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Shock Tube based Study on Damage Prediction of Soft Rocks

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Abstract

The principal objective of this paper is to develop a controlled laboratory test for predicting the damage of soft rocks when exposed to blast or shock waves. Shock tube experiment is proposed to generate shock/blast waves that are strong enough to create fracture in soft rocks by release of tremendous amount of energy over a small duration of time. Plaster of Paris is used as test sample in this study, as a substitute for soft rocks. The evaluation of damage is based on the energy absorbed by the sample on exposing to the incoming shock waves. The critical energy is the measure, where the sample resistance is surpassed and the absorbed energy is released in the form of crack or fracture. The incident, transmitted (absorbed) and residual energy is evaluated based on the principles of gas dynamics and global mass, momentum and energy conservation equations. The rate of loading is varied by producing shock waves of different Mach number (strength). It is observed that energy absorbed by the sample varies linearly with impulse imparted.

Keywords: Shock Tube, Blast Wave, Absorbed Energy, Brittle Fracture.

1. Introduction

Accurate prediction of the blast induced damage has always been a concern for a geotechnical engineer in the purview of drilling and blasting. For over a century, until today, the most common method of testing involves field test with explosives, which is highly sophisticated and delimited. Numerous analytical expressions and numerical studies (Zheming et al., 2008; Zu et al., 2007; Babanouri, 2013) have also been reported in the past decade. However, very few laboratory studies have succeeded in predicting the blast induced damage.

The dynamic behavior of materials is widely studied using shock tube. Many researchers are used shock tube to generate shock waves to study the impulsive behavior of materials. Ben-Dor (1970) studied the reflected and transmitted pressure pulse through weak granular layer using a shock tube. Toutlemonde et al. (1995) performed experimental studies on concrete by generating high loading rates using a shock tube. Kazemi-Kamyab (2011) studied the attenuation of shock wave through porous aluminum materials.

It is very difficult to evaluate the energy absorbed during a real blasting event. Wang and Shukla (2010) succeeded in evaluating the energy and impulse generated in a blast waves within a shock tube, and they developed an analytical equation to determine the energy absorption by the metal panel plate and validated with experimental observations. Detailed steps to calculate the energy and impulse during a shock tube test is described in Wang and Shukla (2010).

This paper aims at predicting the threshold energy limit for a rock sample during a blast loading. The blast load is generated using shock tube (Kleinschmit NN, 2011) which is similar to Friedlander wave. This blast wave profile matches the conditions created by the explosive and is generated in the laboratory under controlled and repeatable conditions. The rock sample considered in the present study is brittle in nature and is assumed to be under no confinement zones (i.e. surface rock formation). In this experiment, researchers have an opportunity to observe the impact that shock waves can have on small scale soft rock sample. When a blast wave from a shock tube impinges onto the rock sample, part of the energy gets absorbed the sample and rest of it get reflected as shock wave. When this absorbed energy reaches a threshold value in the rock sample, the specimen is expected to abruptly fail. This critical energy or threshold energy is the measure where the sample resistance is surpassed and the excessive absorbed energy is released in the form of brittle fracture. Having the knowledge of this threshold energy level for a particular rock samples will increase the efficiency of mining during surface blasting and also, help in designing blast resistant structures like bunkers and tunnels.

2. Theory

Energy evaluation on rock sample is made using the planar shock wave generated by the shock tube. Wang and Shukla (2010) developed the theory for determining the energy loss taking place during the impact of shock wave on a flat panel. The theory and the method to determine energy and Impulse is briefly described below [for detail derivation refer section 2.1of Wang and Shukla (2010)].

