DEVELOPING AN EMPIRICAL RELATIONSHIP TO PREDICT THE FRACTURE LENGTH IN HYDRO FRACTURING PROCESS

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ABSTRACT

When mechanically induced progressive failure of rock and the associated changes in hydro fracturing process, it is difficult to track the dynamic evolution of fractures beneath the earth. To overcome this, recent developments in hydro-fracturing technique have tended to follow hybrid approaches. An attempt was made to develop an empirical relationship to predict the Fracture length in millimeters of Hydro fracturing process using RSM technique. Three factors and a central composite design were used to minimize the number of experimental conditions. Response surface method was used to develop their relationship. The developed relationship can be effectively used to predict the Fracture length as a mechanical property in Hydro fracturing process at 95% confidence level whereby the most pertinent aspects of each of the continuum and discrete approaches are combined.

KEYWORDS: *Hydromechanical, Hydrofraturing, RSM technique, Fracture length.*

I. INTRODUCTION

The analysis of the hydro-mechanical behavior of rock masses remains an important topic in rock mechanics, due to it being a critical phenomenon in ongoing challenging issues such as tunneling under high groundwater pressures, extraction of hydrocarbons from deep, pressurized petroleum reservoirs, and underground nuclear waste disposal. Despite continuing and extensive efforts, such analysis continues to be difficult. Hydro-mechanical response in a rock mass is identified as the interaction between the solid phase of the rock materials and any interstitial fluid [1]. This technique involves pumping a fluid under pressure into a borehole. This pressurized fluid introduced into the borehole produces stress concentration in the surrounding rock causing the development of fractures due to micro mechanical effects [2]. Because of the heterogeneity of the material properties, rock structure and in situ stress state, the hydraulic fracturing process is highly complex [3]. A common difficulty in the hydraulic fracturing process in the real time is in observation and measurement of the fractures that develop beneath of the earth. Generally, the induced fracture geometry is measured by cutting the sample after the test [4] [5] [6] or by using an acoustic monitoring system [7] [8].
This method gives valuable results but limitations are there. The final results are observed by cutting the samples after the test. The resolution of the acoustic method is currently insufficient to capture details of the fracture propagation process. As a result, laboratory experiments on hydraulic fracturing in transparent materials have also been performed. These studies allowed the visualization in real time of the developing geometry of the fracture [9] [10] and the direction of fracture propagation [11] [12] [13]. Commonly used transparent geometrical analogues for fracturing are poly methyl methacrylate (PMMA, acrylic) [14] [15].

In brief, the Fracture behavior is hard to predict because the relationship between stress and permeability is complex and it is occurred beneath of the earth. An experimental set up was established to study the fracture propagation by applying the process parameters like pressure, temperature and injection hole diameter. The resulting fractures can be used to analysis the basis of hydraulic fracture propagation in real time field applications. In this Research paper, the developed empirical relationship can be effectively used to predict the Fracture length in millimeters of Hydro fracturing process.

II. PRINCIPLE OF FRACTURE PROPAGATION

The Hydrofraturing process works on the principle of Pascal's law or the principle of transmission of fluid-pressure. It is a principle in fluid mechanics that states that pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid such that the pressure ratio remains the same and stated mathematically as

$$\Delta P = \rho g\,(\Delta h) \qquad (1)$$

Where, ΔP is thehydrostatic pressure, ρ is the fluid density, g is acceleration due to gravity and Δh is the height of fluid above the point of measurement. Therefore Pascal's law can be interpreted that any change in pressure applied at any given point of the fluid is transmitted undiminished throughout the fluid. The hydrofraturing technique works on the principle of Pascal's law, the injected fluid follows the least resistance paths and therefore the initiations of fractures or opening of the fractures takes place in the weathered zone. Hence, this application of hydraulic fracturing have been recently found in geo technical engineering for ground reinforcement and in environmental engineering for solid waste and nuclear waste disposal and geo thermal engineering shown in figure 1. [16]

