.5	487	110.23	122.06	109.73
2	15.56	7.5	626	141.7	158.32	142.34
3	15.17	7.5	334	75.6	84.21	75.71
4	15.09	7.5	411	93.03	103.56	93.1
5	14.94	7.5	481	108.88	121.05	108.82
			Average =	105.89	117.84	105.94

Table 11(b). Uniaxial Compressive Strength test results for Ramtha core specimens.

Specimen No.	Length (cm)	Diameter D_0 (cm)	P_{max} (kN)	C_0 (MPa)	$C_{1:1}$ (MPa)	$C_{2:1}$ (MPa)
1	15.54	7.5	598	135.36	161.22	135.95
2	15.22	7.5	397	89.86	100.13	99.02
3	15.54	7.5	314	71.08	79.41	71.39
4	15.59	7.5	331	74.92	83.73	75.29
5	15.37	7.5	368	83.3	92.93	83.55
			Average =	90.90	103.48	93.04

Table 11(c). Uniaxial Compressive Strength test results for Al-Mafraq core specimens.

Specimen No.	Length (cm)	Diameter D_0 (cm)	P_{max} (kN)	C_0 (MPa)	$C_{1:1}$ (MPa)	$C_{2:1}$ (MPa)
1	14.64	7.5	344	77.87	86.36	77.63
2	15.43	7.5	317	71.75	80.09	72
3	15.43	7.5	563	127.44	142.25	127.89
4	15.4	7.5	434	98.24	109.65	98.56
5	15.47	7.5	284	64.28	71.77	64.53
			Average =	87.92	98.02	88.12

Table 11(d). Uniaxial Compressive Strength test results for Al-Azraq core specimens.

Specimen No.	Length (cm)	Diameter D_0 (cm)	P_{max} (kN)	C_0 (MPa)	$C_{1:1}$ (MPa)	$C_{2:1}$ (MPa)
1	15.47	7.5	516	116.8	130.41	117.25
2	15.20	7.5	313	70.85	78.94	70.97
3	15.54	7.5	373	84.43	94.32	84.80
4	15.39	7.5	409	92.58	103.30	92.87
5	15.75	7.5	434	98.24	109.92	98.83
			Average =	92.58	103.38	92.94

Table 11(e). Uniaxial Compressive Strength test results for Um-Qais core specimens.

Specimen No.	Length (cm)	Diameter D_0 (cm)	P_{max} (kN)	C_0 (MPa)	$C_{1:1}$ (MPa)	$C_{2:1}$ (MPa)
1	15.09	7.5	349	79.00	87.94	79.06
2	15.40	7.5	331	74.92	83.61	75.16
3	15.78	7.5	648	146.68	164.16	147.59
4	15.35	7.5	375	84.88	94.68	85.12
5	15.66	7.5	461	104.35	116.68	104.9
			Average =	97.97	109.41	98.37

Modulus of Elasticity (Young Modulus, E) and Poisson's Ratio (ν)

The determination of the Young modulus of elasticity, (E), of rocks is an important factor in evaluating rock deformation under various loading conditions. It is affected by rock type, porosity, water content, and texture. Due to the variation in rock formation the modulus of elasticity varies from one geologic region to another.

The capacity of a rock strain under applied load, or its response to unload on excavation is considered as a measure of deformability [19].

Several practical cases, such as dams foundations, underground structures, rock slopes stability require a precise determination of rock strains. Therefore, several strain gauges are used depending on the nature of work needed. In this study, two Linear Variable Differential Transducers (LVDT) were used to measure the diametric strains since rock specimens do not normally deform uniformly. Axial strains, as stated earlier, were determined through the plotter attached to the compression machine.

A standard method of testing suggested by the ISRM and ASTM D-3148-86 was followed to determine the elasticity constants (E and ν). Variation in the test results were observed. The variations could be attributed to the non-homogeneity and anisotropy of the specimens and to the testing environmental conditions.

Figure 2 and Figure 3 represent the stress strains relationship for the basalt selected from Irbid location northeast Jordan. Similar figures were produced for the other locations. Each figure was generated from testing five different samples from each location. From these figures the longitudinal, axial tangential moduli were calculated. Table 12 presents the values of the average moduli of elasticity for the different locations while Table 13 presents the average values of Poisson's ratio for the different locations as calculated from the lateral strains and axial strains from the previous tests.

