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Investigation of Compressive Strength of Shale Rock under Impact Loading

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Abstract – Static and dynamic uniaxial compressive strength of shale rock is studied in the present study. Shale rock is exposed to explosive loading/ impact loading during hydraulic fracturing. Which necessitate that strength of the shale rock under impact loading should be studied before performing hydraulic fracturing. For this purpose, outcrop shale rock from Khyber Pakhtunkhwa, Pakistan has been investigated under high strain-rates of order of 10^2 s^{-1}, using Split Hopkinson Pressure Bar (SHPB). Two specimens were cored out from a single sample of shale rock for dynamic testing and static testing. Static compressive strength 11.84 MPa, was investigated using Universal Testing Machine (UTM). Average dynamic compressive strength 38.83 MPa was observed during testing. The compressive strength increased 3.27 times that of the static compressive strength.

Key words – shale rock, impact loading, hydraulic fracturing, Split Hopkinson Pressure Bar.

I. INTRODUCTION

The ever-increasing need for sustainable energy is challenging Engineers and Scientists to continue their quest for energy resources. To support and sustain economic growth a country not only needs energy but continuous supply of energy. Pakistan is a developing country and need continuous and sustained energy supply more than ever for its economic growth. The conventional resources of Pakistan are depleting at a very rapid rate. To maintain the energy supply, exploring new energy resources including unconventional resources is the need of the hour. Pakistan has abundant of these unconventional resources. In the Survey [1] conducted by the Energy Information Administration (EIA), US estimated that Pakistan has potential of 105 tcfg of shale gas and 9 bb of shale oil. According to the report Pakistan is ranked 8th globally, with 9 bb of shale oil. The technology used to extract these resources is different from the one used for the conventional resources. Mechanical especially dynamic mechanical analysis, which is the focus of this study, and in-situ analysis of the geological formation (rock) are very necessary for successful and economic production oil and gas from these resources.

Properties of materials at dynamic or impact loading or high strain-rate are different from the static properties. In order to make sure that materials are safe and reliable under dynamic loadings, mechanical response of materials under these conditions should be accurately known. In our case, we want to break or fracture shale rock for a successful hydraulic fracturing. For this purpose, dynamic compressive properties of shale rock should be known accurately.

II. LITERATURE REVIEW

In late 70s researchers started investigating different properties of shale rock. Results of these investigations are less-accessible [2]. One of the investigations accessed [3] which reported shale rock`s mechanical properties. Test of low to intermediate strain rate ranging from 1.9×10^{-4} s^{-1} to 2.4×10^{-1} s^{-1} were performed on servo-controlled hydraulic ram and higher strain rate test up to about 10^3 s^{-1} were carried out using SHPB. By changing static confining pressure, organic content and strain rate, during the 98 samples testing, it was found out that fracture strength was affected more by strain rate compared to static confining pressure and organic content. As strain-rate increased from about 10^{-4} s^{-1} to 10^3 s^{-1}, the fracture strength increased almost three times the actual strength. In the study [2] twenty-one oil shale samples of different organic contents were tested for modulus of elasticity at strain-rates 10^{-4} s^{-1} to 10^1 s^{-1}. Young`s modulus for samples of 20% organic contents increased with increased from 3333 $MN/m^2$ at $10^{-4}$ $s^{-1}$ to 11316 $MN/m^2$ at $10^1$ $s^{-1}$. Oil shale cored from Colorado oil shale, U.S. were investigated by [4] for different strain-rates. elasticity and Poisson`s ratio of the shale was affected by strain-rate. The result showed that the two parameters depend on strain rate. For samples with organic content, both the parameters showed no dependence on strain rate of the order of about 10^{-3} s^{-1} and showed increase in the parameters for higher strain rates. In similar study, samples dried for 3 and 7 days and water saturated samples of oil shale obtained from New Albany oil shale, U.S. were tested at strain-rates 10^{-5} s^{-1} to 10^0 s^{-1} using servo-hydraulic loading system by [5] to find effect on Poisson`s ratio and Young`s modulus of the shale rock due to strain-rate. The study concluded that Poisson`s ratio is almost unaffected by strain-rate. On the other hand, Young`s moduli increased rapidly with increase in strain rate. Triaxial tests of two non-swelling outcrop shale under different strain-rates and pore and confining pressures were performed by [6]. The results showed that with high pore pressure, increasing strain-rate beyond 10^{-1} s^{-1} causes large increase in ductility and strength of the shale. In one of the recent study [7] reported the effect of strain rate of about 2×10^{-2} s^{-1}, on the fracture toughness and energy release rate of oil shale. Three-point bending method using notched semi-circular bending specimen of shale were used. Strength and stiffness were increased at high strain rate, which in turn increased fracture strength, and energy release rate. Another study [8] also reported increase in uniaxial compressive strength.

