Relationship between Hydraulic Conductivity of Rock and Rock Quality Designation of Itisi Multi-Purpose Dam

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Abstract—The relationship between hydraulic conductivity/permeability of rocks and rock quality designation (RQD) index of cored rock specimens from the dam axis of the proposed Itisi Multipurpose Dam in Kaduna State was established in this work. The research involved conducting packer/lugeon test in ten (10) borehole locations at two (2) different depths in the 30 m deep boreholes and at 3 different depths in the 60 m deep boreholes. RQD index of the tested zone was measured and ranged from 0 to 100 %. In situ permeability of the site ranged from 0 -5.69 LU. Non-linear analysis approach was adopted to determine the relationship between the variables. The result of the correlation coefficient was -0.77. There was an inverse relationship between all the variables considered. Furthermore, the coefficient of determination was 0.61 for the RQD versus lugeon, which suggests that there is a moderate relationship among the variables.

Keywords-*hydraulic conductivity; rock quality designation; lugeon; dam; boreholes.*

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I. INTRODUCTION

Underground seepage is one of the major factors responsible for the failure of most dams over the years. Seepage is the escape of water through soil pores or fractures/joints of rock mass. Permeability of both soil and rock under a proposed dam embankment is usually evaluated to aid in deciding requirement for grouting in order to have a water tight wall, which will in turn reduce or eliminate seepage. Based on findings, the affordable methods used in evaluating soil's permeability in-situ are the falling head and constant head permeability tests. While Packer/Lugeon test is normally used to estimate the hydraulic conductivity/permeability of rock masses. Dams generally serve the primary purpose of retaining water. However, many dams constructed over the years failed. This is as a result of their inability to retain water all year round, and a number of factors are responsible for that.

Engineering geology studies play a key role in dam site studies. In recent years, the geotechnical evaluation of the dam site properties was the main attention for many researchers (e.g. [9], [12], [6], [8], [14], [15]. In the early times, Terzaghi encountered many cases of failures, significantly due to lack of ability to predict and control ground water. Piping failures were abundant and also slope failures, bearing capacity failures and excessive settlements [17]. Investigations carried out by [2] also showed that about 35 % of failures of earth dams are due to hydraulic failures, about 30% are attributed to seepage failures and about 20% are as a result of structural failure. The remaining 7% of the failure are due to other miscellaneous causes such as accidents and natural disasters. Moreso, on the basis of investigation reports on most past failures by [16] types of failures were categorised into three main classes: (1) Hydraulic: 40% (2) Seepage: 30% (3) Structural failures: 30%.

Rock quality designation (RQD) is a rough measure of the degree of jointing or fracture in a rock mass, measured as a percentage of the drill core in lengths of 10 cm or more. This research was initiated from observation that many dams in Nigeria failed due to improper geotechnical investigation of the geologic formations underlying the dams. As some of them may require grouting and this can only be determined through Lugeon/Packer test. However, Packer test is costly and the equipment are owned by very few companies in Nigeria. Therefore, the permeability results may be obtained from some other cheaper tests. Reference [13] estimated lugeon values at the abutments of Bakhtyari Dam site using velocity structures resulted from seismic travel time tomography. In order to counteract the problem of non-uniqueness with cross-hole (or between gallery) data, 3-D tomographic inversion on Bakhtyari dam seismic data was performed. However, the lugeon values used in their research work were estimated by the formula [4], which states that $L \approx 10^{(3.5-V_p)}$, where L = lugeon number and Vp = velocity of P waves in hard rocks.

This research work is aimed at establishing a relationship between the hydraulic conductivity or permeability and Rock Quality Designation by carrying out lugeon test. In-situ tests were carried out at the Proposed Itisi Multipurpose Dam near Kasuwan Magani in Kajuru Local Government Area of Kaduna State. The in-situ tests were carried out in 10 boreholes. The location map is shown in Fig. 1, while the map showing test locations is presented in Fig. 2 below.

