Predicting rock mass properties for nuclear waste repositories from laboratory strength data

G.M. Nagraja Rao, S. Udayakumar, Praveena D. Jennifer

Abstract

Using the laboratory strength data for charnockite rock tested at 28°C, 100°C and 200°C and field parameters, rock mass properties were estimated using Rocdata software for a nuclear waste repository. Three parameters that influence the rock mass properties are temperature, Disturbance factor (D) and Geological Strength Index (GSI). Both uniaxial compressive strength and cohesive strength of rock mass increase exponentially, and angle of friction increase linearly as GSI varied from 30 to 80 and Disturbance factor (D) from 0.1 to 0.5 for the range of temperatures investigated. As GSI decreases, both the uniaxial compressive strength and cohesive strength converge which indicate that below a GSI value of 30, rock mass is highly fractured and is having very low strength. The effect of D on rock mass strength is significant only at higher values of GSI than at lower GSI values. As the GSI decreases, variation in D does not influence the rock mass strength significantly as the rock mass is highly fractured. Rock mass strength is largely controlled by GSI and D, the effect of temperature on rock mass strength is very small. Although higher GSI is preferable for any permanent underground excavation, but rock mass strength is very sensitive to Disturbance factor (D). Therefore, it is preferable to have a GSI more than 70 for a rock mass strength greater than 30 MPa. It is possible to predict the rock mass strength by optimizing Disturbance factor (D) for a given set of geological conditions. Thus, laboratory investigation on intact rock samples produces invaluable results in predicting the rock mass strength.

Introduction

Apart from the generation of power by conventional methods, most of the advanced and developed countries are using the nuclear energy for generating the electric power. The nuclear waste, which is a by-product of power generation, is highly radioactive and should be permanently and safely disposed. The safest way of disposing is to store it in the canisters and place them in repositories constructed deep below the earth at a depth of about 1 to 1.5km. The repositories have to remain in a stable condition for more than a few hundred years depending on the radioactivity of nuclear waste. Their long term stability is very critical and important. Rocks, being a natural engineering material, contain defects like cracks, pores, joints, faults, folds etc. In deep earth the situations are very complex and the stresses within the earth are triaxial and compressive in nature with the three principal stresses having different values. In the case of nuclear waste repositories, the generation of heat by radioactive materials, induces thermal stresses in addition to the prevailing stress regime. Reasonably high temperatures of 150°C to 200°C are encountered in nuclear waste repositories. Rock mass strength is very important for analyzing the stability of any underground structure. The simplest way of estimating the rock mass strength is based on the laboratory results of core samples collected from a site. In the present investigation, uniaxial and triaxial compression tests were carried out on charnockite samples at ambient and at elevated temperatures of 100°C and 200°C. The laboratory results were analysed using the ROCDATA software to estimate the uniaxial compressive strength, cohesive

National Institute of Rock Mechanics, Kolar Gold Fields-563 117, Karnataka, India

strength and angle of friction of rock mass. In order to estimate these rock mass properties appropriate Geological Strength Index (GSI) and Disturbance factor (D) were assumed. The experimental data were analysed for a different combination of GSI and D at ambient temperature (28°C), 100°C and 200°C.

Experimental Details

The diameter of the charnockite sample was approximately 54.4mm, and the length to diameter ratio was maintained at 2.5 for both uniaxial and triaxial compression tests. Dimensional tolerances were maintained as per the ISRM suggested methods. To carry out the experiments at elevated temperature a triaxial cell was used for both uniaxial and triaxial compression experiments. The fluid in the triaxial cell was used as a medium for heating the rock samples. The heat exposure time in these tests were restricted to 6 hours. Uniaxial compression tests were carried out under heated conditions without lateral confining pressure. The samples were jacketed with a thin foil of copper and placed inside the triaxial cell. The cell was filled with hydraulic oil such that the sample was fully immersed in it. The cell was heated externally using heaters to the desired temperature over a period of a time and the temperature was maintained using a thermocouple kept inside the cell. A duration of 6 hours was chosen, so that uniform temperature is attained throughout the sample. At the end of 6 hours, sample was tested using MTS compression testing machine and the required temperature was maintained while carrying out the compression test. The rate of loading was maintained at 5 tons/min for all the tests. Triaxial compression tests were carried out using the same cell but with confining pressure of 20, 40, 60, 80 and 100 MPa. The confining fluid was a general purpose hydraulic oil and the pressure was applied using a pneumatic pump.