III. METHODOLOGY

A. Split Hopkinson Pressure Bar

Split Hopkinson Pressure bar (SHPB), also known as Kolsky bar is a tool widely used for the dynamic loading of brittle, soft and ductile materials at high strain-rates (10^2 to 10^4 s^{-1}). The original version this apparatus was capable only of compression testing. The improved version of the Kolsky bar can conduct compression, tensile, torsion and combined torsion/ axial loading tests under high strain rates [9].

In this research only the compression version was used. Consequently, procedure and theory are limited to the compression version of SHPB.

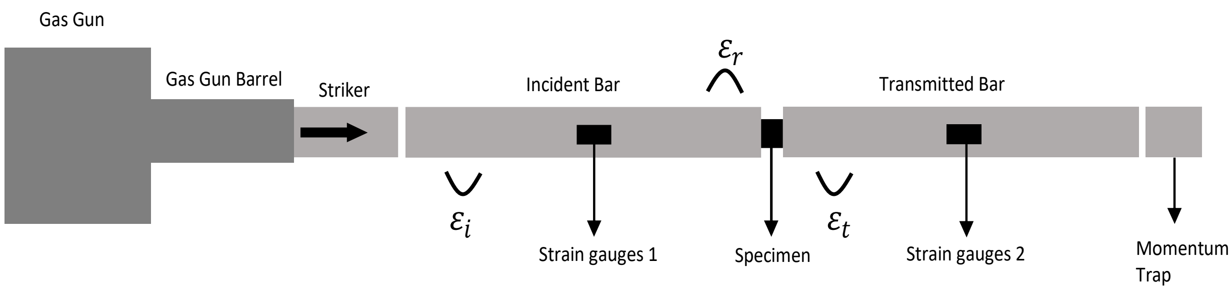

Figure 1: Schematic of Split Hopkinson Pressure Bar

B. Principle and Theory of SHPB

SHPB apparatus available in the Impact Research Lab Peshawar (IRLP), University of Engineering and Technology, Peshawar (UETP) consists of two main parts namely three bars and gas gun. The three bars are: Striker, Incident and Transmitted bars. **Erreur ! Source du renvoi introuvable.** shows the SHPB setup in the IRLP. When the gas gun is charged and released it pushes the striker bar coaxial at incident bar. An elastic compressive pulse is generated in incident-bar. When the stress pulse reaches mid span of the bar, strain gauges on the bar records the magnitude of the compressive strain pulse denoted by $\varepsilon_i(t)$. At the interface of specimen-incident bar, part of the pulse reflects in the incident bar, denoted by $\varepsilon_r(t)$. The other part of the pulse propagates through the specimen to the transmitted bar, denoted by $\varepsilon_t(t)$.

Two assumptions provide the working principle for SHPB — (a) 1D wave propagation in bars and (b) homogeneous deformation of specimen and bars [10]. The mathematical equations for the SHPB are based on purely elastic behavior of the bars. In order to satisfy this condition, the strength of the bars should be much higher than the stress in the bars upon the impact of the striker bar. In the current setup the bars material is AISI 4340, Young`s modulus is E=210 GPa, which satisfy this condition.