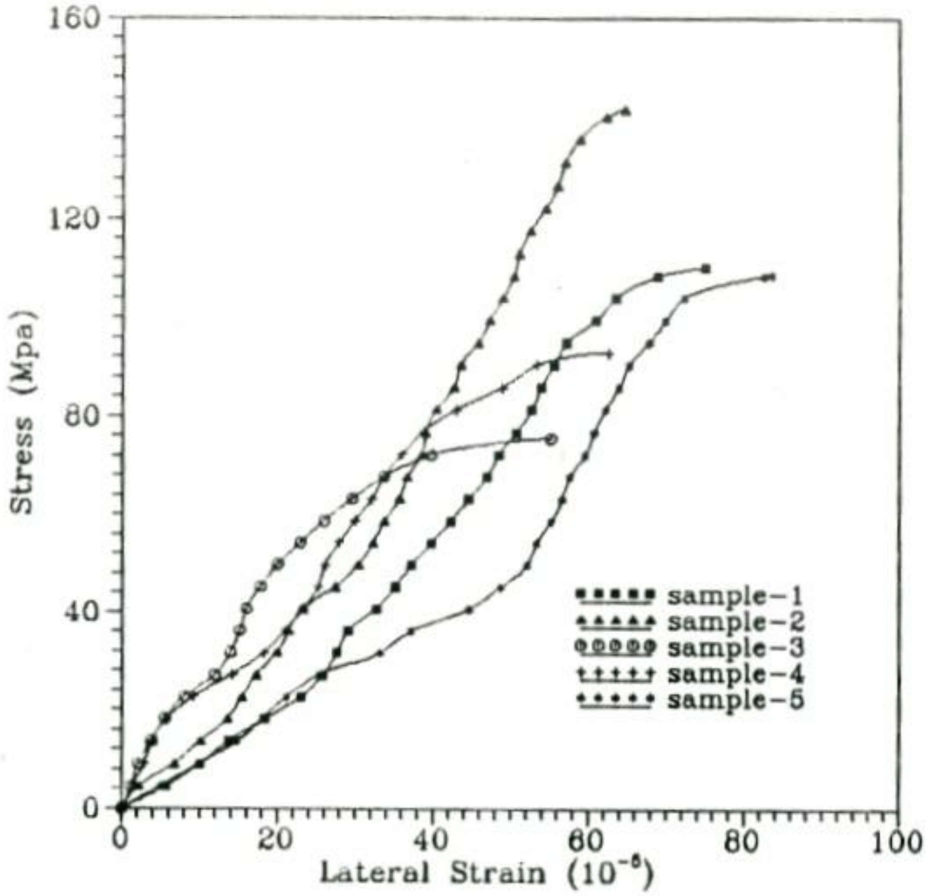

Figure 2. Stress-Strain relationship for Irbid basalt sample.

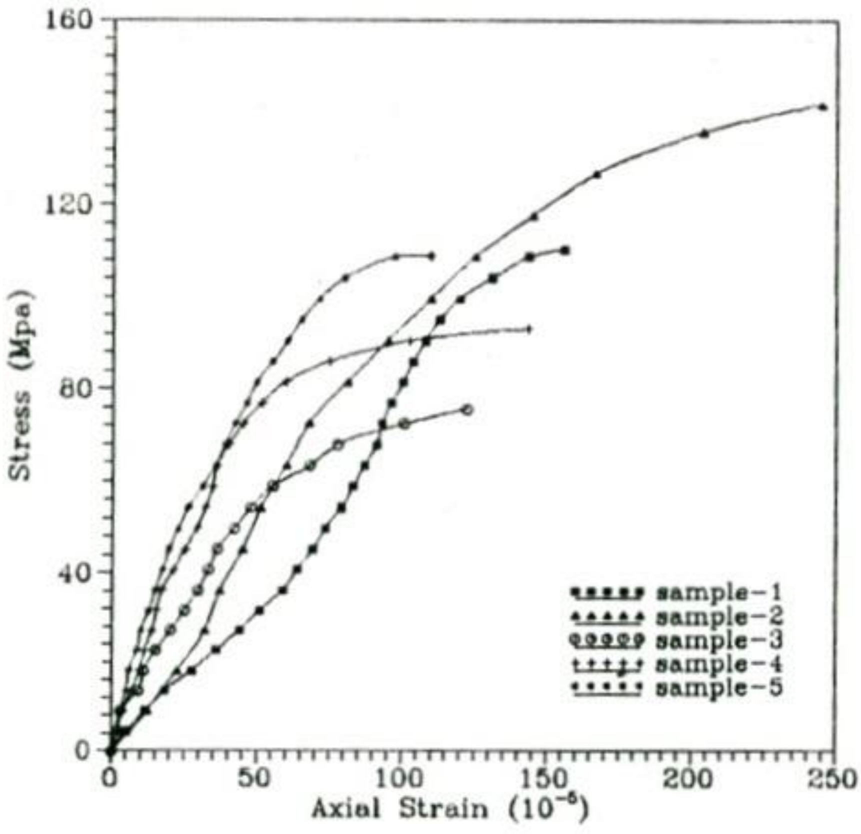

Figure 3. Stress-Strain relationship for Irbid basalt sample.

Table 12. Average values of axial and lateral moduli of elasticity for the basalts specimens selected from different locations northeast Jordan.

	E_{avg} **(GPa)**	
Location	**From Axial Stress Strain Relationship**	**From Lateral Stress Strain Relationship**
Irbid	149.8	239.7
Ramtha	109.8	250.6
Al-Mafraq	102.9	335.8
Al-Azraq	104.5	361.4
Um-Qais	91.4	279.1

Table 13. Average Poisson's values for basalt specimens selected from different locations northeast Jordan

Location	**Poisson's Ratio (ν)**
Irbid	0.353
Ramtha	0.357
Al-Mafraq	0.252
Al-Azraq	0.338
Um-Qais	0.335

ANALYSIS AND DISCUSSION OF THE EXPERIMENTAL RESULTS

The properties of any rock depend directly on mineralogical and chemical composition, the texture and arrangement of particles, as well as on the cementing material and surrounding environment.