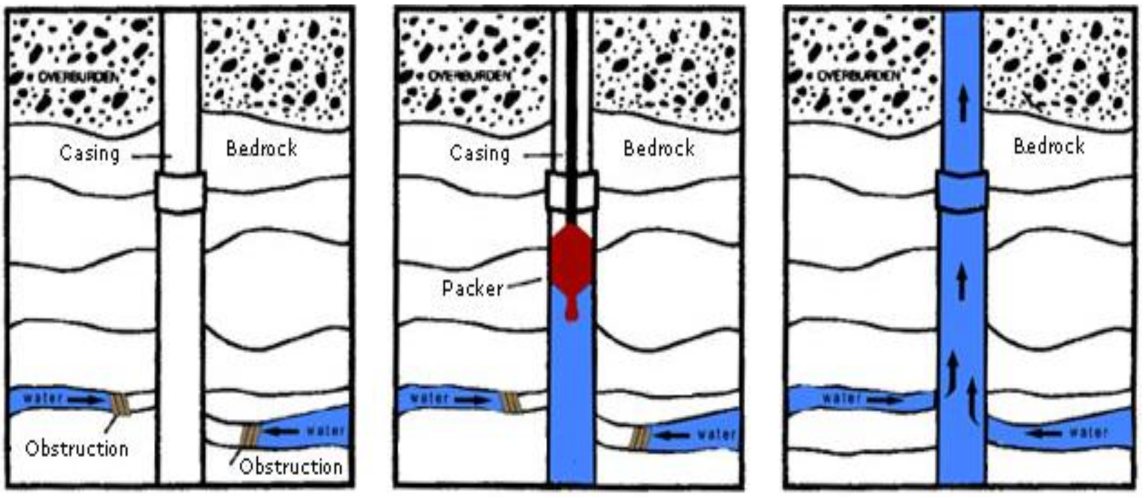


Figure 1. Process of before and after hydrofraturing

III. EXPERIMENTAL WORK

3.1. Fabricating the Experimental set up

The experimental set up in figure 2 consists of a container for storing the fluid, a commercially available feed pump to feed pressurized fluid to the inner casing pipe provided in the PMMA test sample. The 20 nos. of PMMA test samples were prepared for the test. The PMMA test sample has a length of 300mm and outside diameter of 150mm. The inner casing pipe made up of stain less steel and inner diameter was 6 to 10 mm. The applied pressure can be varied manually by adjusting the two control valves provided in the experimental setup in the range of 4 to 8 $N/mm^{2.}$ Before starting the experiment, the required pressure applied in to casing pipe is to be ensured by adjusting the flow control valves. A separate by pass line is provided in the experimental setup for achieving the required pressure for the same. A 555 timer IC is provided for feed pump to control the pressurized fluid rate with respect to the time, say 5 sec to 15 mins. The PMMA test sample is placed over the heater for heating purpose in the range of 40 to 60ºC. The heater control unit is made up of Nichrome heater having a capacity of 400W. The Dimmersat is 0-2A, Single phase, open type and it is provided for varying the input to the heater and measurement of input is carried out by a voltmeter, ammeter. The Voltmeter – Digital range is 0 to 200V AC, The Ammeter digital range is 0 to 2A AC, The temperature indicator is digital 0 to 199.9ºC. The electrical supply for the experimental setup is AC single phase, 230V earthed stabilized current. By varying the Dimmerstat, adjust the heat input at desired value for desired temperature on the PMMA sample. The commercially available thermocouples are embedded to the PMMA test sample for temperature measurement through a temperature gauge. The experimental table and Stand made up of MS square hollow pipe and angle. The pressure applied in the range of 4 to 8 N/mm^2 to the casing pipe, the temperature range for the study is 40ºC to 60ºC and the casing pipe diameter is 6mm to 10mm. [17]

