Laboratory Assessment of Sandstone's Strengths

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Abstract

Four sandstones have been evaluated for uniaxial compressive strength (UCS) and shear strength parameters (apparent cohesion and angle of internal friction), both under saturated state, in addition to assessment of waves' velocities (compression and shear) in dry and saturated, both, states, through the investigated samples. The collation of the data of all the four sandstones helps in the assessment of strengths. The histogram has been prepared in case of UCS, whereas the tangents to the lower bound and upper bound curves (in 'axial stress at failure' versus 'confining pressure' plot) have been treated as 'failure envelops', to recommend the ranges of shear strength parameters. The evaluation of waves' velocities helps deal with the scatter in the data.

Introduction

The laboratory evaluation of uniaxial compressive strength (UCS) and shear strength parameters, i.e., apparent cohesion (C) and angle of internal friction (ϕ) of sandstones - in saturated state - have been carried out. In case of UCS, the application of loading, until failure, was static and the samples of Nx size, with length to diameter ratio of 2.5 were tested.

The assessment of UCS is expected to give *'a value'* of strength. However, in certain situations, such as the present one, the heterogeneity and inherent variability of rock requires that a large number of carefully selected samples are tested so that the natural range of UCS values for the investigated rock gets revealed. Here, histogram is plotted to arrive at the range of representative UCS values.

In case of assessment of shear strength parameters, in general, it is expected that the confining pressure, especially at higher levels, would lessen the scatter in the response of the rock, and the triaxial test data would be amenable to standard Mohr-Coulomb analysis; and, except near the unconfined state of stress, the 'axial stress at failure', σ_a, and 'confining pressure', σ_c, would be linearly related.

The problem, however, arises when the range of 'scatter in σ_a values at a given σ_c' exceeds the 'increase in σ_a due to increase in σ_c'. In such a situation, the testing of carefully selected large number of samples becomes inevitable, because that is likely to throw up the entire spectrum of the inherent natural response of the involved rock - an overall trend of 'increase in σ_a with increasing σ_c' in a *curvilinear* band encompassing most of the data, and demarcated by upper bound and lower bound curves - as has been shown by Abdullah and Dhawan (2003, 2004) for granite gneiss and by Abdullah et al. (2009) for sandstone.

The tangents, to these lower, and upper, bound curves, are treated as the traditional 'strength envelops', thereby yielding the range of shear strength parameters.

As has been shown by Abdullah et al (1995), and Abdullah and Dhawan (2002), the unorthodox use of the data of waves' velocities - compression wave velocity in dry state, $V_{p(dry)}$, shear wave velocity in dry state, $V_{s(dry)}$, compression wave velocity in saturated

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state, Vp(sat), and shear wave velocity in saturated state, $V_{s(sat)}$ - is a great help in dealing with the scatter in the UCS and triaxial tests' data, and arrive at the representative values. That is so because the evaluation of the waves' velocities, being non-destructive, different samples - later employed for the determination of an engineering parameter involving samples' destruction, such as shear strength - can be compared.

The Study

Four sandstones from one project area have been evaluated for UCS and shear strength (employing Mohr-Coulomb failure criterion), under saturated state. The assessment of uniaxial compressive strength of two of these sandstones ('A' and 'B') gave 200% and 100% scatter. Because the evaluation of waves' velocities (compression and shear) in both dry and saturated states, helps in understanding scatter, therefore the waves velocities were evaluated for the remaining specimens before conducting any further UCS or triaxial tests.

The data of four sandstones has been collated for each of the three parameters - UCS, triaxial and waves' velocities - and the representative values of UCS and shear strength parameters computed, and recommended, on the basis of these combined data and holistic comprehension of the four sandstones.

Investigations Performed

Waves' Velocities

The compression wave velocity (V_p) and shear wave velocity (V_s), through the specimens - that are subsequently used for UCS/ triaxial test - are evaluated, employing P-wave transducers with wave length of 200kHz and S-wave transducers of 33kHz. The waves' velocities are evaluated for the specimens in two states - dry and saturated - thereby yielding four velocity values for each specimen. The drawing of 'V_p versus V_s' plot (in dry and saturated, both states) helps in better understanding of the specimens.

Uniaxial Compressive Strength

After evaluation of waves' velocities, the saturated Nx size specimens, with length to diameter ratio of 2.5, were tested for UCS, through application of static loading, under stress-controlled condition.

Triaxial Compression

After evaluation of waves' velocities, the saturated Nx size specimens, with length to diameter ratio of 2, were placed inside the Hoek's cell, and tested at different confining pressures, under triaxial compression - through application of static loading, under stress-controlled condition. The 'axial stress at failure' versus 'confining pressure' is plotted for each of the four sandstones, to see the possibility of drawing the 'Mohr-Coulomb failure envelop'.