For this study, five different locations in the north and northeastern parts of Jordan were selected. These locations were selected based on their abundance and huge deposits of basalt formation. For economic reasons, only surficial boulders of basalt were tested taking into consideration that these locations were exposed to the same degree of weathering. Physical and engineering properties of rocks are highly affected by weathering. Therefore, the results obtained should be considered as conservative ones.

The term index properties refers to the following physical properties: apparent porosity, specific gravity, water content, degree of saturation, void ratio and dry density. All the test results showed slight or no variation in these properties except for specific gravity and dry density for Ramtha and Al-Mafraq locations which showed small variation due to weathering of the core specimens collected from these locations. Jumikis [35] has reported specific gravity values for rock basalt, elsewhere, as low as 2.21, while [22] reported even a lower value that reached 2.04. Nevertheless; the values obtained in this study are very much within the range of the reported values.

The International Association of Engineering Geologists (IAEG) has adopted criteria for rock classification [23]. These criteria are presented in Table 14.

Table 14. Rock Classification Criterion as adopted the IAEG [23]

Class	Dry Density P_d (gm/cc)	Description	Porosity (%)	Description
1	Less than 1.8	Very low	Over 30%	Very High
2	1.8 – 2.2	Low	15 – 30	High
3	2.2 – 2.5	Moderate	5 – 15	Moderate
4	2.5 – 2.75	High	1 – 5	Low
5	Over 2. 75	Very High	Less than 1	Very low

Based on the IAEG criteria, the basalt rocks from the selected five locations are classified as shown in Table 15.

Table 15. Classification of the basalt rock from the different locations based on IAEG classification criteria.

Location	Dry Density P_d (gm/cc)	Porosity (%)	Class
Irbid	2.669	1.95	4
Ramtha	2.547	3.1	3 – 4
Al-Mafraq	2.519	2.32	3 – 4
Al-Azraq	2.604	2.47	4
Um-Qais	2.686	1.69	4

It can be seen that both RAMTHA and AL-MAFRAQ rock specimen s fall between two classes of specification namely 3 and 4 while the remaining specimens fall under class 4 category.

Ultrasonic wave velocity

This test was conducted on basalt core specimens at their natural water content. The results obtained showed no great variation in the values of longitudinal wave velocity from one location to another. Touloukian et al. [22] reported values for longitudinal wave velocity of basalt specimens in the range of (3940 -5150) m/sec. The effect of water content was minimal in this study due to the fact that the water content for all the tested specimens was nearly the same. For comparison purposes, Table 16 presents the values of the wave velocities along with the other measured basalt properties in this study.

Table 16. Measured wave velocities versus other basalt properties for the different locations northeast Jordan

Location	Wave Velocity (m/sec)	Moisture Content (%)	Porosity (%)	Dry Density P_d (gm/cc)	Compressive Strength (MPa)
Irbid	5480	0.98	1.85	2.669	105.89
Ramtha	5250	0.37	2.1	2.547	90.9
Al-Mafraq	5464	0.41	2.32	2.519	87.92
Al-Azraq	5495	0.36	2.47	2.604	92.58
Um-Qais	5305	0.36	1.69	2.686	97.97

Based on the IAEG classification presented in Table 17, all the tested specimens from the five locations are ranked as class–5 indicating that the tested basalt specimens possessed the highest values of wave velocities.

Table 17. Rock Classification Criterion set by (IAEG) based on Ultrasonic wave velocity

Class	**Ultrasonic Wave Velocity (m/sec)**	**Description**
1	Less than 2500	Very low
2	2500 – 3500	Low
3	3500 – 4000	Moderate
4	4000 – 5000	High
5	Over 5000	Very high

Abrasion Test

For this study, the Los Angeles abrasion machine was used to determine the abrasiveness of grade (A) of basalt aggregates. The results presented in Table 7 showed that no variation in the abrasion values from one location to another. All the results obtained are in the range of (19 -23)% for the 500 revolution cycle. The 100 revolution cycle was also carried out and the uniformity of wear ratio (100/500) was then calculated. The purpose of conducting such test was to determine the suitability of basalt aggregates for concrete and road construction projects which require in most cases a maximum of 40% abrasion after 500 revolutions and that the uniformity of wear should not exceed 0.25.

Hardness

The hardness test by itself does not furnish direct information about rock properties in general. However, Aufmuth [24] and Irfan and Dearman [25] established many relationships through which other rock properties could be quantitatively predicted once the hardness of the rock becomes available.

Hardness is an index property that describes how strongly the grains are chemically bonded. In this study, the Schmidt Impact hammer was used to determine this property, although it was originally devised to determine the strength of concrete. Results of this study did not indicate any correlation between hardness and abrasion. However, according to [24], the uniaxial compressive strength and the Schmidt impact number can be correlated by the following formulae

$$Log(C_0) = 1.831 Log(SHR) + 1.533 \quad (16)$$

$$C_0 = 7.75(SHR) - 213.35 \quad (17)$$

Where:

C_0 : Uniaxial compressive strength

SHR : Schmidt Impact Number.