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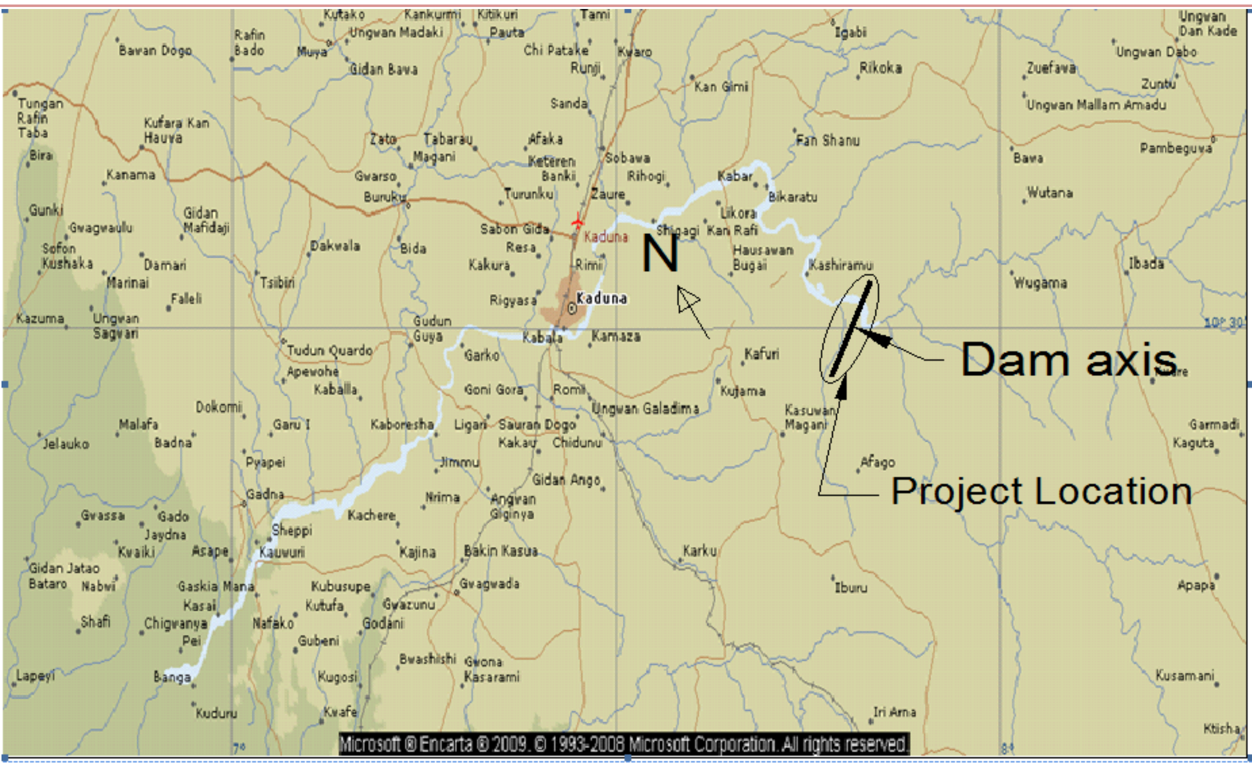