The stain time histories in the bars are detected by the corresponding strain gauges. These histories are then used to calculate stress σ(t), strain ε(t) and strain-rate $\dot{\varepsilon}(t)$ in the specimen using the following three equations.

$$\sigma(t) = \frac{A_b}{A_s} E\varepsilon_t \ldots(1)$$

$$\dot{\varepsilon}(t) = \frac{2C}{L_s}\varepsilon_r \ldots(2)$$

$$\varepsilon(t) = \frac{2C}{L_s}\int_0^t \varepsilon_r(t)\, dt \ldots(3)$$

σ (t) = stress in the specimen

ε (t) = strain in the specimen

$\dot{\varepsilon}(t)$ = strain-rate in specimen

C = speed of wave in bar

E = modulus of elasticity of bar materials

A_s = cross sectional area of specimen

A_b = cross sectional area of bar

L_s = length of specimen

Table 1: Dimensions of bars of the SHPB

S.NO	Bar		Length	Unit
1	Striker bar	L_s	600	mm
2	Incident bar	L_i	1828	mm
3	Transmitted bar	L_t	1828	mm
4	Diameter	D	20.75	mm

Figure 2: Experimental setup available UETP

C. *Pulse Shaping*

Pulse shaping technique is used to in SHPB for brittle material testing. A disc of pure copper is pasted on impact surface of bar (incident) for pulse shaping in order to achieve dynamic-stress-equilibrium in the rock specimen. Diameter of the shaper is 8 mm and thickness is 1.7 mm. Dimension were chosen according to the criterion given in [11].

D. *Sample Preparation*

For this research outcrop shale rock was obtained from Chichali formation (Mesozoic geologic formation) located at Sheikh Badin station Khyber Pakhtunkhwa (KP), Pakistan.

The dimensions of the specimen were chosen according to the standards given by Gray George in "Classic Split Hopkinson Pressure Bar Testing" [12]. The slenderness ratio (length to diameter) of 0.5 was chosen. The diameter of the specimen 18 mm is slightly smaller than the diameter of the bars 20.75 mm, to reduce the effect of dispersion of pulse. *Table 2* gives the dimensions of the specimen used in this study.

Table 2: Dimensions of the specimen

Diameter	19 mm
Length	9.5 mm

Figure 3: Test Specimens

IV. RESULTS

Static strength of the shale rock was 11.94 MPa. Universal testing machine (UTM) was used for the static testing.

Two specimens extracted from same rock were tested under different strain-rate conditions. Different strain-rate can be obtained by changing one of the two parameters, striker bar length and striker bar velocity. In this study different strain-rate were obtained by changing the gas gun pressure which ultimately changes the striker bar velocity. Striker bar of the same length is used for all the experiments. Size of the specimen is also same for all the tests, which is, length, L= 9.5 mm and diameter, D=19 mm.

Table 3: Results of the two tests on Split Hopkinson Pressure Bar

S.NO	**Specimen No.**	**Striker Bar Length (mm)**	**L/D (mm/mm)**	**Ave. Strain-Rate (s^{-1})**	**Peak Stress (MPa)**	**Strain at Peak Stress (mm/mm)**
1	KP01	600	0.5	406.8	39.31	0.0952
2	KP02	600	0.5	630.4	38.36	0.0842

