Laboratory Study of Strong, Moderate and Weak Sandstones

Abstract
Sandstones from seven different hydroelectric projects have been assessed to compare their water-related properties and engineering parameters and the comprehensive analysis has been presented. The study has been done by categorizing the sandstones in to three categories i.e. weak, moderate & strong sandstones. The study leads to four broad inferences: (1), there could be very large variation between two sandstones; e.g., here, sandstone S2, S4 & S5, vis-à-vis other two strong sandstones, is superior in all respects. (2), the four weak sandstones differ in respect of some – not all – properties and parameters. (3), none of the four weak sandstones is better than the other two in respect of all properties and parameters. (4), moderate sandstone shows higher values of shear strength parameters in comparison to all the sandstones (including stronger sandstones also) except S3 strong sandstone. In respect of individual properties, the grain density of all sandstones is similar, though their bulk densities, apparent porosity and water content show great variation. The weak, moderate and strong sandstones show qualitative difference in their uniaxial compressive strength and wave velocity (compression and shear, both); and the two are directly proportional. The study clearly demonstrates that there is no one-to-one correspondence between any two properties and parameters, but there is a diffused and/or qualitative relationship between different sandstones, or certain properties and parameters of a particular variant.

Keywords: Correlation, Laboratory, Modulus, Sandstone, UCS, Wave Velocity

I. INTRODUCTION

Twelve Sandstones of Himalayan region, comprising the subsurface of seven major hydro-electric projects, have been investigated for various identification and water-related properties and engineering parameters. Water-related and identification properties include densities [bulk – dry (γ_bdry), and saturated (γ_sat); and grain (γ_grain)], water content at saturation (wc), apparent porosity (η) and slake durability index (SDI). And, engineering parameters include strength and deformability characteristics in uniaxial compression [Uniaxial compressive strength (UCS), Tangent Modulus (E) and Poisson ratio (μ)], waves’ velocities [both compression (V_p) and shear (V_s) waves], indirect tensile strength (σ_t; through Brazilian test) and shear strength parameters [cohesion (c) and internal angle of friction (Ø); through triaxial test]. The engineering parameters have been assessed in saturated state, unless otherwise stated.

UCS is one of the most widely used engineering parameters of rock engineering and also the only laboratory parameter which is used for the classification of rock mass through Rock Mass Rating (RMR) methodology proposed by Bieniawski (1989). These sandstones have been categorized in weak (<20MPa), moderate (20-60MPa) and strong (60-200MPa) sandstones, as per ISRM classification and these have been further arranged in the increasing order of their representative UCS values. There are 4 weak sandstones – namely W1, W2, W3 and W4. W1 has the lowest UCS and W4 has the highest. Similarly, there are 3 moderate sandstones named as M1, M2, M3, and 5 strong sandstones, named as S1, S2, S3, S4 and S5 in increasing order of their UCS.

Mineralogy, density, water content and porosity are some of the properties that influence the behavior of rock. Sandstone is unique in behavior amongst other variants of rock; and the sandstones may also hugely vary in respect of engineering parameters (Goodman, 1993). Hence, these physical properties have also been discussed in details.

The main objective of this study is to explore the possibilities to establish relation, if any, between weak, moderate and strong sandstones based on analysis of properties and parameters. The study has also aimed to find out correlation between UCS and other properties and parameters. Here, the representative values of different properties and parameters of twelve sandstones under consideration have been presented. The representative values were obtained by analyzing the data of each sandstone holistically, i.e., by neglecting higher and lower non-representative values and taking the average of the rest of the data. After
presenting the data of each property and parameter, the possibility of correlation between different properties and parameters has been explored.