Prepared rock samples were jacketed with Teflon heat shrink tube kept inside the cell. The cell was filled with hydraulic oil and heated for 6 hours to the desired temperature with an accuracy of temperature maintained at ± 5°C. At the end of 6 hours, the cell was kept inside the MTS compression load frame, confining pressure was applied using a pneumatic pump and simultaneously axial load was also increased. The rate of loading was maintained at 5 ton/min. The confining pressure was maintained at the desired level (± 3 MPa) and axial load was increased till the failure of the sample.

Results and Analysis

Results from the uniaxial and triaxial compression tests were utilized to estimate the rock mass strength properties using ROCDATA software, based on the generalized Hoek-Brown failure criterion (Hoek E, 1994; Hoek et al., 1995; Hoek et al., 2002). In order to estimate the rock mass strength properties two field parameters namely Geological Strength Index (GSI) and Disturbance factor (D) are required. The Geological Strength Index (GSI), introduced by Hoek (1994) and Hoek, Kaiser and Bawden (1995) provides a number, which on combining with the intact rock properties, can be used for estimating the reduction in rock mass strength for different geological conditions. Disturbance factor (D) depends upon the degree of disturbance due to blasting and stress relaxation. It varies from 0 for undisturbed *in situ* rock masses to 1 for very disturbed rock masses. Guidelines for the selection of GSI and D are given in the software menu and the following values were used for the analysis of laboratory strength data.

1. Geological Strength Index(GSI): 30,40,50,60,70, and 80
2. Disturbance factor: 0.1,0.3 and 0.5
3. Application : Cavern/repository
4. Depth: 1000m

It is assumed that the repository is at a depth of 1000m from the earth surface. Uniaxial compressive strength data was treated as the strength at zero confining pressure.

Table 1: Intact rock properties (laboratory)

Temperature (°C)	Uniaxial compressive strength (MPa)	Cohesive strength (MPa)	Angle of friction (deg)
28	180	39.10	47.33
100	160	36.53	39.46
200	194	49.20	31.45

Table 1 gives the uniaxial compressive strength, cohesion and friction angle of intact rock (from laboratory experiments).

From Table 1, it is observed that the uniaxial compressive strength and cohesive strength decreases as the temperature is increased to 100°C but increases at 200°C and the strength at this temperature is more than the strength of unheated rock sample. However angle of friction decreases with the increase of temperature. Irrespective of the temperature, uniaxial compressive strength of intact rock varies from 164 to 194 MPa and friction angle from 36.53° to 49.20°.

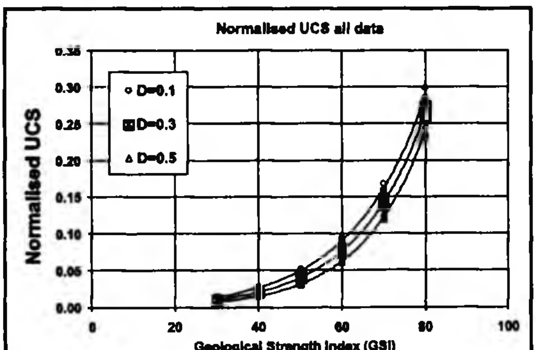

Figure 8: Normalised Uniaxial Compressive Strength for different values of D & GSI

From these figures/ tables, it may be deduced that among the three parameters, GSI largely controls the strength of rock mass, and the other two parameters (D and temperature) affect the strength much less. At 200°C the strength of rock mass is comparable to the strength at the ambient temperature, which may be due to the development of residual stresses arising out of the differential thermal expansion of minerals. Evidences are also available that micro cracks do introduce toughening depending on the density and orientation of microcracks (Nagraja Rao and Murthy, 2001). Based on these, it may be inferred that the effect of temperature on rock mass strength is very small.