Figure 1. Project Location Map

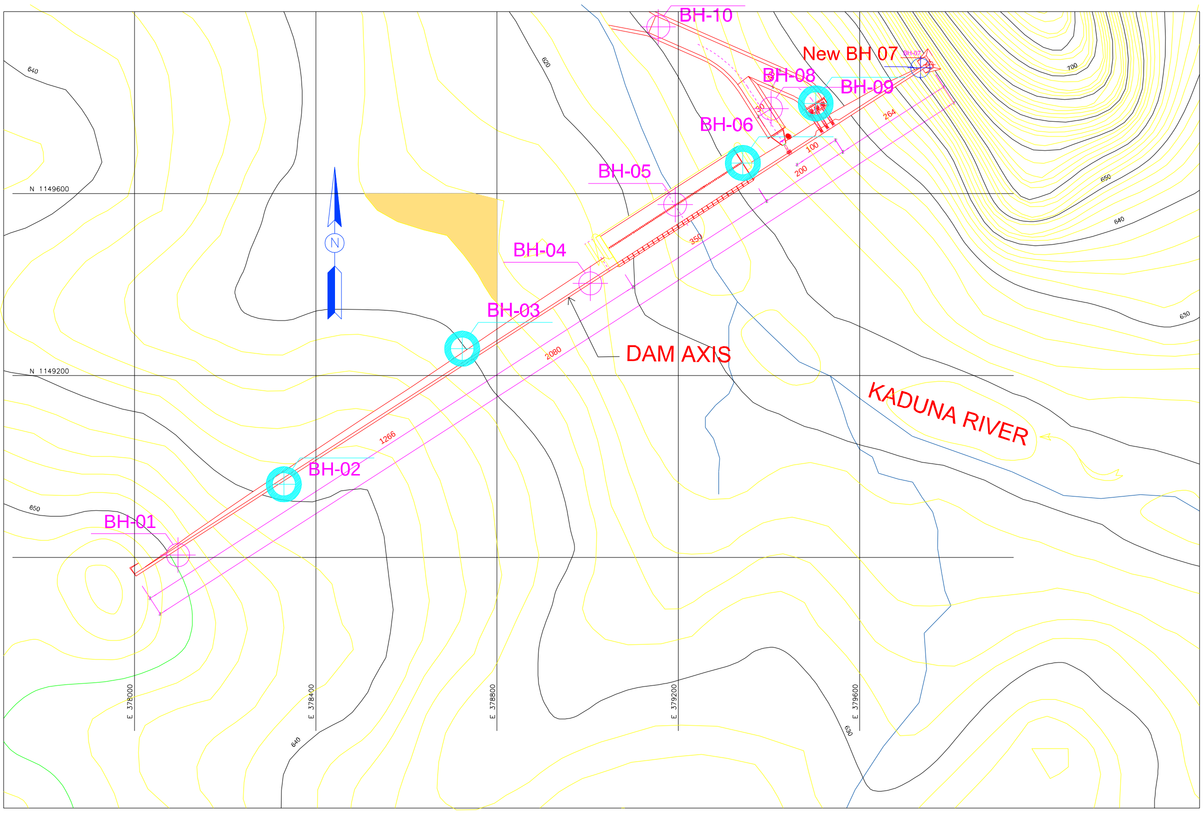

Figure 2. Map of the Proposed Itisi Multipurpose Dam Axis Showing Test Points

II. RESEARCH METHODOLOGY

The samples used for this research work were mainly rock cores obtained from drill holes at the proposed dam site. Borehole BH1, BH2, BH7, BH8, BH9 and BH10 were drilled to depth of 30 m each, while BH3 - BH6 were drilled to depth of 60 m.

A. *Packer Test Preparation*

The basic steps for preparing for a packer test are outlined below.

1) Packer assembly was prepared: two packers with open bottom for single test or three packers with perforated middle pipe section and closed cap on the bottom for straddle Packer test;
2) Inflation line connecting the packers and fittings was checked – over tightening was avoided as it might strip the threads;
3) Packer assembly was checked for any leakage. It was then inflated to maximum gland working pressure in appropriate length and diameter of drill casing or drilling rods; 4) Wire line connectors on Packer assembly and stuffing box components (especially seals) were checked;
4) Water feeding system was prepare and checked: tank, supply, pump, connection hoses, pressure gauges, valves and flow-meter;
5) Test parameters were designed: depth and length of tested zone, drilling bit depth (double checked drillers count of rods in drill-hole), position of packers, inflation pressure and water pressure for three stages;
6) Drill hole preparation: drilling mud and cuttings were removed (flushed with clear water);
7) Pulled rods up to drill bit at selected depth;
8) Prepared wire line winch;
9) Installed stuffing box on drill rods;
10) Measured groundwater level prior to installing Packer system several times to assess static groundwater level;
11) Packer assembly was lifted using the wireline and lower to landing ring at drill bit– it was checked if seats on landing ring by "listening" to rods using wrench, etc.
12) Packer was inflated slowly (by 50 psi steps) until working pressure was reached. This will require filling to working pressure plus calculated hydrostatic pressure;
13) After inflation was complete, Packer inflation line pressure was monitored for 2 minutes minimum to see if system is leaking;
14) Sealed stuffing box cap and attached water feed system;
15) Inflation lines and inflation pressure were checked to ensure no leakage occur, water feeding system was also checked, stop-watch and field test form were prepared;
16) Packer system was ready for testing.

