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Mechanical Properties of Natural Building Stone: Jordanian Building Limestone as an Example

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Abstract

This experimental investigation is intended to study the mechanical properties of natural building stone usually used in the construction of load-bearing concrete backed stone masonry walls and columns used in the construction of the majority of buildings in Jordan and some middle-eastern countries. Six types of building limestone, brought from different quarries in Jordan, were used in this study. The characteristics studied were the stress-strain curves, the modulus of rupture, the modulus of elasticity, the Poisson ratio and the compressive strength. An experimental method is suggested to determine the modulus of elasticity of limestone; the results were compared with those obtained from stress-strain curves carried out on prisms. The results indicated that there are remarkable differences in strength and behavior of stone specimens loaded parallel to the bedding (or rift) and perpendicular to it in both dry and wet conditions. It is also indicated that the differences in results of the modulus of elasticity obtained by the suggested method and the stress-strain curves are not significant. On the basis of the test results a new formula is suggested for estimating the modulus of elasticity of limestone when compressive strength is known.

Keywords: Building stone; mechanical Properties; prisms; cubes; compressive strength; limestone.

1. Introduction

Concrete-backed stone masonry is one of the most important construction method used in Jordan and the Middle East. Until the nineties of the last century, most of Jordan's low rise buildings are constructed from the assemblage of dimension stone, mortar and concrete constructed as structural walls; namely, stone masonry bearing walls where stone thickness varies from 40 to more than 80 mm (Abdel-Halim et al., 1989). The thickness of the stone at the edges is usually smaller than in the center, backed by 200-250 mm of concrete with total wall thickness of 300 - 350 mm for the buildings raising up to four stories; higher buildings usually have thicker bearing walls. For the 300 - 350 mm thickness wall, strengthening columns are concentrated at the corners of the wall usually 200 × 400 mm in dimension, reinforced by six vertical bars and confined by stirrups each 200 mm, the steel reinforcement area usually kept to minimum.

Other strengthening columns 200 × 200 mm in dimension, reinforced by four vertical bars and confined by stirrups each 200 mm are concentrated at a distance about four meters from each other.

2. Materials

Six different types of building limestone with 14 varieties were brought from different quarries in Jordan. A location map showing the position of each quarry is given in fig. 1.

The stone were sawed to appropriate dimensions. Among the large number of stone specimens, three different kinds of limestone were used: soft, hard and very hard. According to ASTM C 568-89 (1992) limestone may be classified into three categories. These are, *I* (*Low-Density*), for limestone having a density ranging from 1760 through 2160 kg/m^3; *II* (*Medium-Density*) for limestone having a density greater than 2160 and not greater than 2560 kg/m^3 and *III* (*High Density*) for limestone having density greater than 2560 kg/m^3. At least one type of each category was chosen to be included among the tested specimens.

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Fig. 1 Map showing the limestone quarry locations of the tested samples (the quarry names are underlined

3. Experimental Program

3.1. Testing Procedure

Water absorption and specific gravity were carried out in accordance with ASTM C 97-90 (1992). For determining the compressive strength 60 × 60 × 60 mm cubes were tested by axial compression in accordance with ASTM C 170-90 (1992). More than twenty sawed cubes from each type of stone were tested: ten specimens in dry conditions and ten in wet conditions. Each group of specimens was tested with load direction parallel to bedding (or rift) and perpendicular to it.

The modulus of rupture was carried out on specimens approximately 101 × 203 × 57 mm in size. For each type of stone, twenty specimens were prepared, ten specimens were tested in dry conditions where specimens lift in the oven at temperature of 60° C for 48 hours. The other ten specimens after being lift in water tank for 48 hours at temperature of about 22° C. For each test condition, five specimens were tested with load direction parallel to bedding (or rift). The other five specimens were tested with load direction perpendicular to bedding (or rift). The test was carried out in the accordance with ASTM C 99-87 (1992). A suggested technique based on the standard test method on specimens used to determine the modulus of rupture (ASTM C 99-87, 1992), was used to determine the modulus of elasticity of building limestone. The results were compared with test results obtained from stress-strain curves of stone prisms tested with strain measurements. In this method which is specified in ASTM C 120-90 (1992) Standard as methods of flexure testing of slate, and is under the jurisdiction of ASTM Committee C-18 to be applied on dimension stone, the modulus of elasticity was determined in conjunction with the modulus of rupture test (ASTM C 120-90, 1992). The deflection was measured at mid-span of the specimens by a deflection scale capable of reading 0.01 mm. The loading was stopped at each 222 N increment, and the corresponding deflections readings were taken.