Table 1 : UCS Test Data

----- 'A' ------		------- 'B' -------		------- 'C' ------		------- 'D' -------	
Sample	UCS	Sample	UCS	Sample	UCS	Sample	UCS
	(MPa)		(MPa)		(MPa)		(MPa)
A11	52	B11	77	C15	103	D13	72
A12	76	B12	94	C11	122	D14	98
A13	137	B13	125	C12	126	D15	108
A14	140	B14	128	C16	140	D11	212
A15	145	B15	159	C13	150		

Discussion of Individual Sandstones

Uniaxial Compressive Strength

The perusal of UCS data for four sandstones (Table 1) reveals that there is around 50% variation for sandstone 'C', 100% for 'B', and 200% for both, 'A' and 'D'. The maximum UCS for sandstones 'A', 'B' and 'C' is around 150MPa, whereas for 'D' it is 212MPa, though the rest of the UCS data for 'D' (72, 98 and 108MPa) is on the lower side. The lowest UCS for sandstone 'A' is 52MPa, whereas for 'B' and 'D' it is in 70s and, for 'C', it is 103MPa. Perhaps, rather uncomfortably, UCS values of 100, 100, 110 and 80MPa for sandstones 'A', 'B', 'C' and 'D' respectively, can be recommended. Given such a large variation in the UCS data for three of the four sandstones and largely overlapping ranges of UCS data, the possibility of clubbing the entire data of the four sandstones has been explored ahead.

Triaxial Compression

The triaxial test data is listed in Table 2, and the axial stress at failure versus confining pressure for sandstone 'A', 'B', 'C' and 'D' is plotted in Figures 1 to 4 respectively. The Figures reveal that the Mohr-Coulomb strength envelop can be plotted only for sandstone 'B' - but only after ignoring two of the seven samples.

In Fig. 1, three separate groups, comprising two, three and three samples, are in evidence. Two samples, tested at 1.5MPa confining pressure, give both, the lowest (65MPa) and the highest (198MPa) value for . Mohr-Coulomb failure envelop cannot be plotted here.

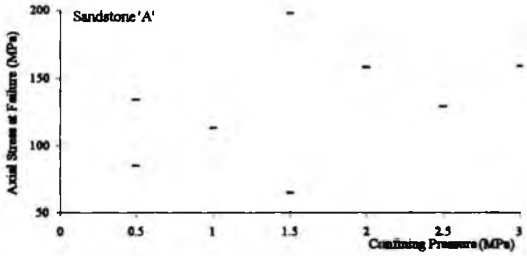

Fig. 1: Axial Stress v/s Confining Pressure

Figure 2 suggests that two samples need to be rejected, if a satisfactory correlation of the strength envelop is desired; and, it is interesting to observe that the ignored

Table 2 : Triaxial Test Data

Conf. Pr.	----- 'A'	----	----- 'B'	----	---- 'C'	---	------- 'D'	
(MPa)	Sample	σ_a (MPa)	Sample	σ_a (MPa)	Sample	σ_a (MPa)	Sample	σ_a (MPa)
0.5	A1	134	B5	208			D6*	109
0.5	A2	85					D5	181
1	A3	113	B1	102	C4	116	D4	187
1					C6	75		
1.5	A4	65	B6	140	C2	60	D7*	145
1.5	A8	198	B7	153				
2	A5	158	B2	167	C5	111	D1	103
2			B9*	178				
2.5	A7	129			C3	95	D2	164
3	A6	159						
3.5					C1	106		
4			B8*	212				

samples not only pertain to the minimum and maximum confining pressure of 0.5MPa and 4MPa, but also for both these ignored specimens, is around 200MPa. The computed shear strength parameters are 2.4MPa and 76o.

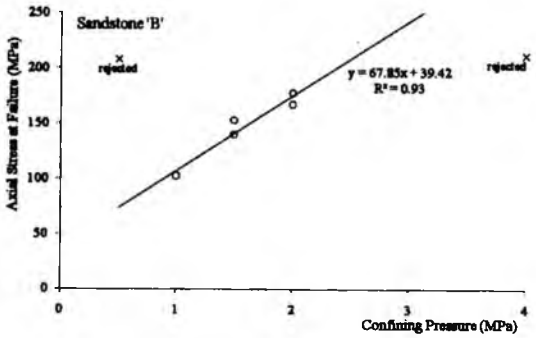

Fig. 2: Strength Envelop

Figure 3, with just six specimens' data, shows three/four groups, for the range of confining pressure from 1MPa to 3.5MPa. And, if the highest three values of are considered, then a reverse trend, i.e., 'decreasing with increasing ', is seen.