B. *Packer Test Procedures*

Procedures for various packer testing methods are described below:

- Injection (Lugeon) Tests

Injection (Lugeon) tests consist of isolating a section of borehole and injecting water under pressure in to the rock to determine the effective transmissivity (T) of the zone. The transmissivity can be related to the hydraulic conductivity (K) of the rock or hydrogeological features (fractures, etc.) by means of $K = T/L$, where L = length of test zone).

The data recorded during the test simply consisted of the flow rate and the corresponding pressure when “steady-state” condition was achieved. These data were recorded over a number of increasing and decreasing steps, as explained below.

- Test Description

Based on the drill core, an assessment of the expected injection rates and pressure was made. This became easier as the testing program proceeded and the tester became familiar with the hydrogeological setting.

Observations of flows were made every minute until three consecutive, consistent readings are taken. This represented steady-state flow. The pressure was then increased, usually for 5 or 3 equal increments, followed by 3 decreasing pressures. The steady-state flow at each pressure was recorded.

To begin the test, the tester will need to have an idea of the pressures to be tested (these are referred to as pressure steps A, B, and C below). The expected pressure range will be based on the estimated permeability of the rock and the expected intake of injected water. These will have to be assessed based on previous experience in the drill-hole(s), and correlated to the pumping equipment available. If insufficient, or excessive, pressures are used for Pressure A, the test can be extended (more pressure steps for the former) or stopped and restarted for the latter at a lower initial pressure.

It is common practice to "ramp up" over at least three (3) "increasing" steps in the test, and to "ramp back down" two or three decreasing steps (at pressures that match the ramping up pressures). This is done to test for hysteresis in the plotted data. Deviation from a straight line match can indicate hydrofracturing (if decreasing data is above the line) or non-Darcian flow (if decreasing data is below the line).

Note that it is assumed that injection losses due to friction losses in the drill rods will not be significant because of the large diameter. Friction losses through the packer assembly flow pipe would be significant, but the short length involved reduces this impact and so it will be ignored in the calculations.

TABLE I. PACKER TEST PRESSURES

Pressure Step	Pressure (psi)
A	20
B	40
C	60
D	80
E	100
Dr	80
Cr	60
Br	40
Ar	20

Note that step “Br” refers to recovery pressure B, which should equal, or be similar, to ascending pressure step B.

Figure 3. Packer apparatus with flow meter

Figure 4. Packer apparatus with packer inflator

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Figure 5. Test running the flow line with packer inflated

Figure 6. Measurement of water level using deep meter

Figure 7. Packer inflator pressure gauge

Figure 8. Pumping in progress through the packer tube

- Basic Testing Procedures

Data were plotted on a flow rate vs. pressure graph, for each pressure step. The shape of the plot, especially with regard to the decreasing pressure curve match, was used to assess the test results.

The test usually consists of 3 to 5 ascending pressure steps, and 2 to 4 recovery pressure steps, as illustrated in TABLE I.

Using the expected initial pressure and estimated range of steps as a starting point, the following procedures were followed. If pressures and/or required pumping rates are not as expected, the tester will have to adjust the pressure steps as required.

The basic test procedures are as listed below:

1) The water feeding system valve was opened and maintained constant initial pressure A until it appeared to have stabilized;
2) During this time, the elapsed time and total volume of consumed water were recorded every 0.5 min, for the first 2-3 min of the test stage, then every minute;
3) After pressure A stabilized for approximately 3 minutes, the pressure was increased to pressure B;
4) Time vs. flow rates were recorded as for A;
5) The pressure was increased, after pressure B stabilized for approximately 3 minutes, to pressure C;
6) Pressure stage B was repeated – when formation was tight, pressure was released by bypass valve on water feeding system to decrease pressure from C to B quickly;
7) Pressure stage A was repeated – when formation was tight, pressure was released by bypass valve on water feeding system to decrease pressure from B to A quickly;
8) After repeating stage A, recovery test was performed: shut the feed valve and record pressure decrease vs. time for about 10-15 min, or until 90% recovery occurred;
9) Packer assembly was deflated and removed stuffing box cap and seal;
10) Sometimes were allowed for all nitrogen to escape from the Packer cells, additional 5 minutes waited and then pulled the assembly carefully to top of drill rods, watching for the marker flag to prevent pulling assembly into overhead sheave; and
11) Groundwater level after the test was measured several time to assess level recovery and static level.