To study the relationships between compressive stress and strain, modulus of elasticity and Poisson ratio, a set of more than three prisms 100 × 100 × 200 mm were prepared for each type of stone. At least two of the prisms were fitted with demec points for measuring vertical and horizontal strains at the middle of the stone face; the gauge length was 50 mm. The demec points were glued on identical positions on two opposite sides of the chosen prisms at least 72 hours prior to testing. For each type of stone, a set not less than three prisms were tested with load direction parallel to bedding (or rift). Another set of each stone type not less than three prisms was tested with load direction perpendicular to bedding (or rift). All specimens were tested at a loading rate of 10 N/mm^2 per minute in accordance with BS 6073: Part 1: 1981 (1981).

4. Results and Discussion

Table 1 gives the results of specific gravity, water absorption and compressive strength for studied limestones. Compressive strength ranges from 9.4 N/mm^2 for soft stones tested in wet conditions when load direction was perpendicular to rift, to 116.3 N/mm^2 for very hard stones tested in dry conditions when load direction was parallel to rift. The results show that the decrease of stone absorption has great significance in increasing the compressive strength of the stones (Abdel-Qader, 2002; Akroush, 1994). It also shows that the specimens tested with loading parallel to rift possess higher compressive strengths. The table clearly reveals that the compressive strength for specimens tested in dry conditions is higher than those in wet conditions.

The results also show that some specimens with smaller percentage of water absorption i.e., Ma'an Sateh 1 and Ma'an Sateh 2, have little difference in compressive strength compared to specimens with higher percentage of water absorption like Hayyan Soft.

Table 1 Results of average compressive strength of specimens loaded parallel and perpendicular to bedding (or rift).

Type of Stone	Specific Gravity	Water Absorption (%)	Average Compressive Strength (N/mm^2) of 60 × 60 × 60 (mm) Cubes			
			Dry		Wet	
			Load parallel to rift	Load perpendicular to rift	Load parallel to rift	Load perpendicular to rift
Ma'an Sateh 1 (first class)	2.51	0.81	56.2	51.3	55	47.9
Ma'an Sateh 2 (second class)	2.55	0.59	64.4	51.9	67.8	65.4
Ma'an Jazeerah	2.47	1.71	65.1	48.7	57	50.3
Ma'an Onizah	2.42	1.07	82	58.7	67.7	51.5
Ruwaished Hard	2.58	0.55	116.3	83.1	87.4	68.8
Ruwaished Medium	2.39	3.11	100.2	Not tested	79	Not tested
Ruwaished Soft	2.31	3.71	79.4	71.5	70.9	49
Hayyan Hard	2.49	1.96	64.5	54.2	55.1	45.7
Hayyan Medium	2.32	3.59	62.6	47.2	50.7	45.7
Hayyan Soft	1.99	9.43	16.3	15.5	11.3	9.4
Azraq Reddish	2.48	1.71	61.2	53.0	57.2	45.7
Sahrawi Yallowish	2.37	2.00	58.6	39.5	45.6	37.9
Qatranah	2.25	4.66	63	66.5	51.5	40.2
Qatranah Reddish	2.35	2.89	69	39.4	38	32.4

Note: Stone types are ranging between soft, for type Hayyan Soft, and very hard for Ruwaished Hard. All remaining types are hard stones.

Table 2 summarizes the results of the modulus of rupture and the modulus of elasticity of limestone specimens loaded parallel and perpendicular to bedding (or rift) for average of dry and wet conditions. The results indicated that the modulus of rupture perpendicular to the rift is slightly greater than that parallel to it. Modulus of elasticity parallel to the rift is greater than that perpendicular to it.

Table 2 Results of the modulus of rupture and the modulus of elasticity of limestone loaded parallel and perpendicular to the bedding (or rift).

Type of Stone	Modulus of Rupture (N/mm^2) Average of dry and wet conditions		Modulus of Elasticity (N/mm^2) Average of dry and wet conditions	
	Loading parallel to rift	Loading perpendicular to rift	Loading parallel to rift	Loading perpendicular to rift
Ma’an Sateh 1 (first class)	11.5	13.6	39431	36038
Ma’an Sateh 2 (Second class)	Not tested	Not Tested	41179	38212
Ma’an Jazeerah	Not tested	12.4	46292	33335
Ma’an Onizah	10.5	12.3	Not tested	37125
Ruwaished Hard	14.7	15.7	49873	43821
Ruwaished Medium	11.3	12.2	47457	40577
Ruwaished Soft	10.5	11.9	39010	36038
Hayyan Hard	12.1	13.1	38810	36038
Hayyan Medium	5.9	6.7	43931	37840
Hayyan Soft	1.85	2.0	21623	18435
Azraq Reddish	9.8	11.8	Not tested	35317
Sahrawi Yallowish	8.5	10.5	36857	313372
Qatranah	Not tested	11.35	41725	37840
Qatranah Reddish	9.14	8.64	Not tested	37179

