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Effect of petrological characteristics on tensile strength of limestone using hydraulic fracturing tests

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1. Introduction

Hydraulic fracturing is a highly efficient technique for simulating oil and gas reservoirs. It is used to measure in situ stress and is an indispensable tool for design in rock engineering and geophysical research. Hydraulic fracturing involves pressurizing a well or borehole to induce a tensile fracture that generally runs perpendicular to the lowest principle compressive stress.[1] The amount is determined by calculating the breakdown pressure by measuring the critical borehole pressure required to induce fracture. Breakdown pressure is dependent on the in situ stress and the mechanical characteristics of the rock.

Factors affecting fracture propagation and fracture geometry include the state of the stress, injection rate, fracture fluid, Young's modulus, fracture toughness of the rocks (tensile strength), initial pore pressure, leak-off coefficient, relative bed thickness of the formation, and specimen size.[2] It is not possible address all factors in one program; these parameters can be obtained from large data from.[1,3–29]

Testing in the current study concentrated mainly on the influence of tensile strength on fracture propagation. The most important parameter related to the mechanical characteristics of the rock is tensile strength as obtained through hydraulic fracturing testing, which is important to the design and implementation of hydraulic fracturing on all scales. Ratigan[30] stated that the apparent tensile strength of hydraulic fracturing depends upon the sample size and type of test being performed. Haimson[3] found that the apparent tensile strength decreases as the internal borehole diameter increases. For these reasons, the sample size, type of test, and parameters such as the length and diameter of samples should be considered constants for all tests.

The present study compared the rock tensile strength values obtained from the hydraulic fracturing test with that from the (indirect tensile) Brazilian test. The results were compared as related to the petrological characteristics of the samples. Few experimental data sets have been published on this type of comparison of the results of hydraulic fracturing and Brazilian tests.[31,32] Three types of limestone were selected and 10 samples were prepared for each type of limestone. The sample set comprised bioclastic-wakestone limestone (Asmari formation), biomicrite limestone (Sarvak formation), and dolomitized-biomicrite limestone (Dalan formation).

2. Geology of region

The geology and location of the type sections of the formations studied. The Asmari formation outcrop is an anticline with a northwest-southeast strike. The name of this formation derives from the Asmari Mountains southeast of Masjed-Soleiman. This is the youngest reservoir rock of the Zagros range and formed mainly as a sequence of semi-fractured and porous limestone with marl stone inter-bedded layers and shale. The thickness of this formation is approximately 470 m and formed in the Oligo-Miocene period.

The Sarvak formation is located in north Behbahan in Iran and is an anticline that lies in the same direction as the Asmari formation. The Sarvak formation formed as a sequence of fine-grained white to gray limestone with calcite-filled joints, chalk, and marly limestone. The thickness of this formation is approximately 300 m and formed in the Cretaceous period.

The Dalan formation is representative of carbonate facies from the upper Permian sequences of the Zagros. The type section of this formation has a thickness of 630 m and is located in Surmeh Mountain. This type section has three members. The Lower Carbonate member contains dolomite, limestone, fine foraminifera-bearing dolomite, algae and, rarely, Fusulinida. The Nar evaporative member contains thick Eolithic, gypsum, and anhydrite-bearing layers. The Upper Carbonate member contains oolitic limestone at the bottom and micritic limestone and dolomite at the top. The age of the Dalan formation is Permian.

3. Petrological study

The thin sections prepared from these rocks (Fig. 1) showed that the main component of Asmari limestone is carbonate with miliolids, borealis, and foraminifera fossils and vuggy and intergranular porosity. The Sarvak limestone matrix is composed of 97% micrite ($CaCO_3$) and calcisphere fossils dominate. The samples show no porosity and display fractures filled with calcite cement. The rock texture is homogeneous and dense. Small amounts of autogenic pyrite is spread throughout the main texture of the rock in form of raspberry seeds. All rock in the Dalan formation is carbonated and the rock is primarily composed micritic limestone. Dolomitization has partially replaced the limestone