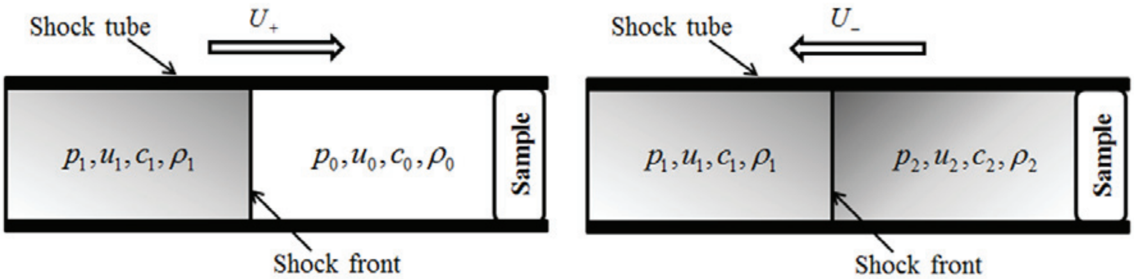

Fig. 1. Incident and reflected shock parameters (Wang and Shukla, 2010)

Two shock waves are considered in the process, the incident shock wave and reflected shock wave as shown in Fig.1. The energy of the shock wave is stored in the gas and it is divided into three parts: the internal energy, the translational energy and the work done by the gas in the shock tube.

During small elemental time dt, the internal energy of the gas (dE(I)), the translational energy(dE(T)), and the work done by the gas (dE(W)) is described below (Wang and Shukla, 2010).

$$dE(I) = \frac{p * A * |u(t)|}{\gamma - 1} dt \tag{1}$$

$$dE(T) = \frac{1}{2} * (\rho(t) * A * |u(t)|) * |u(t)^2| dt \tag{2}$$

$$dE(W) = p * A * |u(t)|) dt \tag{3}$$

Where, p is the pressure profile recorded, A is the cross section area of the shock tube, $\rho(t)$ is the density, u(t) is the particle velocity, c is the sound velocity and γ is the adiabatic exponent of gas. From the equation (1) to (3), gas density $\rho(t)$ and particle velocity u(t) are unknown and these are calculated using theory of gas dynamics and modified Hugoniot relations.

$$\text{Conservation of mass,} \quad \rho_0 v_0 = \rho_1 v_1 \tag{4}$$

$$\text{Conservation of momentum,} \quad \rho_0 v_o^2 + p_0 = \rho_1 v_1^2 + p_1 \tag{5}$$

$$\text{Conservation of energy,} \quad \frac{1}{2} v_o^2 + e_0 + p_0 \tau_0 = \frac{1}{2} v_1^2 + e_1 + p_0 \tau_1 \tag{6}$$

Where, e and τ are specific internal energy and specific volume. Through the jump conditions (4)-(6), two modified Rankine-Hugoniot relations are derived (section 2.1, Wang and Shukla, 2010).

$$\frac{p_1}{p_0} = (1+\left(\frac{\gamma-1}{\gamma+1}\right)^2)*M_0^2 - \left(\frac{\gamma-1}{\gamma+1}\right)^2 \quad (7a)$$

$$\frac{p_0}{p_1} = (1+\left(\frac{\gamma-1}{\gamma+1}\right)^2)*M_1^2 - \left(\frac{\gamma-1}{\gamma+1}\right)^2 \quad (7b)$$

$$(1-\left(\frac{\gamma-1}{\gamma+1}\right)^2)(U_+ - u_0)^2 - (u_1 - u_0)(U_+ - u_0) = (1+\left(\frac{\gamma-1}{\gamma+1}\right)^2)c_0^2 \quad (8a)$$

$$(1-\left(\frac{\gamma-1}{\gamma+1}\right)^2)(U_+ - u_1)^2 - (u_0 - u_1)(U_+ - u_1) = (1+\left(\frac{\gamma-1}{\gamma+1}\right)^2)c_1^2 \quad (8b)$$

Where, M is Mach number, $M_1 = \frac{|u_1 - U_+|}{c_1}$ and $M_0 = \frac{|u_0 - U_+|}{c_0}$.

Where, U_+ and U_- are velocities of incident and reflected shock wave.