In the standard test carried to determine the modulus of rupture, the specimen which is supported by two knife edges of the rocker type, is subjected to flexure using a center-point loading until failure. The maximum tensile stress is referred to as the modulus of rupture, occurred at the bottom fiber of the test specimen. The rift is defined as a consistent direction or trend in rock body along which the rock is most easily split or broken (ASTM C 119-91, 1992). The split indicated that the layers that contained the rift are weaker than the surrounding layers. Since the test is flexure test, the values of the modulus of rupture of the specimens tested with the load direction parallel to the rift are lower than those tested with the load direction perpendicular to it.

Table 3 gives the results of tested 100 × 100 × 200 mm prisms. Initial modulus of elasticity was obtained from stress-strain curves; values of Poisson ratio relied also upon initial strain. The results show that the modulus of elasticity parallel to the rift is greater than perpendicular to it.

Table 4 shows a comparison between the results of some physical and mechanical properties obtained from the current study and a previous one (Akroush, 1994). It shows close agreement between the two results. Notable differences in the physical and mechanical limestone properties are expected from stone brought from nearby locations within the same quarry.

Table 3 Results of the compressive strength and the modulus of elasticity of dimensioned limestone prisms loaded parallel and perpendicular to the bedding.

Type of Stone	Compressive Strength(N/mm^2) Average of dry and wet conditions 100 × 100 × 200 (mm) prisms		Modulus of Elasticity (N/mm^2) and Poisson ratio Average of dry and wet conditions			
			Load parallel to rift		Load perpendicular to rift	
	Load parallel to rift	Load perpendicular to rift	Modulus of Elasticity	Poisson Ratio	Modulus of Elasticity	Poisson Ratio
Ma’an Sateh 1	52.2	46.2	42533	0.17	37675	0.2
Ma’an Sateh 2	54.5	47.5	44147	0.14	38212	0.17
Ma’an Jazeerah	51.3	49	39234	0.14	32660	0.17
Ma’an Onizah	67.3	46	50545	0.18	------	------
Ruwaished Hard	103	not tested	42428	0.18	------	------
Ruwaished Medium	71.7	46	41284	0.15	39421	0.19
Ruwaished Soft	47	44	40077	0.14	35610	0.17
Hayyan Hard	59.2	47	43133	0.17	32435	0.25
Hayyan Medium	54	42.4	38110	0.2	30303	0.19
Hayyan Soft	8	9.5	28407	0.2	11645	0.26
Azraq Reddish	60.8	47.2	42692	0.16	40363	0.15
Sahrawi Yallowish	46	38.3	39481	0.15	33193	0.22
Qatranah	41	not tested	40993	0.16	-----	-----
Qatranah Reddish	43	39.8	35318	0.16	31533	0.18

Table 4 Comparison of some physical and mechanical properties obtained from the current study and previous one (Akroush, 1994).

Type of Stone	Specific Gravity		Water Absorption (%)		Compressive Strength (N/mm^2)				Modulus of Rapture (N/mm^2)			
					Load parallel to rift Average of Dry and Wet		Load perpendicular to rift Average of Dry and Wet		Load parallel to rift Average of Dry and Wet		Load perpendicular to rift Average of Dry and Wet	
	Current Study	Ref. 3	Current Study	Ref. 3	Current Study	Ref. 3	Current Study	Ref. 3	Current Study	Ref. 3	Current Study	Ref. 3
Ma’an Sateh 1	2.51	-----	0.81	-----	55.6	-----	49.6	-----	11.5	-----	13.6	-----
Ma’an Sateh	-----	2.59 2.63*	-----	0.69 0.57*	-----	48.56	-----	47.9	-----	8.60	-----	9.64
Ma’an Jazeerah	2.47	2.61 2.58*	1.71	0.58 1.18*	61.05	68.18	49.5	50.3	-----	12.20	12.4	12.63
Hayyan Hard	2.49	-----	1.96	-----	59.8	-----	49.98	-----	12.1	-----	13.1	-----
Mafraq	-----	2.46	-----	2.51	-----	51.86	-----	53.85	-----	8.74	-----	13.06

*Note: Hayyan quarries are within Mafraq area.