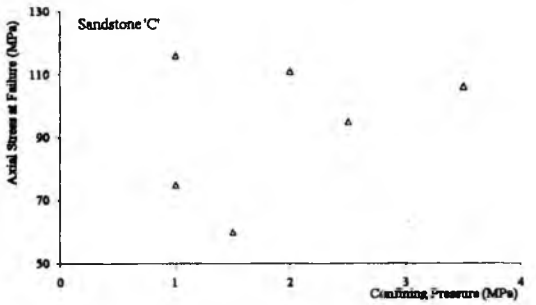

Fig. 3: Axial Stress v/s Confining Pressure

Figure 4 shows that the six tested samples fall in three groups - with one sample at the lowest, three in the middle, and two at the highest value of . And, there is no way that a rationally argued strength envelop can be drawn. One of the two samples tested at confining pressures of 0.5MPa and the one tested at 1MPa, have higher values than all other samples, tested for the 0.5 to 2.5MPa range of confining pressure.

The scatter in the triaxial test data for three of the four sandstones prompts one to club the data of four sandstones, and attempt to understand the rock holistically, as done ahead.

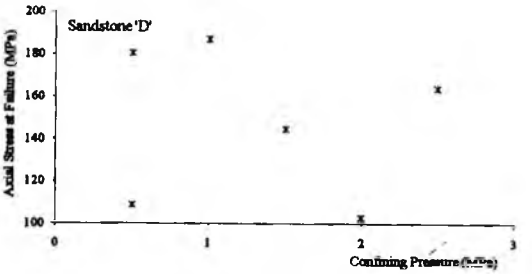

Fig. 4: Axial Stress v/s Confining Pressure

Waves' Velocities

For sandstones 'A', 'B', 'C' and 'D', the compression wave velocity in dry state (V_{pd}), shear wave velocity in dry state (V_{sd}), compression wave velocity in saturated state (V_{ps}) and shear wave velocity in saturated state (V_{ss}) have been evaluated; and, 'V_{pd} v/s V_{sd}' and 'V_{ps} v/s V_{ss}' for sandstones 'A', 'B', 'C' and 'D' plotted (not presented here), in order to identify the samples that do not belong to the cluster, or the dominant trend of the waves' velocities for the involved rock variant.

Clubbing of Data and Holistic Analysis

Uniaxial Compressive Strength

For sandstone 'A', there is incompatibility between the UCS values (52, 76, 137, 140 and 145MPa), and the triaxial test data ('confining pressure/ axial stress at failure': 0.5/85, 0.5/134, 1/113, 1.5/65, 1.5/198, 2/158, 2.5/129, and 3/159MPa) - as if the confining pressure is inconsequential. Also, there is 200% variation in UCS data.

For sandstone 'B', the triaxial test data has an intercept of barely 40MPa on the 'axial stress at failure' axis, and that is almost half the value of lowest UCS data (77, 94, 125, 128 and 159MPa).

For sandstone 'C', there is complete disjunction between the UCS data (103 to 150MPa) and triaxial test data (with axial stress at failure varying from 60 to 116MPa).

Sandstone 'D', besides having a scatter of 200% in UCS data, also has a huge gap between the highest value of 212MPa and the rest of the data. Its triaxial test data also has great scatter.

In view of the foregoing, for any of the four sandstones, there is little justification of recommending a single value of UCS, exclusively on the basis of UCS data.

Moreover, the triaxial test data (Table 2) and the UCS data (Table 1) show that the influence of confining pressure (resulting in increase of axial stress at failure with increasing confining pressure) does not manifest. Hence, the UCS data of the four sandstones is combined, and histogram (Fig. 5) prepared. Ignoring the lone highest value of 212MPa, a modified histogram is plotted (Fig. 6). On reducing the number of samples for 131-150MPa interval from 5 to 3, thereby erring on the safer side, a perfectly normal distribution can be had. On the basis of this modified histogram, UCS ranging from 90 to 130MPa can be recommended. However, in view of the inadequate database of UCS, rather large scatter in the UCS and triaxial test data, and a large chunk of the triaxial test data being below 130MPa, 70 to 100MPa is recommended for four sandstones.

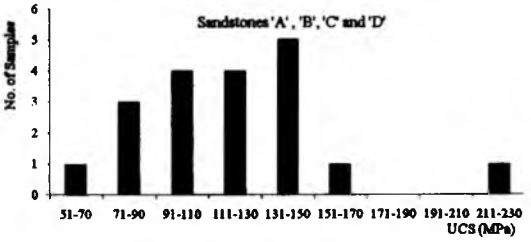

Fig. 5: Histogram of UCS

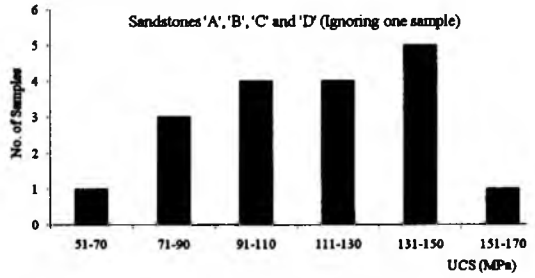

Fig. 6: Histogram of UCS (modified)

Shear Strength Parameters

The triaxial test data for all the four sandstones has been combined, and plotted in Fig. 7, where the natural pattern, because of large number of samples, reveals itself; and the upper-bound and lower-bound curves are conveniently drawn by ignoring few samples. Most, if not all, of these ignored samples are also non-representative in respect of one or the other wave velocity and/ or one or more of their derivative functions. Having drawn the lower-bound and upper-bound curves, the tangents - representing strength envelops - are drawn to each of these. The shear strength parameters, thus computed, circumscribe the range.