For, the reflected process, the subscript are changed from 0 to 1 and subscript from 1 to 2 and direction changes right to left, hence subscript + to -. There are 15 parameters in the above equation, $p_0, p_1, p_2, u_0, u_1, u_2, c_0, c_1, c_2, \rho_0, \rho_1, \rho_2, U_+, U_- and \gamma$ of which $p_0, p_1, p_2, u_0, c_0, \rho_0, U_+, U_- and \gamma$ are known or can be measured. The rest of the 6 unknown parameters are determined using the above set of incident equation and reflected equation. Substituting the parameters in equation (1) to (3) and replacing it in the following equation, the energy is obtained.

$$E(incident) = \int \left[dE(I)incident + dE(T)incident + dE(W)incident\right] \quad (9)$$

$$E(remaining) = \int \left[dE(I)remaining + dE(T)remaining + dE(W)remaining\right] \quad (10)$$

The difference between equation (9) and (10) gives the energy loss (or energy absorbed).

3. Experimental Investigation

3.1 Sample Preparation

Laboratory tests were conducted on cylindrical specimen made of plaster of Paris (PoP) of 100mm in diameter and 200mm in height. PoP was selected as a model material because of the ease of casting, flexibility, quick hardening and low cost (Sitharam et al., 2010). PoP is a product generated when gypsum is heated between 120^0C to 160^0C and it is commercially available in the powder form. Plaster of Paris, scientifically known as calcium sulphate hemi-hydrate, is used here as sample material for soft rocks.

The intrinsic behavior of PoP is brittle in nature with a high value of porosity. When powdered Plaster of Paris is mixed with water, a reverse exothermic reaction takes places leaving coherent solid mass. In the present study, the 71% of water by weight of the dry PoP powder is used to prepare a cylindrical sample with porosity of 40%. The physical and engineering properties of the PoP sample are listed in the Table 1.

Table 1. The physical and engineering properties of the plaster of Paris sample.

Parameter	Dimension	Quantity
Density, ρ	kg/m^3	933
Uniaxial Compressive Strength	MPa	2.2
Tensile Strength, σ_t	MPa	0.3
Young's Modulus, E_t	GPa	0.3
Porosity, φ	%	40
Fracture Toughness, K_{IC}	$MPa\_m^{1/2}$	0.12

3.2 Experimental Setup

Shock tube is used to generate controllable planar shock waves with repeatability. The shock tube consists of a long tube, separated into driver section and driven section by a metal diaphragm. The driver section of the shock tube is filled with high pressure driver gas (either Nitrogen, or air or helium) from a high pressure cylinder, the diaphragm ruptures suddenly creating a planar shock wave travelling into the driven section. Shock wave of desired strength can be created either by varying the thickness of the metal diaphragm or by choosing a lighter driver gas. In the present case, helium is used as driver gas and the driven section is filled with atmospheric air at one atmosphere pressure. The shock tube used in the present study has a driver length of 3.5m, while the driven section is 9m in length and the internal diameter of shock tube is 100mm. Schematic diagram of the shock tube is shown in Fig.2 and photograph of assembled shock tube is shown in Fig. 3.

Fig. 2. A schematic diagram of the horizontal shock tube.

The speed of the shock wave developed inside the driven section and the pressure profile are measured using two piezoelectric pressure gauges P1 and P2 mounted 100 mm apart and toward the end portion of the driven section, sensor P3 is mounted to measure the end-on signals.