*Results of renewed study carried by the Building Research Center (Ref. 3, Akroush, 1994).

Table 5 shows a comparison between the compressive strength of cubes and prisms loaded parallel and perpendicular to rift. The table also gives a correction factor for converting from prism to cube and vice versa

The results show higher compressive strength for the cubes than for prisms. This is due to the frictional forces between the end surfaces of the limestone specimen and the adjacent steel platens of the testing machine. The platen restrains the lateral expansion near the top and bottom surfaces of the specimen. The effect of restraining decreases when the distance from the contact surfaces is increased; at the same time, the lateral forces reached its maximum in the middle of the specimen. This explains the pyramid mode of failure.

In case of prisms; the effect of restraining is limited to the upper and lower contact surfaces and the middle part of the prism is free from the restraining effects. Prisms failed by splitting due to the lateral tensile strains caused by the effect of the Poissions ratio which is 0.18 in average.

The specimens tested with the load direction parallel to the rift, exhibited higher compressive strength than those tested with the load direction perpendicular to the rift. This is explained by the nature of the rift that defines a consistent direction in rock body along which the rock is most easily broken. Furthermore, the grain orientation in stone, i.e. that shows how the stone was originally bedded, offers further explanation. The thin layers of solid materials bedded over each other, forming together the stone, have different properties e.g. grain size, voids and hollow; making one layer weaker than the other. When the specimen is tested with the loading parallel to the rift, two stress elements are likely to occur, tri-axial compression and bi-axial lateral tensile with uni-axial compression stresses. The bi-axial lateral tensile stresses tend to split the specimen. Wet Specimens have higher lateral tensile stresses than dry ones; this is related to the additional lateral tensile stresses of the moisture inside the voids.

Table 5 Comparison between the compressive strength of cubes and prisms.

Type of Stone	Compressive Strength (N/mm^2) 60 × 60 × 60 (mm) Cubes		Compressive Strength (N/mm^2) 100 × 100 × 200 (mm) Prisms		Correction Factor Conversion from Prism to Cube (Multiple by) Conversion from Cube to Prism (divide by)	
	Average Dry and wet		Average Dry and wet		Average Dry and wet	
	Load parallel to rift	Load perpendicular to rift	Load parallel to rift	Load perpendicular to rift	Load parallel to rift	Load perpendicular to rift
Ma’an Sateh 1	56.2	51.3	52.2	46.2	1.08	1.11
Ma’an Sateh 2	64.4	51.9	54.5	47.5	1.18	1.09
Ma’an Jazeerah	65.1	48.7	51.3	49	1.27	0.99
Ma’an Onizah	82	58.7	67.3	46	1.22	1.28
Ruwaished Hard	116.3	83.1	103	Not tested	1.13	-----
Ruwaished Medium	100.2	Not tested	71.7	46	1.40	-----
Ruwaished Soft	79.4	71.5	47	44	1.69	1.62
Hayyan Hard	64.5	54.2	59.2	47	1.09	1.15
Hayyan Medium	62.56	47.2	54	42.4	1.16	1.11
Hayyan Soft	16.3	15.5	8	9.5	2.03	1.63
Azraq Reddish	61.2	53.02	60.8	47.2	1.15	1.12
Sahrawi Yallowish	58.6	39.5	46	38.3	1.27	1.03
Qatranah	63	66.5	41	Not tested	1.54	-----
Qatranah Reddish	69	39.4	43	39.8	1.6	0.99

For specimens tested with the load direction perpendicular to the rift, the thin layers are bedded horizontally. Two stress elements are likely to occur; bi-axial lateral tensile with uni-axial compression in the stiffer layers and tri-axial compression stresses in the weaker layers confined by two stiffer ones. Frictional forces occur in the contact surface of the two adjacent layers; it also occurs between the upper and lower surfaces of the specimen and the adjacent machine platens.

The relationship between the compressive strength and the modulus of elasticity is suggested by the following formula for each case of loading:

$$E_{stone} = k \times (f_{cube})^{0.5} \quad (N/mm^2) \qquad (1)$$

Where:

E_{stone} = Modulus of elasticity (average of dry and wet conditions).

f_{cube} = The compressive strength of sawed limestone cubes not less than 50.8 × 50.8 × 50.8 mm in dimensions.

$k = k_1$ load direction factor (loading parallel to rift).

$k = k_2$ load direction factor (loading perpendicular to rift).