In order to make out a qualitative and quantitative effect of GSI and D on rock mass strength, the uniaxial compressive and cohesive strength given in Table 2 were normalized with respect to the intact rock strength and is given as ratio of rock mass strength to intact rock strength in the last two columns of Table 2. The normalized uniaxial compressive strength values of rock mass are plotted for three Disturbance factors as function of GSI as shown in Figure 8. Three separate exponential trends were produced for three Disturbance factors. As the Disturbance factor increases the strength envelopes shift to lower values. At lower values of GSI, Disturbance factor (D) do not influence the strength envelopes much but as GSI increases the gap between the strength envelopes widens. At higher values of GSI, rock mass strength is sensitive to

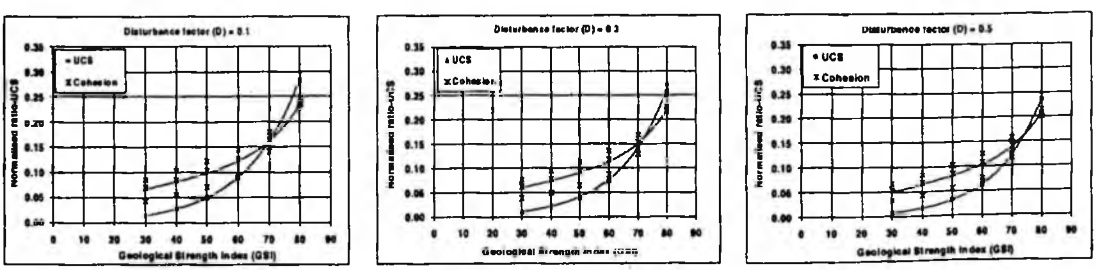

Figure 9: Normalised uniaxial compressive strength and cohesive strength for different values of D & GSI