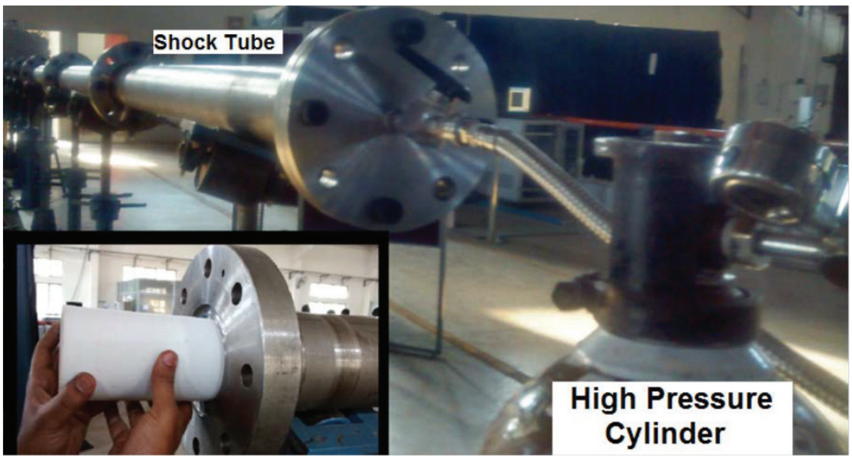

Fig. 3. Photograph of shock tube taken from the driver end which is connected to a high pressure cylinder. (Inset Image: PoP sample is being mounted at end of driven section)

In order to generate a blast wave (Friedlander wave), the shock tube is modified by reducing the driver section to 2m. By using helium as the driver gas, rupturing aluminum diaphragm, the shock waves are generated in the driven section, simultaneously expansion waves gets generated in the driver section. These reflected expansion waves from the end of the driver section tries to catch up with the shock front and decays the overpressure exponentially to form a positive phase of Friedlander wave. The PoP sample is placed in the driven section as shown in Fig. 3, such that sample face is just in front of sensor P2. This blast wave profile generated using a shock tube is considered to replicate the actual blast loading effect of an explosive. The blast wave generated produces a peak over pressure of 34.6 bar and the positive phase duration of 1.5 ms with the shock front velocity of 1020 m/s. Fig. 4 shows a blast wave generated using helium as the driver gas with an impulse of 13.72 N-s.

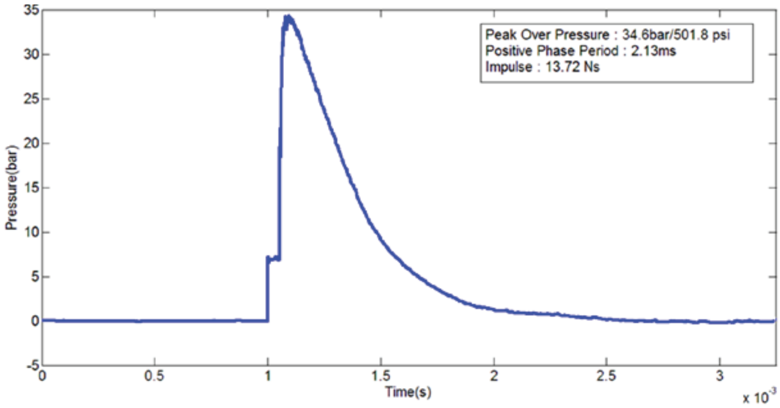

Fig. 4. A Positive phase blast wave profile generated using horizontal shock tube.

The cylindrical PoP sample is mounted at the open end of the driven section facing the incoming shock wave. The PoP sample is shock tested with varying Impulse. At the end of each test, the pressure signals are recorded and the sample is examined for any visible cracks and if not the test is performed with higher impulse rate. The present study will account only the visible or macro level damage and micro level damages or cracks which develop during shock interaction are not considered.

4. Results and Discussions

The Incident shock wave is travelling in the driven section, passing through sensor P1 and sensor P2, on receiving the shock wave sensor P1 shows a jump in the profile and the pressure remains constant until a second jump is seen, due to the presence of reflected shock wave. The reflected shock wave is generated once the incident shock wave is impinged onto the surface of the sample. Meanwhile, the reflected expansion wave from the driver section will catch up with the reflected shock wave to decay the peak over pressure to form a blast wave.