Plotting best fit line representing the data, k_1 and k_2, the mentioned factors could be taken as 5.47×10^3 and 4.88×10^3, respectively.

Figure 2 shows the stress-strain curves for Ruwaished Stone where a very hard stone specimen is compressed parallel to the rift. When compared to other types of stone specimens with parallel and perpendicular loading, the curves show a steady increase in strength with stress and vertical strain values higher than all other types of stones. Also, a sudden increase in the vertical strain values at around 90 N/mm^2 is observed. This is caused by the tendency of the prism to increase its stiffness after a lateral deformation.

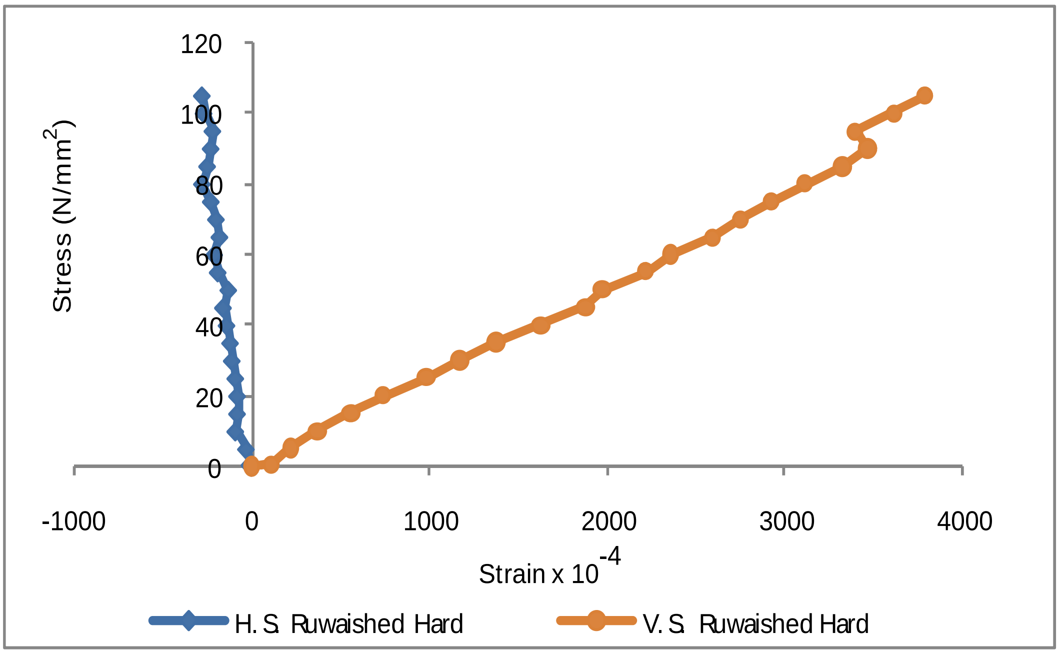


Fig. 2 Compressive stress-strain curves for very hard stone tested parallel to rift in dry conditions.

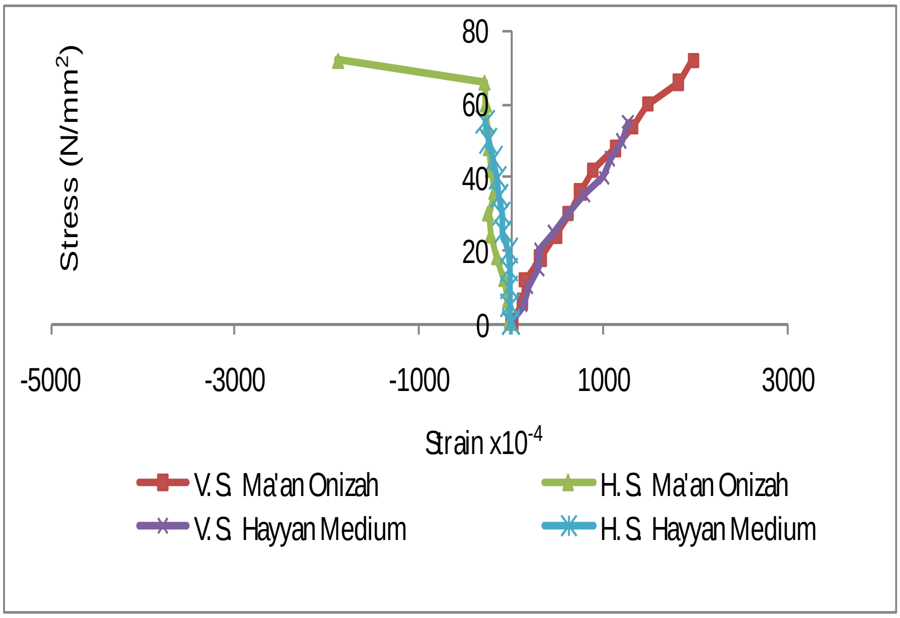
All the stress-strain figures show the relationship between the compressive stress and both compression and tension strains. For this reason the compression and the tension strain graphs are plotted in two opposite sides, namely the +ve and the –ve sides of the X axis.