Table 2: Rock mass properties

T	D	GSI	UCS	C	ø	Normalised UCS	Normalised Cohesive strength
28	0.1	30	2.54	3.33	40.45	0.01	0.09
28	0.1	40	4.99	4.02	43.81	0.03	0.10
28	0.1	50	9.27	4.76	46.90	0.05	0.12
28	0.1	60	16.80	5.67	49.79	0.09	0.14
28	0.1	70	30.10	7.00	52.44	0.17	0.18
28	0.1	80	53.66	9.30	54.75	0.30	0.24
100	0.1	30	2.12	2.53	33.56	0.01	0.07
100	0.1	40	4.16	3.11	37.00	0.03	0.09
100	0.1	50	7.73	3.75	40.19	0.05	0.10
100	0.1	60	14.01	4.61	43.17	0.09	0.13
100	0.1	70	25.10	5.98	45.87	0.16	0.16
100	0.1	80	44.75	8.51	48.13	0.28	0.23
200	0.1	30	2.61	2.11	28.54	0.01	0.04
200	0.1	40	5.13	2.70	31.98	0.03	0.05
200	0.1	50	9.55	3.46	35.08	0.05	0.07
200	0.1	60	17.30	4.68	37.84	0.09	0.10
200	0.1	70	30.99	6.95	40.06	0.16	0.14
200	0.1	80	55.25	11.50	41.48	0.28	0.23
28	0.3	30	1.86	2.99	37.76	0.01	0.08
28	0.3	40	3.84	3.67	41.58	0.02	0.09
28	0.3	50	7.48	4.40	45.12	0.04	0.11
28	0.3	60	14.16	5.30	48.43	0.08	0.14
28	0.3	70	26.48	6.60	51.48	0.15	0.17
28	0.3	80	49.27	8.86	54.17	0.27	0.23
100	0.3	30	1.55	2.26	30.92	0.01	0.06
100	0.3	40	3.20	2.82	34.76	0.02	0.08
100	0.3	50	6.23	3.44	38.35	0.04	0.09
100	0.3	60	11.81	4.27	41.75	0.07	0.12
100	0.3	70	22.09	5.58	44.87	0.14	0.15
100	0.3	80	41.09	8.04	47.52	0.26	0.22
200	0.3	30	1.91	1.86	26.05	0.01	0.04
200	0.3	40	3.95	2.41	29.83	0.02	0.05
200	0.3	50	7.70	3.12	33.31	0.04	0.06
200	0.3	60	14.58	4.23	36.48	0.08	0.09
200	0.3	70	27.27	6.34	39.14	0.14	0.13
200	0.3	80	50.73	10.69	40.97	0.26	0.22
28	0.5	30	1.30	2.60	34.35	0.01	0.07
28	0.5	40	2.84	3.27	38.72	0.02	0.08
28	0.5	50	5.82	4.00	42.81	0.03	0.10
28	0.5	60	11.61	4.89	46.66	0.06	0.12
28	0.5	70	22.83	6.17	50.23	0.13	0.16
28	0.5	80	44.63	8.38	53.41	0.25	0.21
100	0.5	30	1.08	1.94	27.66	0.01	0.05
100	0.5	40	2.37	2.49	31.94	0.01	0.07
100	0.5	50	4.86	3.10	36.02	0.03	0.08
100	0.5	60	9.68	3.90	39.92	0.06	0.11
100	0.5	70	19.04	5.16	43.56	0.12	0.14
100	0.5	80	37.22	7.54	46.73	0.23	0.21
200	0.5	30	1.33	1.58	23.03	0.01	0.03
200	0.5	40	2.92	2.10	27.15	0.02	0.04
200	0.5	50	6.00	2.76	31.06	0.03	0.06
200	0.5	60	11.95	3.78	34.72	0.06	0.08
200	0.5	70	23.50	5.71	37.92	0.12	0.12
200	0.5	80	45.95	9.86	40.26	0.24	0.20

Note:

T	Temperature (deg.C)	GSI	Geological Strength Index	C	Cohesive strength of rock mass,MPa
D	Disturbance factor	UCS	Uniaxial compressive strength of rock mass,MPa	Ø	Angle of fricftion, deg.

Normalised UCS	$\frac{\text{UCS of rock mass}}{\text{UCS of intact rock}}$	**Normalised Cohesive strength**	$\frac{\text{Cohesive strength of rock mass}}{\text{Cohesive strength of intact rock}}$

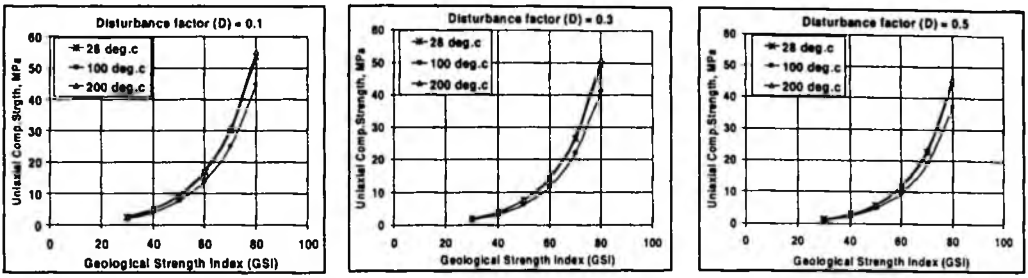

Figure 1: Uniaxial Compressive Strength of Rock mass for different values of D, Temperature & GSI