In order to evaluate the Incident and reflected energy, as mentioned by Wang and Shukla (2010) the reflected pressure profile overlaps on the incident pressure profile and hence incident pressure profile can be taken only from first jump to second jump, while the reflected pressure profile can be considered from the second jump onwards. Since the time period between first and second jump is very less and in order to increase the time span, incident pressure profile is acquired by performing a shock tube test with open driven section (without the sample and without end-on flange) and hence avoiding the formation of reflected shock wave and increasing the time duration for energy evaluation.

The incident Mach number is determined by taking the ratio of the distance between the two sensors P1 and P2 to the time period measured between two initial jumps recorded by P1 and P2 respectively. The reflected pressure profile is recorded by placing the sample at the end of the driven section. Fig. 5 shows the acquired incident and reflected pressure profile with the sample. Fig. 6 shows the modified incident and reflected profile of sensor 2, such that no overlapping of the reflected shock wave is allowed.

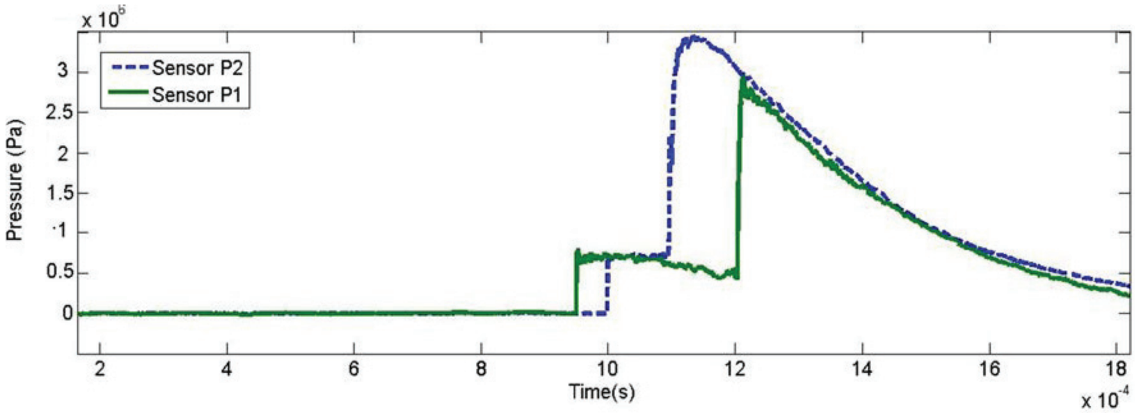

Fig. 5. Pressure profile from P1 and P2 transducer.