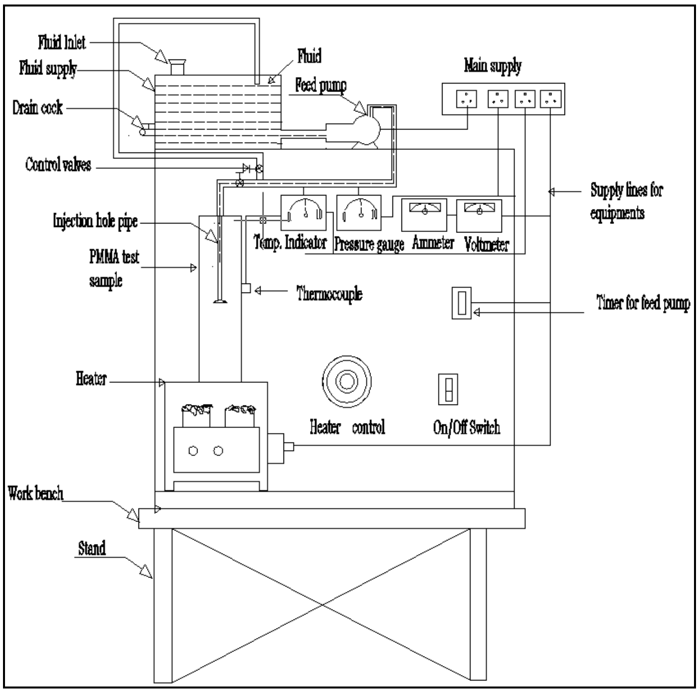


Figure 2. Experimental set up for Hydrofraturing process

3.2 Finding the limits of the Experiments test parameters

From the literature, the predominant factors that have a greater influence on the Fracture rate of Hydro fracturing process had been identified. They were: (i) Pressure applied in N/mm^2 (ii) Temperature in ºC (iii) Injection hole diameter in mm. Large numbers of trial experiments were conducted to identify the feasible testing conditions for obtaining the Fracture length of Hydro fracturing process. The following inferences were obtained:

1. Based on the field trials the pressure applied is limited to 4 to 8 N/mm^2 .
2. From the literature survey, the temperature and the injection hole diameter is limited to the range of 40 to 60 ºC and 6 to 10 mm respectively.
3. Further the Maximum with stand temperature of the PMMA samples is to be
Less than 100ºC, hence the temperature range is fixed to 40 to 60 ºC only. [18]

IV. DEVELOPING THE EXPERIMENTAL DESIGN MATRIX

Owing to a wide range of factors, the use of three factors and a central composite rotatable design matrix were chosen to minimize the number of experiments. A design matrix consisting of 20 sets of coded conditions (comprising a full replication three factorial of 8 points, six corner points and six center points) was chosen in this investigation. Table 1 represents the range of factors considered, and Table 2 shows the 20 sets of coded and actual values used to conduct the experiments.

Table 1. Important factors and their levels.

S. No	Factor	Unit	Notation	Levels				
				-1.682	-1	0	+1	+1.682
1	Pressure applied	N/mm^2	A	4.0	5.0	6.0	7.0	8.0
2	Temperature	ºC	B	40.0	45.0	50.0	55.0	60.0
3	Injection hole Diameter	mm	C	6.0	7.0	8.0	9.0	10.0

Table 2. Design matrix and Experimental results

Ex. No	Coded values			Actual Values			Fracture length (mm)
	Pressure applied (A)	Temperature (B)	Injection hole diameter (C)	Pressure applied (A)	Temperature (B)	Injection hole diameter (C)	
1	-1	-1	-1	5.00	45.00	7.00	210
2	+1	-1	-1	7.00	45.00	7.00	250
3	-1	+1	-1	5.00	55.00	7.00	200
4	+1	+1	-1	7.00	55.00	7.00	400
5	-1	-1	+1	5.00	45.00	9.00	240
6	+1	-1	+1	7.00	45.00	9.00	350
7	-1	+1	+1	5.00	55.00	9.00	360
8	+1	+1	+1	7.00	55.00	9.00	580
9	-1.682	0	0	4.32	50.00	8.00	220
10	+1.682	0	0	7.68	50.00	8.00	460
11	0	-1.682	0	6.00	41.59	8.00	210
12	0	+1.682	0	6.00	58.41	8.00	410
13	0	0	-1.682	6.00	50.00	6.32	260
14	0	0	+1.682	6.00	50.00	9.68	420
15	0	0	0	6.00	50.00	8.00	390
16	0	0	0	6.00	50.00	8.00	420
17	0	0	0	6.00	50.00	8.00	420
18	0	0	0	6.00	50.00	8.00	350
19	0	0	0	6.00	50.00	8.00	430
20	0	0	0	6.00	50.00	8.00	330