C. *Calculation*

The coefficient of permeability (K) of rocks is determined with (1):

$$K = \frac{q}{2\pi LH} \ln\left(\frac{L}{r}\right) \text{ (m/sec)} \quad (1)$$

where:

q = Water intake (m^3)
L = Test zone length (m)
r = Radius of the test zone hole (m)
H = Differential head (m)
$H = Hw + Hg + Hp$
Hw = Height of water level below ground level
Hg = Height of gauge
Hp = Applied pressure

Conversion factor:
1 bar = 10.33
1 Lugeon = 1.3×10^{-7} (m/sec)

III. PRESENTATION, ANALYSIS AND DISCUSSION OF RESULTS

A. *Presentation of Results*

- Packer/Lugeon Test Results

The results of the lugeon test conducted on 10 Nos boreholes of the Itisi Multipurpose Dam Axis is presented in the Table II below:

TABLE II. PACKER/LUGEON TEST RESULTS

S/No	Location	Test Zone Depth (m)	Coefficient of Permeability, K (m/sec)	Lugeon
1	BH 1	4 – 9	2.24×10^{-8}	0.17
2	BH 1	9 - 14	7.39×10^{-7}	5.69
3	BH 2	20 - 25	5.94×10^{-7}	4.57
4	BH 2	25 - 30	0.00	0.00
5	BH 3	23 - 28	3.22×10^{-6}	2.47
6	BH 3	33 - 38	0.00	0.00
7	BH 3	55 - 60	0.00	0.00
8	BH 4	10 - 15	3.80×10^{-8}	0.29
9	BH 4	15 - 20	3.69×10^{-8}	0.28
10	BH 4	35 - 40	4.16×10^{-8}	0.32
11	BH 5	21 - 26	5.18×10^{-8}	0.40
12	BH 5	36 - 41	4.49×10^{-8}	0.35
13	BH 5	51 - 56	0.00	0.00
14	BH 6	23 - 28	7.79×10^{-8}	0.60
15	BH 6	28 - 33	6.73×10^{-8}	0.52
16	BH 6	38 - 43	3.90×10^{-8}	0.30
17	BH 7	6 -11	3.25×10^{-8}	0.25
18	BH 7	16 - 21	3.46×10^{-8}	0.27
19	BH 8	20 - 25	2.29×10^{-7}	1.76
20	BH 8	25 - 30	7.01×10^{-8}	0.54
21	BH 9	13 - 18	3.14×10^{-8}	2.42
22	BH 9	18 - 23	3.17×10^{-8}	2.44
23	BH 10	20 - 25	3.59×10^{-8}	0.28
24	BH 10	25 - 30	3.48×10^{-8}	0.27

- Rock Quality Designation (RQD)

Rock Quality Designation (RQD) is a measure of quality of rocks, which is the sum total of lengths of 10 cm or longer cores recovered from the drilling, expressed as a percentage of the length of run drilled (TCR). Table III below presents the criteria for classifying rocks, while the RQD and the TCR of the test zones measured from the recovered cored samples are contained in Table IV.

TABLE III. ROCK QUALITY AND RQD INDEX

S/No.	Rock Quality	RQD Index
1	Very poor	0 - 25
2	Poor	25 - 50
3	Fair	50 - 75
4	Good	75 - 90
5	Excellent	90 - 100