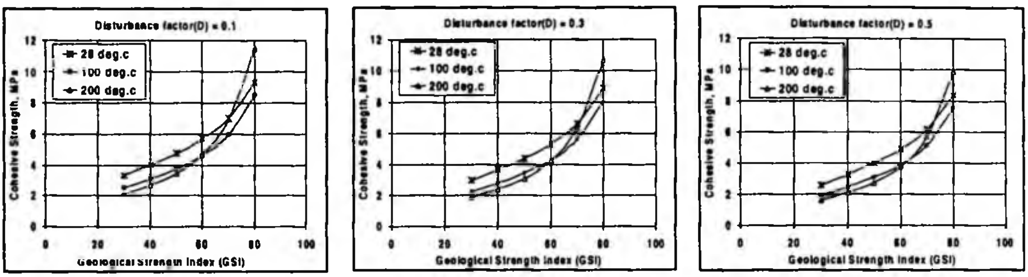

Figure 2: Cohesive Strength of Rock mass for different values of D, Temperature & GSI

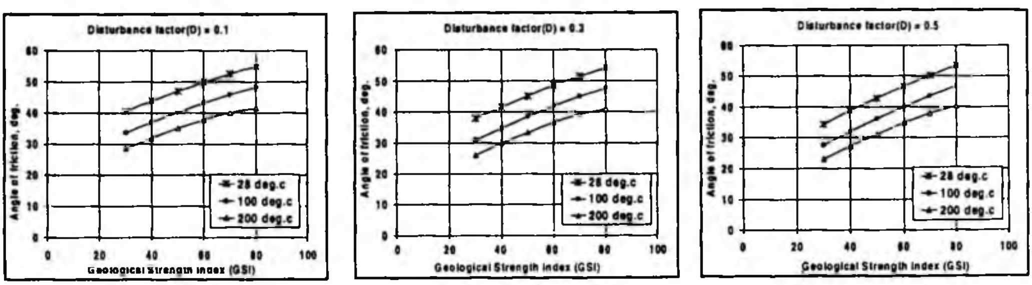

Figure 3: Angle of friction of Rock mass for different values of D, Temperature & GSI

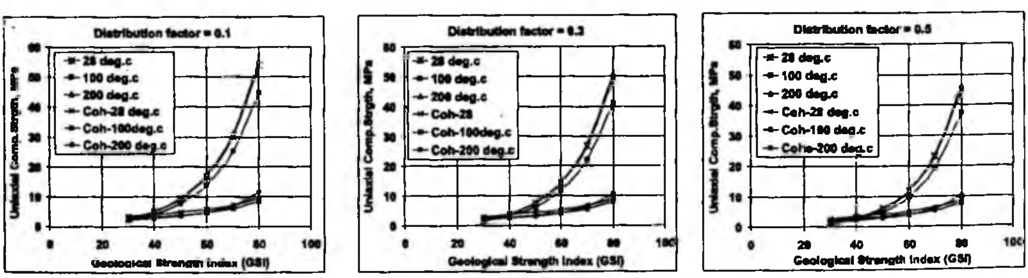

Figure 4: Uniaxial Compressive and Shear Strength variation at different values of D, Temperature and GSI