For the convenience of recording and processing experimental data, the upper and lower levels of the factors were coded here as +1.682 and -1.682 respectively. The coded values of any intermediate value could be calculated using the following relationship.

$$Xi = 1{:}682[(2X - (Xmax - Xmin)] / [Xmax - Xmin] \quad (2)$$

Where Xi is the required coded value of a variable X and X is any value of the variable from Xmin to Xmax, Xmin is the lower level of the variable, Xmax is the upper level of the variable.

4.1 Developing an empirical relationship

In the present investigation, to correlate experimental test parameters and the Fracture length in Hydrofraturing process, a second order quadratic model was developed. The response (Fracture length) is a function of pressure applied in N/mm^2 (A), Temperature in ºC (B) and Injection hole diameter in mm (C) and it could be expressed as,

$$\text{Fracture length (FL)} = f\{A,B,C) \qquad (3)$$

The empirical relationship must include the main and interaction effects of all factors and hence the selected polynomial is expressed as follows:

$$Y = b_0 + \sum bi\ xi + \sum bii\ xi^2 + \sum bij\ xi\ xj \qquad (4)$$

For three factors, the selected polynomial could be expressed as

$$\text{Fracture length (FL)} = b_0 + b_1(A) + b_2(B) + b_3(C)+b_{11}(A^2)+b_{22}(B^2)+b_{33}(C^3)+b_{12}(AB)+b_{13}(AC)+b_{23}(BC) \qquad (5)$$

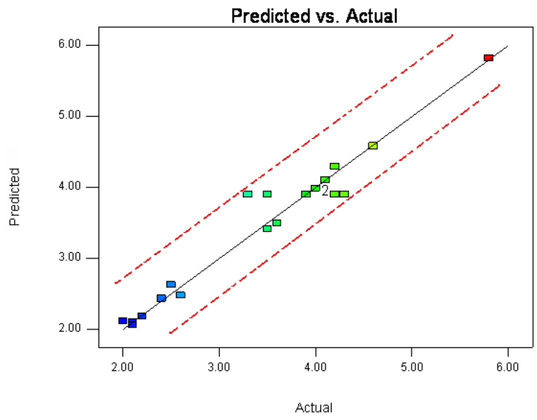
Where b_0 is the average of responses (Fracture length) and $b_1, b_2, b_3, \ldots b_{11}, b_{12}, b_{13}, \ldots b_{22}, b_{23}, b_{33}$, are the coefficients that depend on their respective main and interaction factors, which were calculated using the expression given below

$$B_i = \sum(X_i,Y_i) / n \qquad (6)$$

Where 'i' varies from 1 to n, in which Xi is the corresponding coded value of a factor and Yi is the corresponding response output value (Fracture length) obtained from the experiment and 'n' is the total number of combination considered. All the coefficients were obtained applying central composite face centered design using the Design Expert statistical software package (version 8.0.1). After determining the significant coefficients (at 95% confidence level), the final relationship was developed using only these coefficients. The final empirical relationship obtained by the above procedure to estimate the Fracture length in mm of Hydrofraturing process is given below,

$$\text{Frature Length} = +3.90+0.71*A +0.61*B+0.54*C+0.34*A* B+0.26*B*C -0.18*A^2-0.29*B^2 -0.18*C^2 \qquad (7)\ [19]$$

The Analysis of Variance (ANOVA) technique was used to find the significant main and interaction factors. The results of second order response surface model fitting in the form of Analysis of Variance (ANOVA) are given in Table 3.The determination coefficient (r^2) indicated the goodness of fit for the model. The Model F-value of 22.95 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
The values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, BC, A^2, B^2, C^2 are significant model terms.Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 0.088 implies the Lack of Fit is not significant relative to the pure error. There is a 99.07% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good. The results of multiple linear regression coefficients for the second-order response surface model are given in Table 4. The "R-squared" value of 0.9538. The "Pred R-Squared" of 0.9081 is in reasonable agreement with the "Adj R-Squared" of 0.9123. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. our ratio of 17.344 indicates an adequate signal. The normal probability of the Fracture length shown in Figure 3 reveals the residuals were falling on the straight line, which meant that the errors were distributed normally. All of this indicated an excellent suitability of the regression model. Each of the observed values compared with the experimental values shown in Figure 4.