The primary consideration governing the tangents is that these intersect the σ_a -axis in the neighbourhood of the range for UCS. The computed shear strength parameters, i.e., Apparent cohesion (C) and Angle of internal friction (ϕ), on the basis of lower- and upper- bound curves, are 3.1MPa and 72° and 4.8MPa and 75°, respectively; and this range encompasses the shear strength parameters for sandstone 'B', i.e., 2.4MPa and 76°. One can recommend 2.4MPa/60° and 3.6MPa/60° as the range of shear strength parameters.

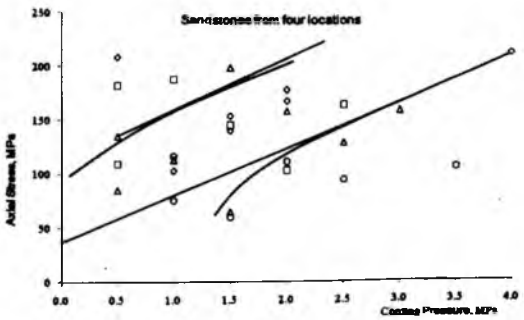

Fig. 7 Strength Envelops

Waves' Velocities

For all the four sandstones, the data of waves' velocities, as Vp versus Vs, has been plotted in Fig. 8, which shows that, for sandstones 'C' and 'D', in general, the UCS samples have higher Vs than the respective triaxial samples, whereas the Vp is similar. That corroborates the disjunction between the UCS and triaxial test data of these sandstones.

Conclusions

The following conclusions are deduced from the above discussion pertaining to the evaluation of four variants of sandstone in CSMRS' laboratory:

- The inherent variability and the overlapping UCS data of the four investigated sandstones can be better understood, and realistic range for UCS recommended, if the data of all sandstones is clubbed.
- The inherent variation of the tested specimens, in case of three of the four investigated sandstones, is so large that it dominates the increase in σ_a due to increase in confining pressure, thereby making the assessment of the shear strength parameters impossible.
- Only if twenty-five or more samples are tested for shear strength, the natural response can be discerned and, ignoring the obviously odd specimens, the 'lower bound' and 'upper bound' curves drawn in 'σ_a versus σ_c' plot.
- These tangents represent the lower and upper limit of the strength envelops, and yield the range of shear strength parameters for the investigated rock variants of sandstone from central India.
- The waves' velocities - $V_{p(dry)}$, $V_{s(dry)}$, $V_{p(sat)}$, and $V_{s(sat)}$ - and their functions, along with the 'V_p versus V_s' plot, are invaluable in identifying the non-representative specimens and in arriving at a rationally valid assessment of shear strength parameters.
- The above are tentative initial steps and much more work would have to be done to get a better insight and refine the employed techniques.

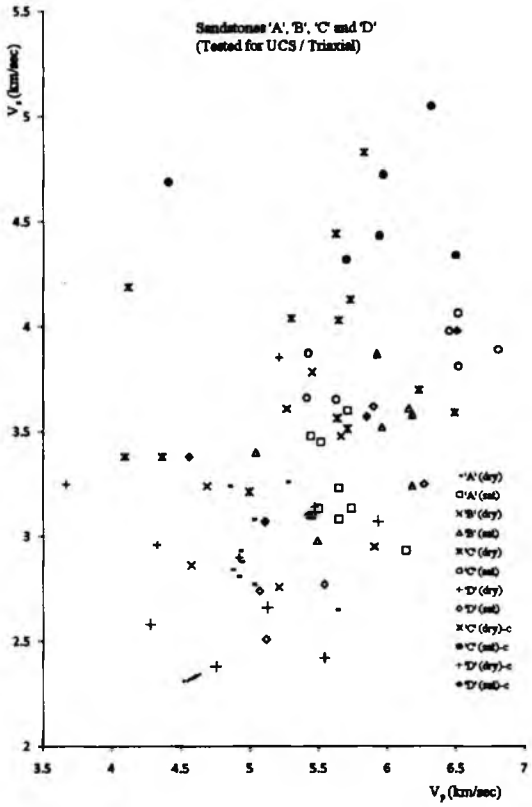

Fig. 8 Vp v/s Vs

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