Table 18 presents a comparison between the predicted uniaxial compressive strength values and the average uniaxial compressive strength values.

Table 18. Comparison of the Average Uniaxial Compressive Strength of the tested basalt specimens

Location	Hardness Number	Measured UCS (MPa)	Predicted UCS (MPa)
Irbid	51.2	105.89	184.45
Ramtha	46.2	90.90	144.70
Al-Mafraq	48.7	87.92	164.08
Al-Azraq	43.7	92.58	125.32
Um-Qais	46.0	97.97	143.15

The average values of the compressive strength of the tested specimen was much lower than the ones predicted by equations (16 and 17) due to the fact that hardness is inversely dependent on cavities and fissures in the rock specimens, which tend to produce low hardness number. Thus, it did not give a comprehensive picture of the actual strength of the basalt.

Slake Durability

The slake durability test was used to measure the susceptibility of rock to weakening and disintegration due to repeated cycles of wetting and drying. Various weathering classification systems have been proposed. For example, the Geological Society Engineering Group (GSEG) classification, which considers granite as the basis for most of weathering schemes. A system more appropriate to the basalt rocks was suggested by Gamble [26] and used in this study.

Comparing the results of durability tests presented in Table 8 to Gamble's Classification in Table 19, all the basalt rock specimens are classified as " very high durable" since the index values for all of the tested specimens gave a value of I_{d2} greater than 98% .

Table 19. Gamble's Slake durability classification [27]

Group Name	% Retained after one 10-minute cycle (Dry weight basis)	% Retained after two 10-minute cycle (Dry weight basis)
Very High Durability	> 99	> 98
High Durability	98 – 99	95 – 98
Medium High Durability	95 – 98	85 – 95
Medium Durability	85 – 95	60 – 85
Low Durability	60 – 85	30 – 60
Very Low Durability	< 60	<30

Brazilian Tensile Strength

This test is referred to as a splitting tensile, and it belongs to the family of the "indirect tensile" strength tests. The test results presented in Table 9 did not show much difference in the average values of the Brazilian tensile strength as we move from one location to another except for Um-Qais location which had slightly lower average value.

Several studies conducted by many investigators have shown that many factors can influence the results of the Brazilian tensile strength tests. Among these factors, the specimen geometry, rate of loading, water content, and degree of saturation, porosity and mineralogy. In this study, most of these factors were kept constant which may explain the uniformity of the average values of the test results.

Flexural Strength

This test was intended to measure the tensile strength of the outer fiber of the rock specimens by loading the rock specimen at its ends. The results obtained in this test were about three times higher than those obtained by the Brazilian tensile test as shown in Table 20. This variation can be attributed to the fact that only a small area (or point) on the opposite side of the specimen, directly under the point of loading, is subject to the maximum tensile strain. Hence, the probability of a direct (plane of weakness) occurring at or near this point is less than that of an equivalent defect occurring across the diameter of a specimen in Brazilian test.

Table 20. A comparison between the average Flexural and the Brazilian Strength values of the tested basalt specimens.

Location	Flexural Strength (MPa)	Brazilian Strength (MPa)	Ratio of Flexural/Brazilian
Irbid	35.15	10.02	3.51
Ramtha	23.56	10.05	2.34
Al-Mafraq	27.14	10.01	2.71
Al-Azraq	30.80	10.00	3.08
Um-Qais	25.98	8.46	3.07

From the test results, it can be seen that Irbid rock specimens have recorded the highest of flexural strength while the Ramtha specimens recorded the lowest values. Although in Brazilian test, Ramtha specimens recorded the highest tensile strength. The reason for this discrepancy can be attributed to the cavities which were observed in Ramtha rock specimens that were used for the flexural test and may have weakened the outer fiber of the rock.

Uniaxial Compressive Strength

This test is probably the most common property used for engineering classification of rocks. Despite its simplicity, extreme care must be emphasized upon conducting this test. For example, in Irbid location, a rock core specimen has withstood a load of 626 kN before failure has occurred, while another rock core specimen from the same location failed at a load value of 334 kN, which is just about half as much. This variation in the test results is attributed to external and internal factors [12] that have affected the results of the (UCS) test conducted in this study.

A. External factors
   I. Specimen geometry which includes
      a. Bearing surfaces.
      b. Specimen shape.
      c. Specimen height to diameter ratio.
      d. Specimen size.
   II. Rate of loading.
   III. Effect of platens conditions and surfaces.
   IV. Effect of non-isotropy.
B. Internal Factors
   I. Mineralogical composition and texture: Mineralogy and texture have a great influence on the compressive strength results. It has been observed, for instance, that the fine grained sandstones are stronger than the coarse grained. Rocks containing quartz as cementing material are the strongest followed by calcite and ferrous minerals, while rocks with clayey cementing material are the weakest. For example, Table 21 presents the results of compressive strength for several samples representative of eight common rock types igneous, metamorphic and sedimentary rocks conducted by others [28].