Comparing the stress-strain curves for hard stone compressed parallel to rift in dry conditions (Fig. 3) to these for hard stone compressed perpendicular to rift under the same conditions (Fig. 4), two curves exhibited a sudden reduction in stiffness and increase in the lateral strain values near failure when load direction was perpendicular to the rift.

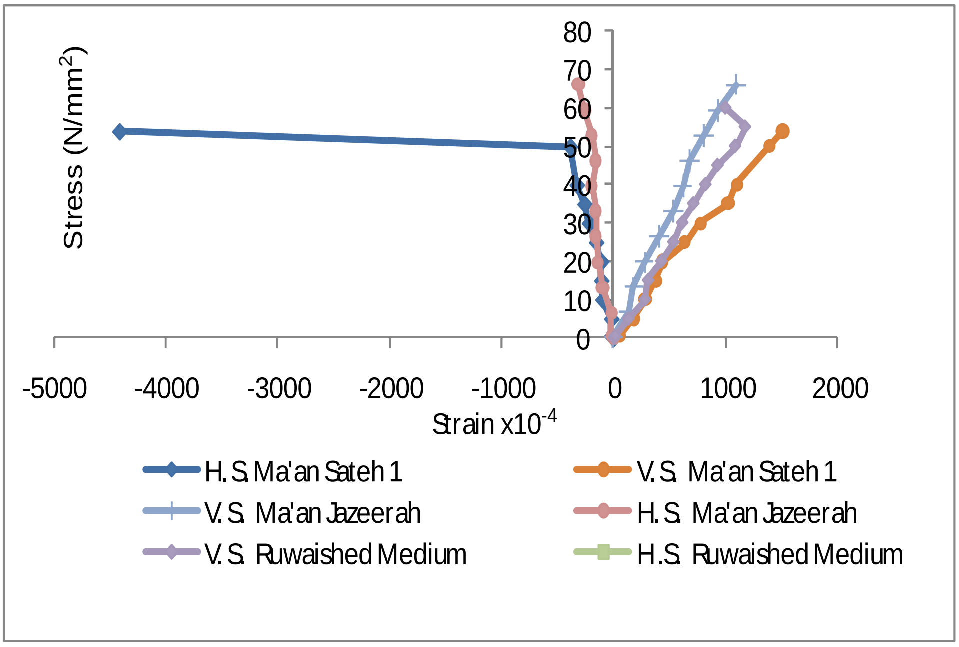
Comparing the stress versus strain curves for hard stone compressed parallel to rift in dry conditions (Fig. 3) to those in wet conditions (Fig. 5), a reduction in stiffness and rapid increase in lateral strains was found when the load direction was parallel to rift in wet conditions.

The stress-strain curves for hard stones compressed perpendicular to rift in wet conditions are given in Fig. 6. Two curves exhibit increase in stiffness occurred near failure; this was caused by the deformation of the stone layers where loading direction was perpendicular to stone rifts, and the deformation also caused high lateral strain values near failure.

Figure 7 shows a comparison between compressive stress-strain curves for soft stone tested parallel and perpendicular to rift in dry conditions. The curves exhibit a decrease in stiffness and high values of both vertical and lateral strains when load direction was perpendicular to rift.



(a)



(b)

Fig. 3. a,b: Compressive stress-strain curves for hard stone tested parallel to rift in dry condition.