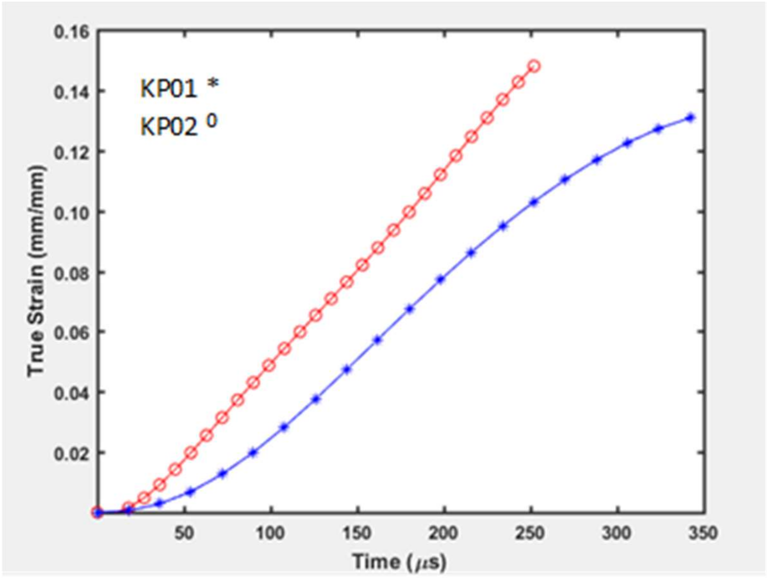

Figure 4: True strain in the specimen vs time

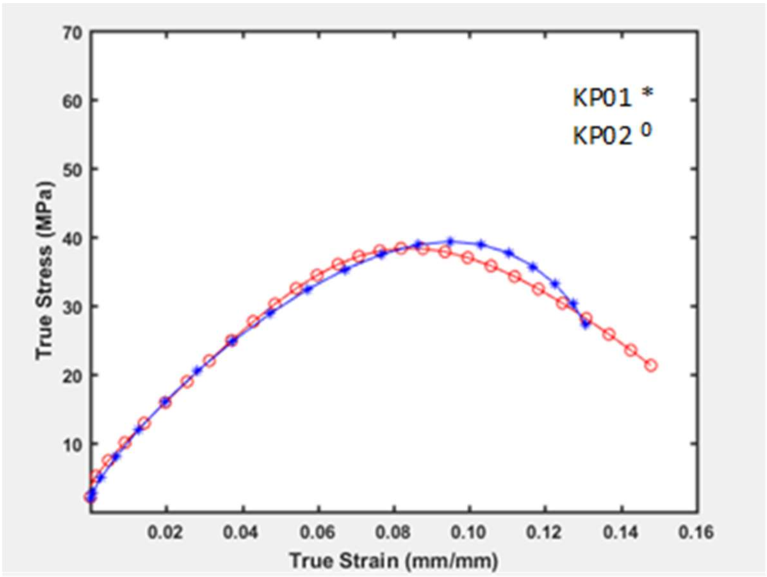

Figure 5: true stress vs true strain in the specimen

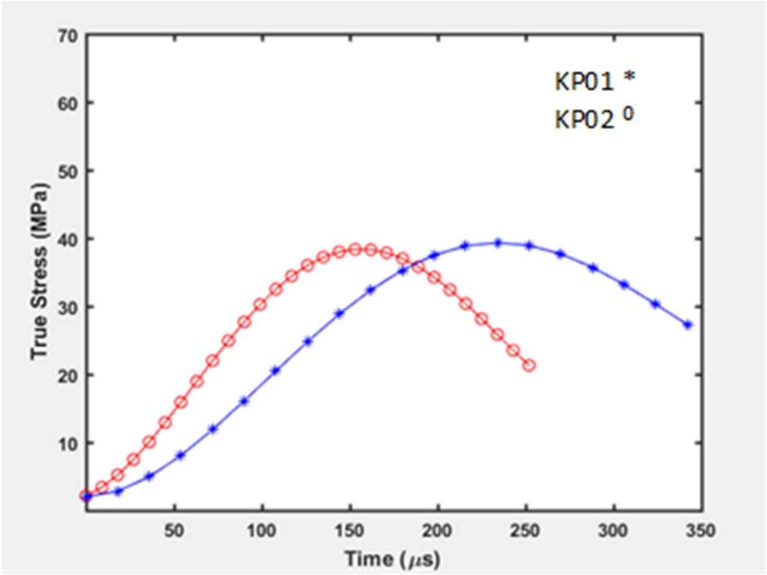

Figure 6: True stress vs time in the specimen

The peak stress in the specimen KP01 is 39.31 MPa at the strain-rate 406.8 s^{-1}. Strain at this peak stress is 0.0952 (mm/mm). The peak stress in the specimen KP02 is 39.31 MPa at the strain-rate 630 s^{-1}. Strain at this peak stress is 0.0842 (mm/mm). At peak stress both the specimen completely breaks down.

V. Conclusion

The shale rock under uniaxial dynamic compressive tests, showed an increase in compressive strength, 38.83 MPa as compared to the static compressive strength, 11.94 MPa was observed. It illustrates that compressive strength of the shale rock increases at high strain-rates as compared to static loading.

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