Table 21. Compilation of uniaxial Compressive Strength data for eight common rock types.

Rock Type	Average Strength (MPa)	Maximum Strength (MPa)	Minimum Strength (MPa)	Strength Range (MPa)	No. of Samples
Granite	181.7	324.0	48.8	275.2	26
Basalt	214.1	358.6	104.8	253.8	16
Gneiss	174.4	251.0	84.5	166.5	24
Schist	57.8	165.5	8.0	157.6	17

Quartzite	288.5	359.0	214.9	144.1	7
Limestone	120.9	373.0	35.3	337.7	51
Sandstone	90.1	235.2	10.0	225.2	46
Shale	103.0	231.0	34.3	196.7	14

From this table, the smaller crystal size in basalt compared with granite is a primary cause for the higher average and maximum strength of basalt. The presence of vesicles, or voids from expanding gas, in some basalt, result in significant reduction in strength and is a major factor in the range of strengths shown. In granite, crystal size is the primary strength factor.

Effect of Porosity

It has been observed by several investigators [29] – [31] that, as the degree of porosity increases, the compressive strength of rocks decrease. High porosity in the rocks tend to weaken the bonding effect of the cementing material and hence producing a relatively weaker rock. However, it is not convenient to relate the weakness of a rock in terms of its compressive strength to the porosity effect. Since there are many other factors that could be involved like fissures and micro cracks, assuming other factors like size, shape, volume are kept constants.

Effect of Moisture Contentthe

Several investigators studied the effect of moisture content on the uniaxial compressive strength and they revealed varying conclusions. For example, while [20] found that the effect of moisture content is not pronounced through studying the ratio of the compressive strength of oven-dried to the compressive strength of air dried of five types of rocks namely: marble, limestone, granite, sandstone, and slate. The authors of [32] found that the compressive strength for saturated specimens of massive epidiorite and schistose epidiorite decreased by (81 – 86)% and (85 – 90)% of dry compressive strength; respectively. Furthermore, in [33] it is stated that the moisture content may decrease the compressive strength of sandstones by 40% and shales by 60 %.

It can be concluded that the moisture content in rocks has a very significant effect on compressive strength in many instances. In this study, specimens were tested under their natural water content. Although they gained some moisture from the drilling and sawing processes, they were allowed to dry out at room temperature for more than 30 days prior to testing.

Elastic Constants

The deformation constants of a material are the most important parameters in any design and their deformation involves the use of measuring techniques for load and deformation.

A material is called elastic when it recovers its original state after being subjected to a loading–unloading cycle. There are a number of elastic constants, some of which can be determined from the uniaxial compressive test, while others can be evaluated from the determined ones. The most commonly determined elastic constants are the modulus of elasticity and Poisson's ratio. Other constants can be determined from the modulus of elasticity and Poisson's ratio.

Young's Modulus (Modulus of Elasticity)

The loading–Unloading behavior of the tested samples shows that the stress strain behavior is not completely elastic material. However, the behavioral trend of the tested basalt rock resembles most of the other rocks and are categorized as elastic material thereby following the law of elasticity for their quantifiable description. Generally, the modulus of elasticity of a rock is affected by rock type, porosity, grain size, water content, fissures and micro cracks. In this study, four types of Young's moduli were evaluated: These moduli are the initial tangent modulus, the secant modulus of elasticity, the tangent modulus of elasticity, and the average modulus of elasticity. However, only the average modulus of elasticity was presented in this paper as shown by Table 12.

Poisson's Ratio

In this study, the values of Poisson's ratio were in the range of (0.252 -0.357) which are within the published values of similar rock types, although higher values were obtained but with different moduli of elasticity.

In general, Poisson's ratio of rocks measured from stress–strain curves is dependent upon the stress level and is greatly influenced by the opening or closing of cracks. Measured values at different stress levels may vary from 0.1 to 1.0, or even more. Under such circumstances, rock specimens should preferably be loaded at a stress level lower than that at which any permanent changes occur in rock and Poisson's ratio should be calculated using incremental values. In other cases, it is suggested to subject the rock specimens to lateral pressures to about 20 – 40% of their strength and then load axially and measure lateral and axial strains at about 50% of their strength under these test conditions [27].

Rock Classification Criteria for Basalt

Table 22 represents the widely recognized rock classification systems showing the classification name and their field of application. There are basically two types of classification systems that have been developed. First, those based upon some selected properties of intact rock which were focused upon in this study. Second, those which consider the properties of rock mass especially the nature of discontinuities such as the spacing of discontinuities, condition of continuities (roughness, separation, joint wall separation, in-filling etc.,) and stress field which were not investigated in this study.