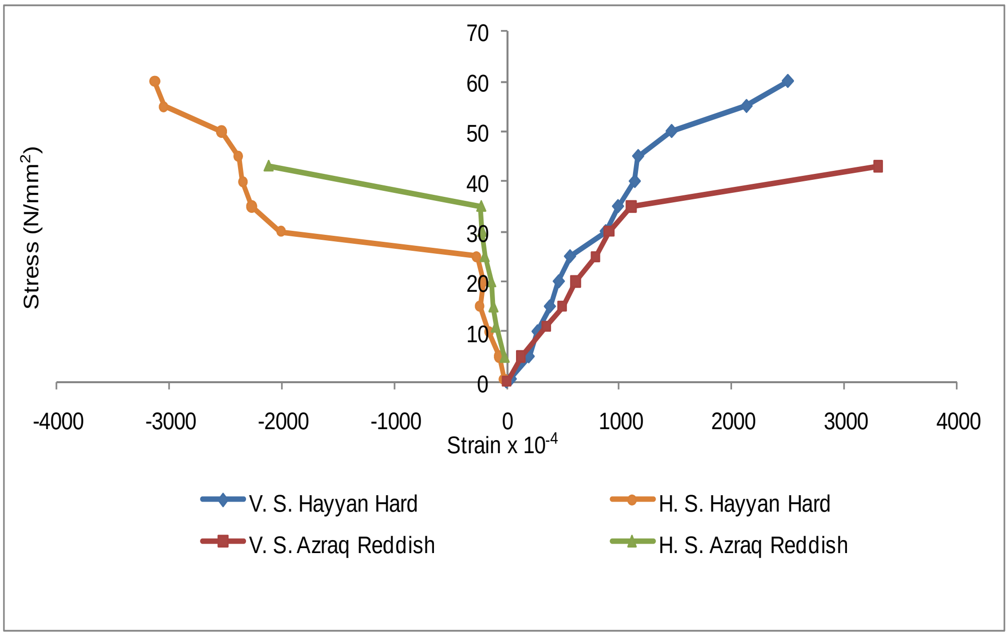


Fig. 4 Compressive stress-strain curves for hard stone tested perpendicular to rift in dry conditions.

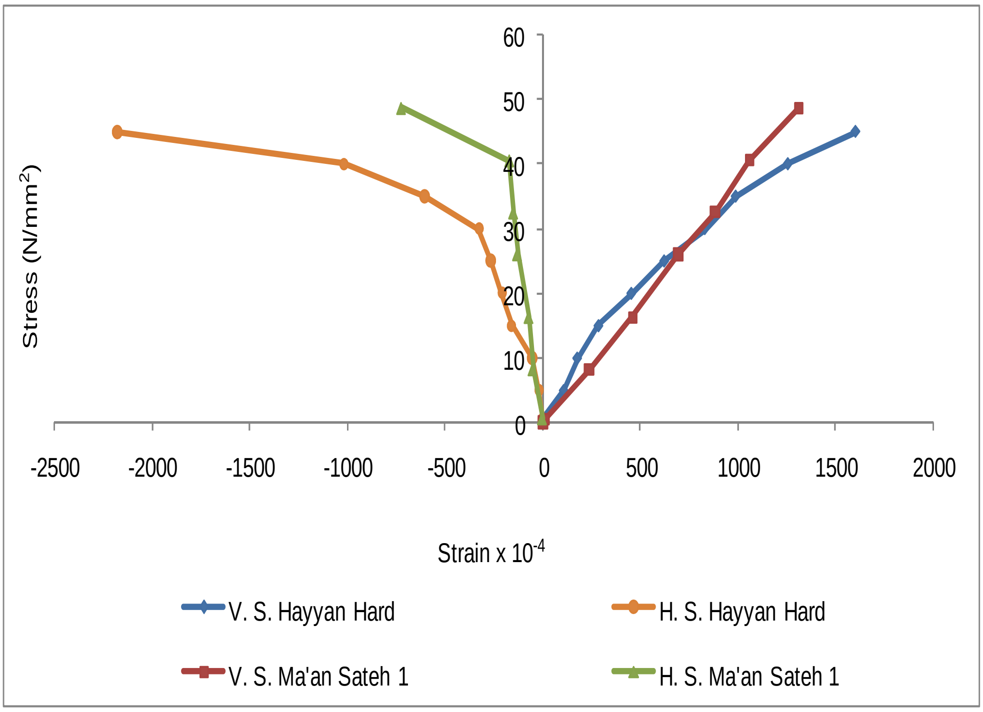


Fig. 5 Compressive stress-strain curves for hard stone tested parallel to rift in wet conditions.