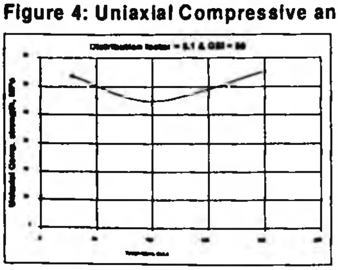

Figure 5: Effect of Temperature on Uniaxial Compressive Strength

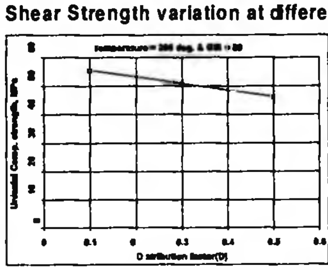

Figure 6: Effect of Distribution factor on Uniaxial Compressive Strength

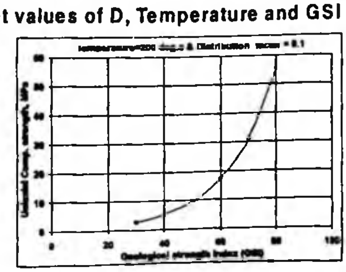

Figure 7: Effect of GSI on Uniaxial Compressive Strength

Table 3: Effect of Temperature, D and GSI on rock mass strength

Temperature, deg.C	Disturbance factor	Geological strength index(GSI)	Uniaxail compressive strength, MPa	Cohesive strength, MPa	Angle of friction, deg.
Constant Damage factor & GSI at variable temperature					
28	0.1	80	53.66	9.30	54.75
100	0.1	80	44.75	8.51	48.13
200	0.1	80	55.25	11.50	41.48
Constant Temperature & GSI at variable Damage factor					
200	**0.1**	80	55.25	11.50	41.48
200	**0.3**	80	50.73	10.69	40.97
200	**0.5**	80	45.95	9.86	40.26
Constant Temperature & Damage factor at variable GSI					
200	0.1	**30**	2.61	2.11	28.54
200	0.1	**40**	5.13	2.70	31.98
200	0.1	**50**	9.55	3.46	35.08
200	0.1	**60**	17.30	4.68	37.84
200	0.1	**70**	30.99	6.95	40.06
200	0.1	**80**	55.25	11.50	41.48

the variation of D. Probably below a GSI of 30, D may not influence the strength envelope and all the strength envelopes converges to a very low value.

Figure 9 (a, b, c) shows a plot of normalized uniaxial compressive and cohesive strength curves for three disturbance factors. It is observed that uniaxial compressive strength increases exponentially whereas cohesive strength shows a semi exponential trend as the GSI varies from 30 to 80. At lower values of GSI, normalized cohesive strength is higher than the uniaxial compressive strength. But at particular value of GSI both the normalized strength parameters becomes equal and beyond which normalized uniaxial compressive strength is higher than the cohesive strength. The intersection point of the two curves depends on D which shifts to a slightly higher GSI value with the increase of D.

The experimental data were analysed for a combination of GSI and D at 28°C (ambient temperature), 100°C and 200°C. Some of the important findings are summarized below:

1. Rock mass strength is largely controlled by GSI and D, the effect of temperature on rock mass strength is very small.
2. Both uniaxial compressive strength and cohesive strength of rock mass increase exponentially, and angle of friction rise linearly as GSI varies from 30 to 80 and Disturbance factor (D) from 0.1 to 0.5 for the range of temperatures investigated.
3. As GSI decreases, both the uniaxial compressive strength and cohesive strength converge as close as possible and D does not influence the rock mass strength significantly at lower values of GSI as the rock mass is highly fractured. The effect of D on rock mass strength is more predominant only at higher GSI values.
4. Normalised uniaxial compressive strength and cohesive strength increases exponentially with the increase of GSI. Initially normalised cohesive strength is more than the uniaxial compressive strength. But at a particular value of GSI both are equal, beyond this point uniaxial compressive strength of rock mass is higher than the cohesive strength. This intersection point varies with the Disturbance factor (D) and occurs at higher value of GSI as D decreases.

Conclusions

Using the laboratory strength data and with field parameters rock mass strength parameters were estimated using ROCDATA software for a nuclear waste repository. Three parameters, which control the strength of rock mass with increasing order of importance, are temperature, Disturbance factor (D) and Geological strength index (GSI). The effect of temperature on rock mass strength is very small. Disturbance factor (D) affects the rock mass strength depending on the value of GSI and is significant only at higher value of GSI. At lower values of GSI, variation in D does not influence the rock mass strength significantly - below GSI of 30, both uniaxial compressive and cohesive strength of rock mass converge and there is hardly any difference of value between these two strength properties. Although higher GSI is preferable for a permanent underground excavation, but rock mass strength is very sensitive to Disturbance factor (D). It is preferable to have a GSI more than 70 for a higher rock mass strength (greater than 30 MPa). Laboratory investigation on intact rock samples produces invaluable results in predicting the rock mass strength by optimizing Disturbance factor (D) for a given set of geological conditions.

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