Table 22. The Major Rock Classification Systems Currently in Use

Name of Classification	Originator and Date	Country of Origin	Application
Rock Loads	Terzaghi, 1946	USA	Tunnels with Steel Supports
Stand-Up – Times	Lauffer, 1958	Austria	Tunneling
Rock Quality Designation (RQD)	Deere, 1964	USA	Core Logging and Tunneling

Intact Rock Strength	Deere&Miller,1966	USA	Communication
RSR concept	Wickham et .al., 1972	USA	Tunneling
Geomechanics Classification (PMR –System)	Bieniawski, 1974	USA	Tunnels, Mines & Foundation
Q- System	Barton et al., 1975	Norway	Tunneling, Large Chambers
Strength/Block Size	Franklin and Dusseault, 1986	Canada	Tunneling
Basic Geotechnical Classification	ISRM, 1981	International	General

Intact Rock Classification

The classification of intact rock is an important category in this regard because the intact strength is a prerequisite for most modern classification. It also is increasingly becoming more important as joint spacing becomes shorter and shorter [28]. The engineering classification proposed by Deere and Miller [34] has been widely recognized as particularly realistic and convenient for use in rock mechanics. This classification is based on uniaxial compressive strength and modulus ratio (m) which is arbitrarily defined as the ratio between the tangent modulus and the unconfined compressive strength. Table 23 presents the engineering classification of intact rock as suggested in [34] on the basis of strength whereas Table 24 presents the engineering classification of intact rock based on modulus ratio.

Table 23. Engineering Classification of intact rock by Deere & Miller on the basis of strength.

Uniaxial Compressive	Description	Class Strength (MPa)
>220	Very high strength	A
110 – 220	High strength	B
55 – 110	Medium strength	C
28 – 55	Low strength	D
< 28	Very low strength	E

Table 24. Engineering Classification of intact tock by Deere & Miller on the basis of modulus ratio.

Modulus Ratio	Description	Class
> 500	High	H
200 – 500	Medium	M
< 200	Low	L

According to this classification system, the basalt rocks of the five locations examined in this study can be classified as shown in Table 25.

Table 25. Classification of the studied locations of basalt in NE Jordan based on Deere and Miller classification criteria.

Location	Average uniaxial compressive strength (MPa)	Tangent modulus (GPa)	Modulus ratio (m)	Classification
Irbid	105.89	102.2	965.1	CH
Ramtha	90.90	81.7	898.8	CH
Al-Mafraq	87.92	90.3	1027.1	CH
Al-Azraq	92.58	102.0	1101.7	CH
Um-Qais	97.97	99.8	1018.7	CH

Referring to Figure 4 which is a classification chart relating the uniaxial compressive strength with the tangent modulus and modulus ratio of 176 igneous rock specimens, it can be seen that basalt and other flow rocks lie in zone 3.

Conclusion

Based on previous work by others and the extensive investigation made in this study the following conclusions are reached:

1. The physical properties tests have shown that:
   a. The specific gravity of the northeastern basalts was lowest in Al-Mafraq rock specimens and highest in Um–Qais basalt rock specimens.
   b. The porosity and void ratio were lowest in Um-Qais rock specimens and highest in Al- Ramtha specimens.
2. According to the IAEG classification criteria, based on dry density and porosity, the following locations are classified as:
   a. Irbid, Al-Azraq and Um-Qais rock specimens are Class 4, which corresponds to high density and low porosity rock category.
   b. Al-Ramtha and Al-mafraq rock specimens are Class 3 -4, which corresponds to moderate density and low porosity rock category.
3. According to IAEG classification criteria set for ultrasonic wave velocity, all of the five locations are ranked as Class-5 which corresponds to “Very high” wave velocity rock category.