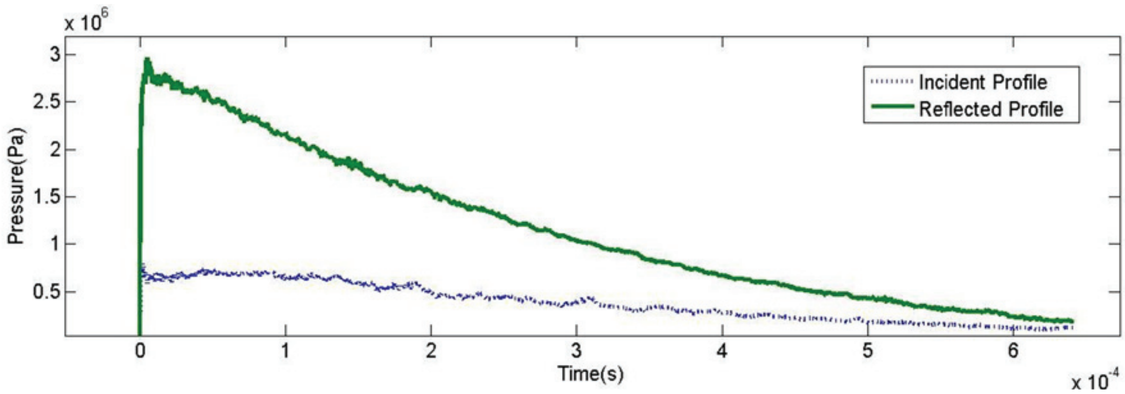

Fig. 6. Incident and reflected pressure profile from sensor P2

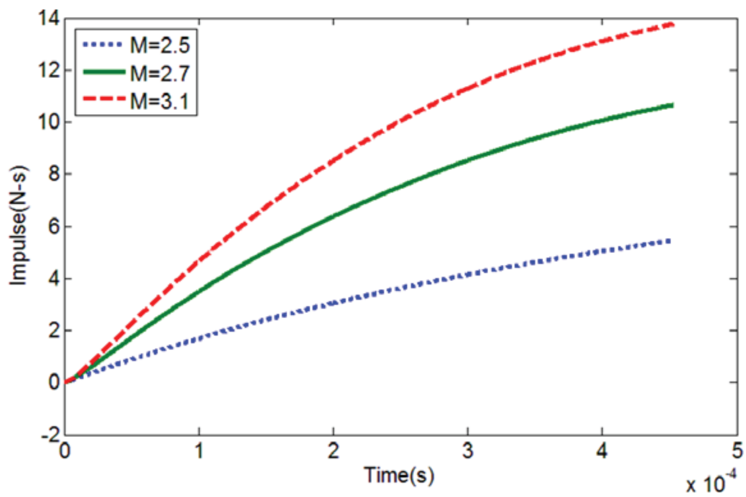

Fig. 7. Impulse generated for various incident Mach numbers

In the event of incident shock wave striking the sample, part of the energy is absorbed by the sample and letting the rest of energy to flow in the form of reflected shock wave. Therefore, the incident energy minus the reflected energy gives the energy absorbed the sample, the energy lost in the form of sound and heat energy is not considered in the present study.

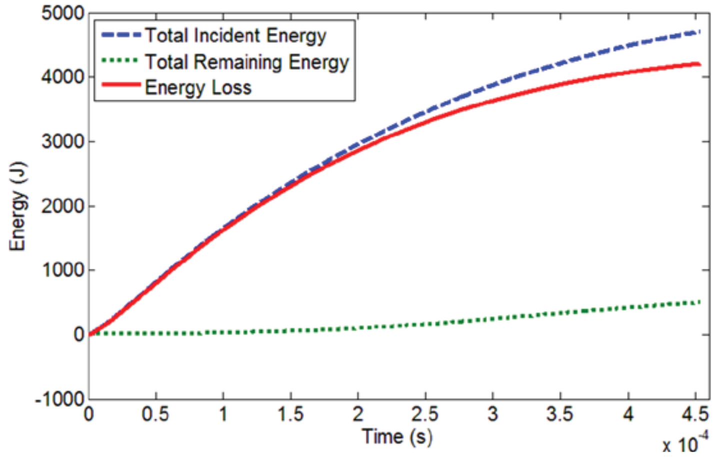

Fig. 8. Energy evaluation during a shock tube test on a PoP sample

The impulse is calculated by measuring the area under the pressure-time curve, times the cross section area of the shock tube. The impulse generated onto the sample of the three shots with varying Mach number of 2.5, 2.7 and 3.1 is shown in Fig.7. The test was performed with varying impulse of 5.8N-s, 11N-s and 14 N-s. The total incident, reflected energy and energy loss (absorbed energy) is calculated based on the equation mentioned in section 2. Fig. 8 shows the test results for a shot 2 having incident Mach number of 2.7 with an impulse of 10 N-s, the maximum energy absorbed by the sample is observed to be 4kJ and no visible damage was observed. With higher incident Mach number of 3.1 with an impulse of 14 N-s, the PoP sample was observed with visible cracks (Fig. 10), the damage could have occurred when the absorbed energy was anywhere between 4kJ to 5.8 kJ. Fig. 9 shows the variation of the absorbed energy with various incident Mach numbers.