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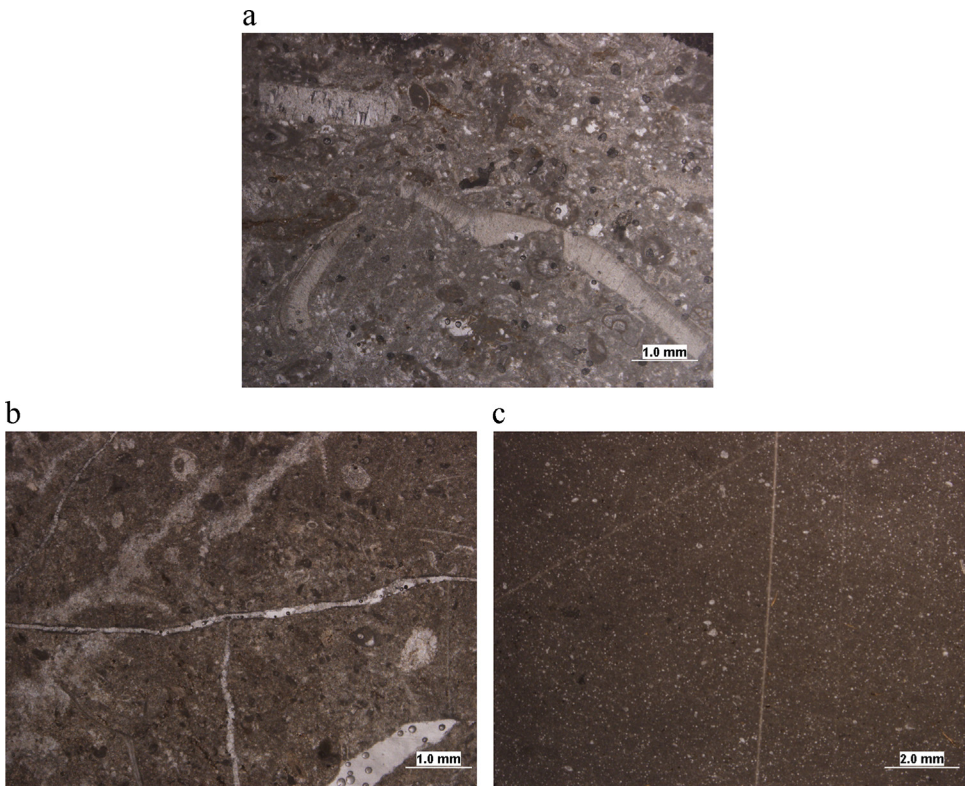

Fig. 1. Microscopic images of thin sections of rock samples: (a) Asmari formation; (b) Dalan formation; (c) Sarvak formation.

with dolomite. The porosity type is vuggy and mainly occurs in the dolomitized part of the rock. The remaining 1% of mineral content includes quartz and pyrite in the rock texture.

4. Materials and methods

4.1. Sample material

To evaluate rock tensile strength and the relationship between the values from different methods, three types of limestone were tested. These samples were selected from three formations of reservoir rock. The Asmari and Sarvak limestone was from Khuzestan province and the Dalan limestone was from Fars province. The petrophysical properties of dry density, porosity, void ratio, water absorption, carbonate content, and compressional wave velocity are presented in Table 1.

4.2. Sample preparation

Twenty samples were prepared for each type of limestone. To avoid discontinuity in the structure of the samples, the ten best samples of each formation were used. Hydraulic fracturing was carried out on all samples at different confining pressures. Each sample was 110 mm in height and 54.6 mm in diameter. The samples for the borehole test were 85 mm in length and 4 mm in diameter. The Young's modulus from the Asmari, Sarvak, and Dalan formations was 6.3, 13.3, and 4 GPa, respectively. Fig. 2 shows schematic and actual images of the core samples.

Table 1
Petrophysical properties of rock samples.

Formation (Location)	Rock type	ρ_d (gr/cm^3)	n%	e	w%	C%	V_p (m/s)
Asmari (Khuzestan)	Limestone	2.44	6.76	0.07	2.77	92.6	5526
Sarvak (Khuzestan)	Limestone	2.61	1.83	0.02	0.7	80.36	6153
Dalan (Fars)	Dolomitized Limestone	2.64	3.49	0.03	1.33	48.2	6104

$\rho_{d:}$ dry density, n: porosity, e: void ratio, w- water absorption, C: carbonate percent, Vp: compressional wave velocity.

4.3. Test set-up

A biaxial set-up at the Faculty of Basic Sciences of Tarbiat Modares University in Tehran was employed for the hydraulic fracturing test. This system comprised a biaxial cell, one inner pack hydraulic jack used to impose axial loading and one to inject fluid, and one pump to apply confining pressure to the sample. The sample and the upper and lower metal parts of the apparatus was fastened together using a neoprene membrane and two clamps, which was then placed in the triaxial cell. A pipe 20 mm in length and 4 mm in diameter was used to connect the sample to the upper part of the device. The neoprene sleeve prevented hydraulic fracturing fluid from penetrating the sample. The hydraulic fracturing fluid was oil-based with a viscosity of 85 cP. The axial hole was pressurized at a constant rate until a hydraulic fracture was observed at the breakdown pressure (P_c) point. A time-pressure plot of hydraulic fracturing test using oil on Sarvak sample is shown in Fig. 3.

4.4. Hydraulic fracturing test

Laboratory testing was used to accurately simulate hydraulic fracturing. Core material was used to simulate field conditions to achieve the best results. The sample was placed into the triaxial cell and confining and vertical pressure was applied. The samples were loaded at confining pressures of 0, 2.5, 5, 7.5, and 10 MPa. The vertical stress was 10% greater than the confining pressure. The hydraulic fracturing fluid was injected at a constant rate (1.1 ml/s) until a fracture appeared in the rock. The pressures and breakdown pressure were recorded using separate gauges. The peak injection pressure (P_i) corresponded to the