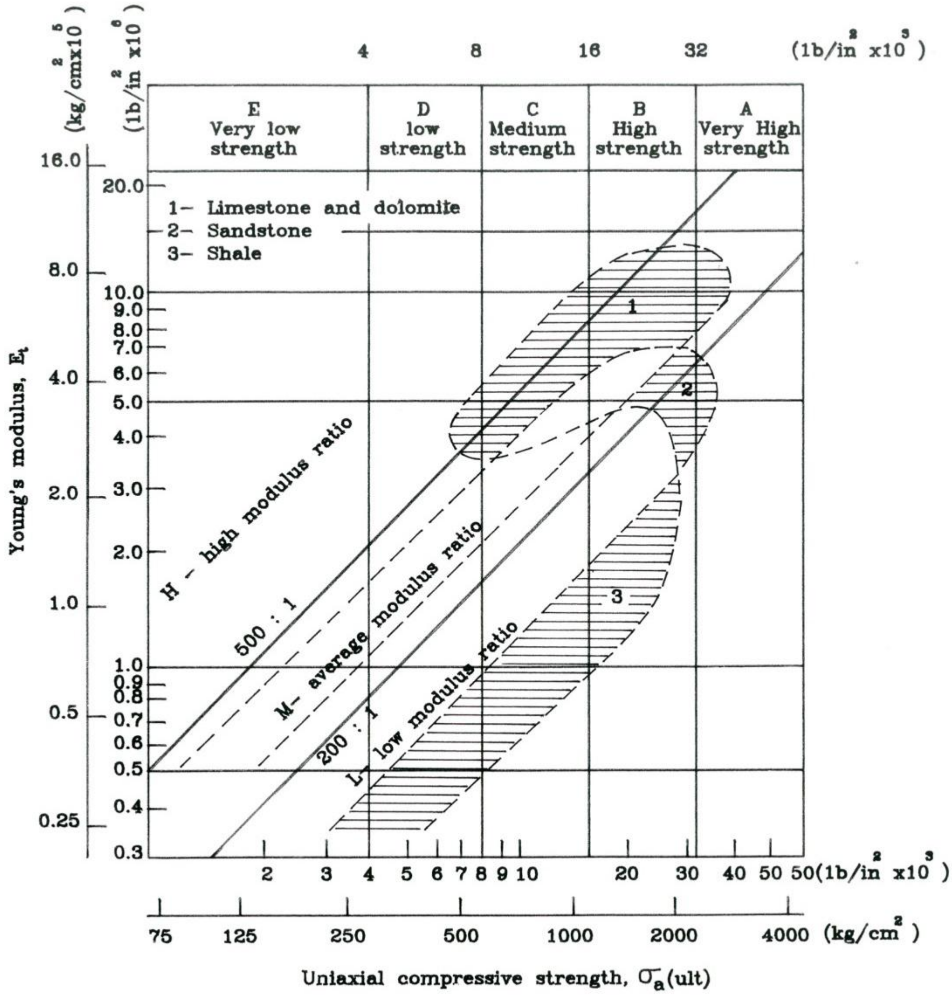

Figure 4. Engineering classification for intact rock substance.

4. Ramtha and Al-Mafraq rock specimens were the highest among all of the tested locations to suffer from abrasion using the Los Anegles abrasion machine, while Um-Qais specimens were the lowest, although all the sites tested exhibited abrasion of less than 25% which indicates the high durability of basalt.
5. According to Gambles slake durability classification criterion, all of the basalt specimens are classified as “Very high durable” rocks.
6. Results of indirect tensile strength or Brazilian test, when compared to the flexural strength results, indicated that the flexural is about three times greater than the indirect strength. This deviation can be attributed to the fact that in the flexural strength the possibility of a plane of weakness occurring at or near the point of loading is much less than that occurring across the diameter of a specimen subjected to indirect tensile load.
7. The uniaxial test results have shown great variations. Each location exhibited two extreme values. Since the basalt used in this study is surficial and exposed to all kinds of weathering processes, then the effect of micro cracks resulting especially from the cycles of wetting and drying and freezing and thawing processes may be the major causes of such variation.

8. All of the basalt specimens in the tested locations can be classified as “C – H” which corresponds to medium strength and high modulus ratio, in accordance with the engineering classification of intact rock proposed by Deere and Miller on the basis of uniaxial compressive strength and modulus ratio.
9. Four types of elastic moduli were determined in this study. Only the tangent modulus was considered in the analysis of results, since the corresponding Poisson’s ratio was below the maximum theoretical value of (0.5), while the other moduli of elasticity yielded Poisson’s ratio which were off the maximum theoretical value. However, the reason for such discrepancies can be attributed to experimental and human error.

Basalt rock in north east Jordan can beneficially be used for many engineering applications. Knowledge of the physical and engineering properties can help in the design of many engineering works, such as the construction of tunnels, highways, dams, and water collecting systems.

References

[1] Saffarini, G.; Nassir, S.; and Abed, A., 1985, A contribution to the petrology and geochemistry of the quaternary–neogene basalts of central Jordan: Dirasat, Vol. 12, No. 7, pp. 133 – 144.

[2] Bender, F. K., 1974, Geology of Jordan: Gebrueder Borntraeger, Berlin, Germany.

[3] Tarawaneh, K.; El-Hamed, S.; Abdel Hadi, N.; and Rabba, I., 2001, Evaluation of the geological and engineering properties of basalt of northeast Jordan for construction uses (Case Study) Jordan Engineering Association, Amman, Jordan.

[4] Ibrahim, K., 1974, The Geology of Al-Azraq., Map sheet No. 3353, The National Resources Authority (NRA), Amman, Jordan.

[5] Tarrad, M.; Al-Omari, O.; and Mohammed, A., 2012, Natural stone in Jordan: characteristics and specifications and its importance in interior architecture: Journal of Environmental Science and Engineering, Vol. 1, No. 6, pp. 720 – 727.

[6] Ibrahim, A.; Faisal, S.; and Jamil, N., 2009, Use of basalt in asphalt concrete mixes: Construction and Building Materials, Vol. 23, No. 1, pp. 498 – 506.

[7] Rosenbaum, M. and Skene, G., 1995, Airfield pavement construction using basalt aggregate: Bulletin of Engineering Geology and the Environment, Vol. 51, No. 1, pp. 71 – 79.

[8] Maiah, H., and Al- Khateeb G., 2005, Effect of Basalt on superpave aggregate properties. Jordan Engineering Association, Amman, Jordan.

[9] Kishore, I.S.; Mounika, L.; Prasad, C.M.; and Krishna, B.H., 2015, Experimental study on the use of basalt aggregate in concrete mixes: International Journal of Civil Engineering, Vol. 2, No. 4, pp. 39 – 42.

[10] Al-Baijat, H., 2008, The use of basalt aggregates in concrete mixes in Jordan: Jordan Journal of Civil Engineering, Vol. 2, No. 1, pp. 63 – 70.