TABLE IV. ROCK QUALITY DESIGNATION RESULTS

S/No	Sample Location	Depth (m)	RQD (%)	TCR (%)	Rock Quality
1	BH1	8	93	93	Excellent
2	BH1	13	64	64	Fair
3	BH2	20	0	0	Very poor
4	BH2	29	94	96	Excellent
5	BH3	23	58	66	Fair
6	BH3	36	87	100	Good
7	BH3	60	82	94	Good
8	BH4	13	91	97	Excellent
9	BH4	18	100	100	Excellent
10	BH4	36	91	93	Excellent
11	BH5	21	83	89	Good
12	BH5	38	94	94	Excellent
13	BH5	53	99	99	Excellent
14	BH6	25	95	97	Excellent
15	BH6	31	100	100	Excellent
16	BH6	41	100	100	Excellent
17	BH7	9	91	95	Excellent
18	BH7	18	90	95	Excellent
19	BH8	25	92	97	Excellent
20	BH8	30	96	96	Excellent
21	BH9	15	27	40	Poor
22	BH9	23	40	100	Poor
23	BH10	24	91	100	Excellent
24	BH10	29	90	90	Excellent

B. ANALYSIS OF RESULTS

The results obtained from Lugeon tests and the RQD index were plotted with depths as shown in Fig. 9 to Fig. 11.

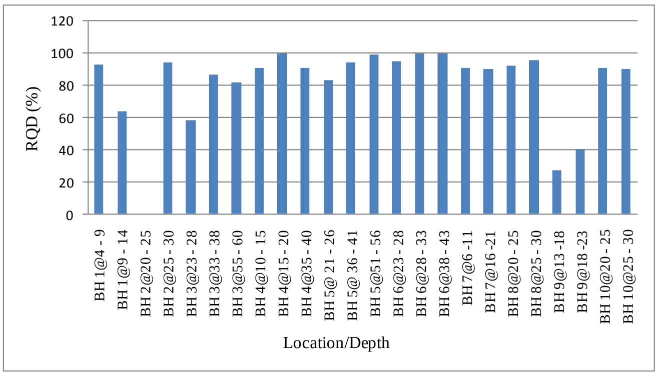

Figure 9. Variation of RQD (%) with Depth

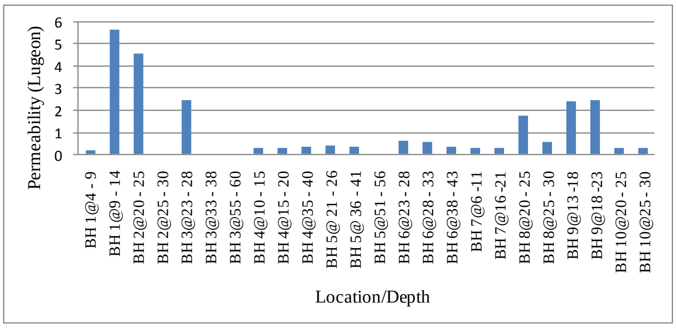

Figure 10. Variation of Permeability (LU) with Depth

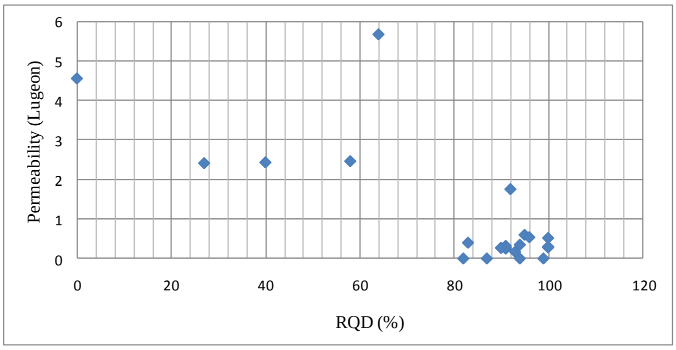

Figure 11. Relationship between Permeability (Lungeon) with RQD

- Correlation Analysis

Lugeon versus Rock Quality Designation (RQD)

To establish the relationship and correlation between lugeon and RQD, let x represent the variables for the RQD results and y represent the variables for the Lugeon results.