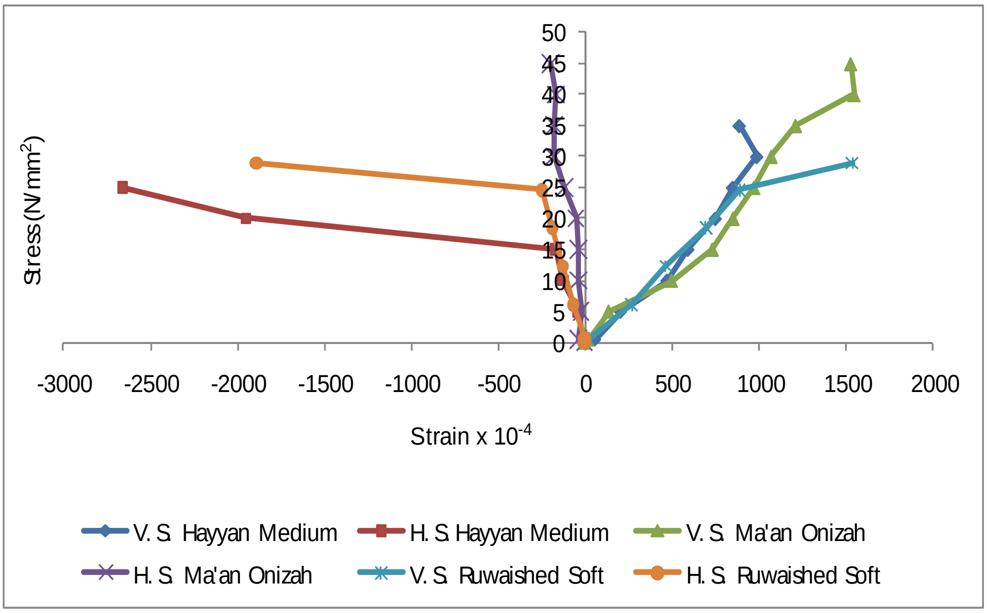


Fig. 6 Compressive stress-strain curves for hard stone tested perpendicular to rift in wet conditions.

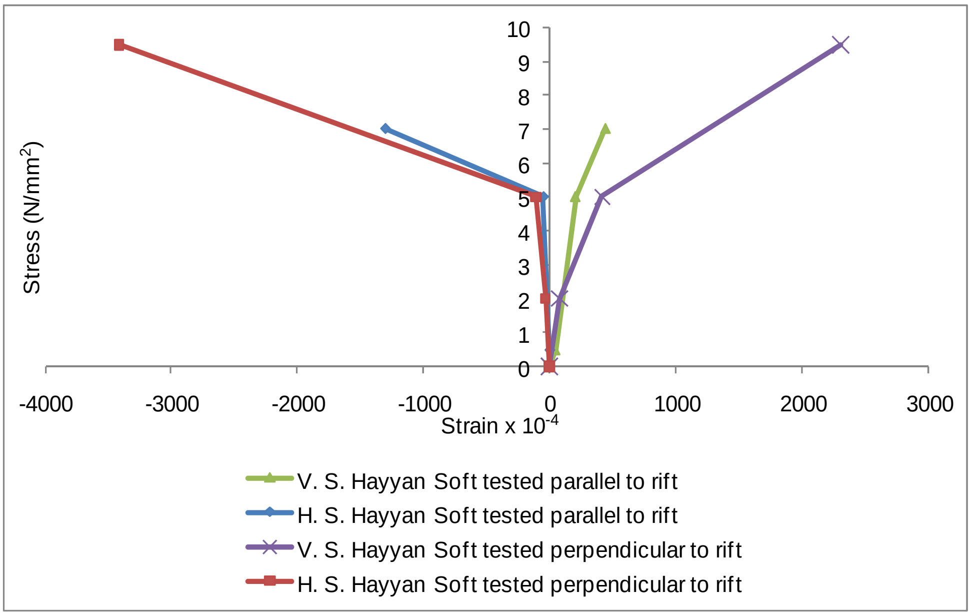


Fig. 7 Comparison between compressive stress-strain curves for soft stone tested Parallel and perpendicular to rift in dry conditions.

5. Conclusion

1. Higher specific weight and lower water absorption contribute to higher strength of the stones, and their elasticity and rupture moduli.
2. The modulus of rupture of limestone with load direction perpendicular to rift is higher than parallel to rift, whereas the modulus of elasticity obtained from the suggested method is higher for specimens tested with load direction parallel to rift.
3. The compressive strengths for limestone cubes tested in dry conditions are higher than limestone cubes tested in wet conditions. Compared to the limestone cubes, the tested limestone prisms exhibited higher decrease in compressive strength.
4. There are slightly differences between the values of the modulus of elasticity obtained from tested stress-strain curves and that obtained by the suggested method.
5. Based on test results, a new formula (equation 1) was suggested to estimate the modulus of elasticity of limestone from compressive strength.
6. The modulus of elasticity of prisms tested in dry conditions with loading parallel to rift is higher than that perpendicular to rift. Poisson ratio perpendicular to rift is higher than that parallel to it.

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