[11] Taqieddin, S.; Al-Homuod, A.; and Al- Zoubi, M., 1995, Physical and engineering properties of some selected limestone rocks in northern Jordan: Mutah Journal for Research and Studies, Natural and Applied Science Series, Vol. 10, No. 3.

[12] Taqieddin, S.; Al-Homoud, A.; and Ababneh, J., 1998, Physical and engineering properties of oil-shale from el-lajjun Jordan: Environmental and Engineering Geoscience, Vol. 4, No. 2, pp. 241 – 260.

[13] Atkinson, R.H.; Bamford, W.E.; Broch, E.; Deere, D.U.; Franklin, J.A.; Nieble, C.; Rummel, F.; Tarkoy, R.J.; and Van Duyse, 1978, Suggested methods for determining hardness and abrasiveness of rocks: International Journal of Rock Mechanics and Mining Sciences, Vol. 15, No. 3, pp. 89 – 97.

[14] Rummel, F. and Vanheerden, W., 1978, Suggested methods for determining sound velocity: International Journal of Rock Mechanics and Mining Sciences, Vol. 15, No. 2, pp. 53 – 58.

[15] Bieniawski, Z.T. and Bernede, M.J., 1979, Suggested methods for determining the uniaxial compressive strength for deformability of rock materials: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Vol. 16, No. 2, pp. 138 - 140.

[16] Franklin, J.A., 1979, Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake-durability index properties: International Journal of Rock Mechanics and Mining Sciences, Vol. 16, No. 2, pp. 143 – 151.

[17] American Society For Testing and Materials (ASTM), various years, Designation D4543-85, D3148-86, C127, C128, C20-73, C29-78, C70-79, C131, and 533-69,C128, D2845-69. Annual Book of ASTM standard : American Society for Testing and Materials, Philadelphia, PA.

[18] Brown, E. T., 1981, ISRM Suggested Methods - Rock Characterization Testing and Monitoring: Pergamon Press Ltd., Oxford, U.K.

[19] Al-Zoubi, M.M., 1993, Evaluation of the Physical and Engineering Properties of Some Selected Northern Limestone Rocks in Jordan: M.Sc. Thesis, Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan.

[20] Obert, L., and Duvall, W.I., 2013, Rock Mechanics and the Design of Structures in Rocks: Wiley, New York.

[21] Brady, B.H., and Brown E.,T., 1985, Rock Mechanics for Underground Mining: George Allen and Unwin Publishers Ltd., London, U.K.

[22] Touloukian, Y.S., Judd, W.R., and Roy, R.F., 1981, Physical Properties of Rocks and Minerals: McGraw–Hill, New York.

[23] Matula, M., 1981 Rock and soil description and classification for engineering geological mapping report by the IAEG commission on Engineering Geological Mapping: Bulletin International Association of Engeering Geology, Vol. 24, No. 1, pp. 235 – 274.

[24] Aufmuth, R.E., 1974, Site engineering indexing of rocks: Field Testing and Instrumentation of Rock, American Society of Testing & Material, Special Technical Publication, pp. 81 - 99.

[25] Irfan, T.Y. and Dearman, W.R., 1978, Engineering classification and index properties of a weathered granite: Bulletin of Engineering Geology and the Environment, Vol. 17, No. 1, pp. 79 – 90.

[26] Goodman, R.E., 1980, Introduction to Rock Mechanics: Wiley, New York.

[27] Lama, R.D. and Vutukuri, V.S., 1978, Handbook on Mechanical Properties of Rocks-Testing Techniques and Results: Trans Tech Publications.

[28] Johnson, R. and Degraff, J., 1988, Principles of Engineering Geology: Wiley, New York.

[29] Price, N.J., 1960, The compressive strength of coal measure rocks: Colliery Engineering, Vol. 37, No. 437, pp. 283 – 292.
[30] Kowalski, W.C, 1966, The independence between the strength and void ratio of limestones and marl in connection with their water saturation and anisotropy: In proceeding of the first International Congress on Rock Mechanics, pp. 143 – 144, Lisbon, Portugal.
[31] Smorodinov, M.I.; Motovilov, E.A.; and Volkov, V.A., 1970, Determinations of correlation relationships between strength and some physical characteristics of rocks. In proceedings of the 2nd Congress of the International Society of Rock Mechanics, Belgrade, Vol. 2, pp. 35 – 37.
[32] Turk, N. and Dearman, W.R., 1986, Influence of water on engineering properties of weathered rocks: Geological Society, London, Engineering Geology Special Publications, Vol. 3, No. 1, pp. 131 – 138.
[33] Steiger, R.P. and Leung, P.K., 1990, Predictions of wellbore stability in shale formations at great depth: In Maury, V. and Fourmaintraux, D. (Editors), Rock at Great Depth, Balkema, Rotterdam, Netherlands, pp. 1209 – 1218.
[34] Deere, D.U.; and Miller, R.P., 1966, Engineering classification and index properties for intact rock: Technical report no. AFNL-TR-65-116, Air Force Weapons Laboratory, Albuquerque NM.
[35] Jumikis, A. R., 1983, Rock Mechanics: Gulf Publishing Co., Houston, TX.