The Pearson's correlation coefficient equation was used in this work and is given by (2):

$$r = \frac{n\sum xy - \sum x \sum y}{\left(\left(n\sum x^2 - \left(\sum x\right)^2\right)\left(n\sum y^2 - \left(\sum y\right)^2\right)\right)^{1/2}} \quad (2)$$

TABLE V. CORRELATION DATA FOR LUGEON AND RQD

y	x	xy	y^2	x^2
0.17	93.00	16.02	0.03	8649
5.69	64.00	364.16	32.38	4096
4.57	0.00	0.00	20.86	0000
0.00	94.00	0.00	0.00	8836
24.77	58.00	1436.60	613.50	3364
0.00	87.00	0.00	0.00	7569
0.00	82.00	0.00	0.00	6724
0.29	91.00	26.39	0.08	8281
0.28	100.00	28.00	0.08	10000
0.32	91.00	29.12	0.10	8281
0.40	83.00	33.20	0.16	6889
0.35	94.00	32.90	0.12	8836
0.00	99.00	0.00	0.00	9801
0.60	95.00	57.00	0.36	9025
0.52	100.00	52.00	0.27	10000
0.30	100.00	30.00	0.09	10000
0.25	91.00	22.75	0.06	8281
0.27	90.00	24.30	0.07	8100
1.76	92.00	162.10	3.10	8464
0.54	96.00	51.74	0.29	9216
15.55	27.00	419.85	241.80	0729
12.25	40.00	490.00	150.06	1600
0.28	91.00	25.48	0.08	8281
0.27	90.00	24.30	0.07	8100
Σ=69.4293	Σ=1948	Σ=3325.92	Σ=1063.6	Σ=173122

Hence, r = -0.77, so, the correlation for our twenty four (24) cases is -0.77, which is a strong negative relationship, as strong relationship ranges from ±0.5 - ±1.0.

- Mathematical Model

The Microsoft Excel Regression analysis (Trendline) approach was adopted in generating the mathematical model relating both Lugeon versus UCS and Lugeon versus RQD. The regression analysis of Permeability (Lungeon) versus Rock Quality Designation (RQD) is presented in Fig. 12.

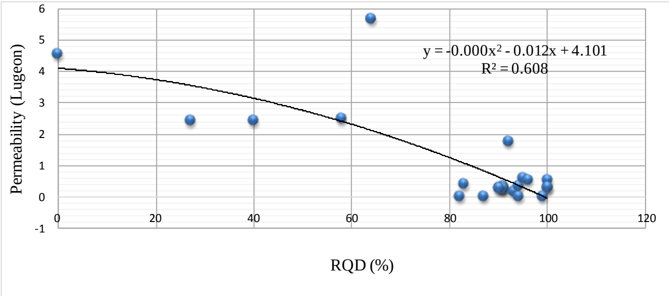

Figure 12. Regression Analysis of Permeability (Lugeon) versus RQD

The equation relating permeability (Lugeon) and UCS is given as: $\mathbf{y = -0.000x^2 - 0.012x + 4.101}$, where y is permeability (Lugeon) and x is RQD.

C. DISCUSSION OF RESULTS

From the analysis of results it was observed that there is a strong negative relationship between Lugeon versus RQD respectively, since the correlation coefficient (r) between Lugeon and RQD is -0.77 which is a strong negative relationship, while the coefficient of determination is 0.61, which means 61% of the total variation in permeability (lugeon) can be explained by the relationship between permeability (lugeon) and RQD, the other 39% of the total variation in permeability (lugeon) remains unexplained. It was also observed that as x increases, y decreases since the Pearson's coefficient of correlation is negative.

IV. CONCLUSIONS

Field test (Lugeon/Packer) was carried in ten (10) boreholes along the dam axis of the proposed Itisi Multipurpose Dam in Kajuru local government area of Kaduna State. Rock Quality Designation (RQD) index was calculated using the same samples retrieved from the boreholes. The Pearson's correlation coefficient between RQD and lugeon is -0.77 and the coefficient of determination is 0.61. Hence the following conclusions can be made.

1) The permeability (lugeon) result obtained ranged from 0 – 5.69 LU and RQD ranged from 0 – 100 %.
2) The relationship between RQD and Lugeon values is moderate considering the result of the coefficient of determination.
3) There is an inverse relationship between RQD versus Lugeon, since the correlation coefficient is negative.
4) The mathematical model relating Rock Quality Designation index (RQD) and Lugeon (L) is $\mathbf{L = -0.000RQD^2 - 0.012RQD + 4.101}$.
5) Low permeabilities were recorded in most of the Packer tests carried out which is due to the rise in water table of site area as the tests were conducted during the rainy season, which is the best period for carrying out such research.

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