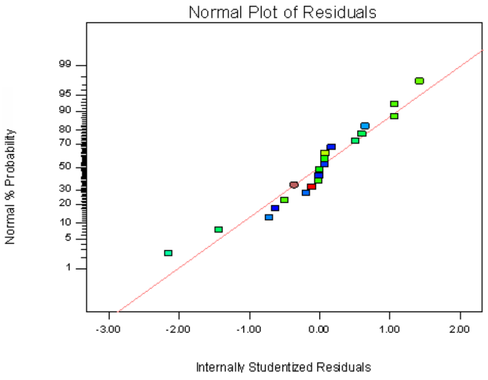


Figure 3. Normal probability plot.

Figure 4. Correlation graph for response (Fracture length)

Table 3 ANOVA test results

Source	**Sum of squares**	**Df**	**Mean square**	**F Value**	**p-value prob.>F**	
Model	19.33	9	2.15	22.95	< 0.0001	significant
A-Pressure	6.94	1	6.94	74.16	< 0.0001	
B-Temperature	5.00	1	5.00	53.43	< 0.0001	
C-Injection hole diameter	4.00	1	4.00	42.74	< 0.0001	
AB	0.91	1	0.91	9.74	0.0109	
AC	0.10	1	0.10	1.08	0.3228	
BC	0.55	1	0.55	5.89	0.0356	
A^2	0.48	1	0.48	5.12	0.0472	
B^2	1.20	1	1.20	12.80	0.0050	
C^2	0.48	1	0.48	5.12	0.0472	
Residual	0.94	10	0.094			
Lack of Fit	0.076	5	0.015	0.088	0.9907	not significant
Pure Error	0.86	5	0.17			
Cor.Total	20.27	19				
Std. Dev. 0.31; Mean 3.46; C.V. % 8.85 PRESS 1.86.						

df -degrees of freedom, CV- coefficient of variation, F- Fisher's ratio, p- probability

Table 4 Estimated regression coefficients

Factor	**Estimated co efficient**
Intercept	3.90
A-Pressure	0.71
B-Temperature	0.61
C-Injection	0.54

hole diameter	
AB	0.34
AC	0.11
BC	0.26
A^2	-0.18
B^2	-0.29
C^2	-0.18

V. DISCUSSION

From Table 4, it shows the Fracture length (mm) obtained from hydro fracturing process at different test conditions like applied pressure(N/mm^2), temperature (ºC), Injection hole diameter(mm). At every increase and decrease in applied pressure, temperature and Injection hole diameter, the test specimen usually exhibited a Fracture. The fluid is pressurized by the feed pump in the range of 4 to 8 N/mm^2. This high pressure fluid is compressed between the casing pipe and surface of the test sample and this energy can be stored in or released from the test medium to the surrounding area subjected to internal pressure which induces the elastic strain energy before the fracture occurs at the peak pressure. The excess of energy is dissipated with the growth of micro cracks during process. The Micro mechanical factor which influences the new crack and porosity generation is heavily influenced by the high pressure. The fracture propagation stops when the elastic strain energy releases over the surface of the test sample. The fracture length is visualized as a collection of coplanar flat cracks. Under low pressure applied the fracture is represented by large, closely spaced cracks, hence the fracture length decreases and measured as 210 mm only. As the applied pressure increases, cracks with the smallest thickness with crack spacing increases. Hence highest fracture length of 580mm was observed when the applied pressure was maximum shown in figure 5. [20]