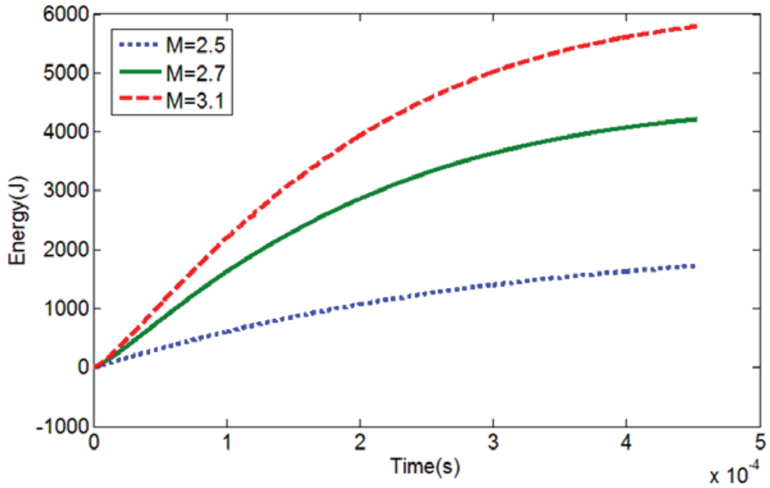

Fig. 9. Energy absorbed by the PoP sample for various incident Mach numbers

The energy loss shown in Fig. 8 and the increase in energy loss observed in the Fig. 9, is due to formation of micro internal cracks. The pores and natural fissures present in the sample, absorbs the energy to a threshold limit and on further increase in the energy, the micro cracks starts expanding and/or collapsing and finally the sample fail by developing a major visible crack. This study accounts only for the final stage damage and not considering the prediction of micro damage. Further, attempts are being made to evaluate the micro damage involved using x-ray tomography.

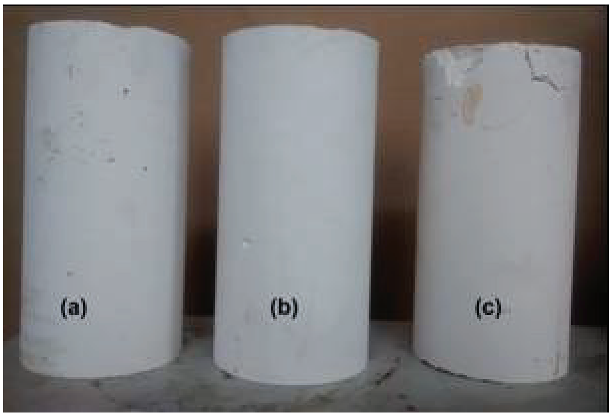

Fig. 9. Plaster of Paris tested sample (a) shot 1: Impulse = 5.8N-s
(b) shot 2: Impulse = 11 N-s (c) shot 3: Impulse = 14 N-s

5. Summary and Conclusions

The damage evolved in brittle soft rock due to blast loading is determined based on the energy method in a controlled environment. Shock tube is used to generate blast waves, of peak over pressure of 30 to 40 bars over a period of 2-3 ms .The energy levels before and after imparting to the sample is determined indirectly based on the established analytical expression. A shock wave of specific incident Mach number produces an impulse of certain magnitude. The plaster of Paris sample is imparted with the blast waves and simultaneous energy evaluations are performed from the recorded pressure data. Further, sample is examined for any visible cracks or fracture.

The plaster of Paris sample was imparted with three shots, having peak pressure of 25 bar, 34 bar and 38 bar generating impulse of 5.8 N-s, 11 N-s and 14 N-s respectively. It is observed that, as the incident Mach number of the shock wave is increased, the impulse rate and the absorbed energy level also increases. The absorbed energy increases to a level, where the sample can't further accommodate and gets released in the form of crack or fracture. The PoP sample started to develop cracks at shot 3 with the absorbed energy of 5.8kJ. The PoP sample is expected to have a fracture energy range in between 4kJ and 5.8kJ. This study is an approximate method of predicting the damage and further requires additional research by considering the energy loss involved in the form of heat and sound. However, this method aid in predicting the fracture energy instantly without much sophisticated instrumentation.

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