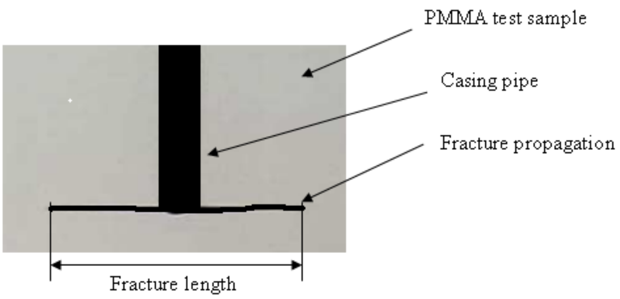


Figure 5. Shows the highest Fracture length of 580mm was observed at a pressure 7 N/mm^2 , Temperature of 55ºC and Injection hole diameter of 9 mm

Because of increase in heating the test sample, the deformation resulting from thermal expansion or contraction is non uniform along the radial and axial directions. This induces the thermal stresses in the sample. For example, under heating condition, the material close to the periphery tends to expand more than the material closer to the axis. Consequently, this produces an outer ring of compression and an inner core of tension. Since fractures in tensile stress fields tend to grow in a plane that is perpendicular to the maximum principle stress, it is expected that loading the sample hydraulically would create a fracture that is oriented perpendicular to the sample axis in figure 6. Hence highest fracture length of 580 mm was observed when the temperature was at its maximum [21]

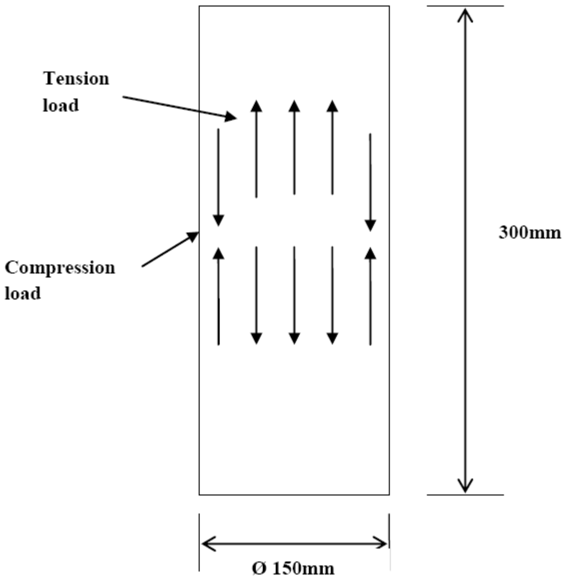


Figure 6 Load acting during temperature effects

As the injection hole diameter is increases from 6 to 10mm, the area of the contact between the injection hole diameter and surface is gradually increased. The fluid which is being impinges on the test sample exert a large internal pressures on the perimeters of underground structures of the test sample and this pressure develops an internal fractures with in the sample. The sample with fractures with large apertures is susceptible to deformation enabling to produce large stresses that induces a further cracking through hydraulic fracturing. Fracture developed due to the mechanical deformation of asperities, as the injection hole diameter gradually increased these asperities deform and additional asperities come into contact. Due to this change in the geometry of test sample structure, changes were observed in the geometry of the fluid flow path. The geometry of the void space affects both the flow properties and the physical properties of the test specimen hence highest fracture length of 580 mm was observed at injection hole diameter was its maximum [22]. This combined technique of Pressure (N/mm^2), Temperature (ºC) and Injection hole diameter (mm) is robust and has consistent role in fracture length (mm) development during all the 20 experimental trials.

VI. CONCLUSIONS

1. An empirical relationship was developed to predict the Fracture length (mm) as a mechanical property of Hydro fracturing process with a 95% confidence level. The relationship developed by incorporating the effect of Pressure in N/mm^2, Temperature in ºC and Injection hole diameter in mm.
2. The micro mechanical factor which influences the new crack and porosity generation is heavily influenced by the high pressure, temperature and injection hole diameter.
3. The highest Fracture length of 580 mm was observed at a pressure 7 N/mm^2, temperature of 55ºC and Injection hole diameter of 9 mm.
4. The Fracture length (mm) of 210 mm was observed with decrease in pressure applied at 5 N/mm^2, temperature of 45ºC and injection hole diameter of 7 mm.

VII. PROPOSED FUTURE WORK

As a continuation of above research work, the statistical tools like Optimization and sensitivity analysis on the process parameter which influence the fracture propagation during the hydrofraturing process will be carried out using Design Expert software (version 8.0).

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