II. TEST METHODOLOGIES

For comprehensive laboratory assessment of the twelve varieties of sandstone, tests were carried out according to ISRM Suggested Methods (Blue Book, 2006). Nx size cylindrical rock core samples were tested. To find the UCS, E and μ, rock specimen of length to diameter ratio of 2.5 were used. For Shear Strength Parameters (c and φ), rock specimen of length to diameter ratio 2.0 were used. For evaluating the Indirect Tensile Strength by Brazilian method, disc samples were tested having length to diameter ratio 0.5 (Brown, 1978). All tests were conducted on samples in the water saturated condition. The V_p and V_s of each cylindrical rock samples were determined by using Ultrasonic Pulse Wave Velocity Tester before conducting the destructive test.

To determine the bulk densities, rock lump 5-15g was selected and the volume of each lump was measured by mercury displacement method. The density of each lump were evaluated both in dry and saturated conditions. For evaluating the grain density, powdered samples of 30-50g were used and the density was calculated by employing specific gravity bottle. Kerosene, a non-reacting fluid was used to find the density. To find the Slake Durability Strength Index, a special apparatus was used which comprises two cylindrical perforated drums, capable of rotating in small water tanks. Ten rock lumps having mass 40-60g were placed in the drum. The drums were given 200 revolutions and the mass retained gives the percentage of slaking.

III. RESULTS & DISCUSSIONS

The representative values of the 12 sandstones have been shown in Table 1. These sandstones have been arranged in the increasing order of their UCS values. Weak sandstones are designated as W1, W2, W3 and W4, the moderate sandstones are designated as M1, M2 and M3; and the strong sandstones are designated as S1, S2, S3, S4 and S5 respectively.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Weaker Sandstones</th>
<th>Moderate Sandstones</th>
<th>Strong Sandstones</th>
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<td>W2</td>
<td>W3</td>
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<tr>
<td>E, GPa</td>
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<td>6</td>
<td>10</td>
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<td>SDI, II cycle, %</td>
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A. UCS & E

The UCS values of W1 to W4 are 5.46MPa, 10MPa, 10MP & 13MPa respectively, i.e., all these variants fall under low strength category. The sandstones M1 to M3 have UCS values 35MPa, 53MPa & 53MPa respectively, i.e., all these variants fall under moderate strength category. The sandstones S1 to S5 has high UCS values - 80MPa, 90MPa, 100MPa, 100MPa and 110MPa, i.e., all these variants belongs to high strength category (ISRM classification; Blue Book).

The representative E values for W1 to W4 are 7.5, 6, 10 and 9GPa. The Typical strain v/s stress curves for W2 and W3 sandstone samples are shown in Fig. 1 and 2. It has been observed that within the weak varieties, there is difference in the deformational characteristics. As can be seen by comparing Fig. 1 and Fig. 2 that in case of W1, the strain at failure is about 1100micron and in case of W2, the strain at failure is about 3000micron. For W2, there is large initial deformation at low stress level. The values of modulus ratio [E/UCS] range from 350 to 1350 for all the 12 sandstones; and there is no correlation of modulus value with UCS or E. It can easily be inferred from the foregoing that there is no relation between the UCS and E.
B. Wave Velocity – Compression/Shear

For W1 to W4 the representative $V_p$ values are 1.63, 2.8, 0.23 & 2.8km/s, whereas for M1 to M3 representative values for $V_p$ are 2.48, 2.68 & 4.6km/s, and representative values of $V_p$ for S1 to S3 are 4.8, 5.6, 5.0, 5.6 & 5.7km/s respectively. An increasing trend is observed for the all sandstones in their respective groups. Porosity plays an important role in modifying the $V_p$ and $V_s$ data. It may be observed that for W3, the low porosity value (5%) yields remarkably low value of $V_p$ and $V_s$ (0.23km/s and 0.25km/s respectively). It may be inferred that the low porosity of the rock helps leads to faster wave propagation.

Range of $V_s$ for weaker group is 1.06 to 1.4km/sec, for moderate group is 1.52 to 2.2km/sec and for stronger group is 2.5 to 4.0km/sec respectively. However, in all three cases, the range for the sandstones is different but has in increasing trend as well. The foregoing ranges of test data show that, notwithstanding the representative values for W2 and W4 being same, a more conservative value is recommended for W4, because of other considerations.

For W3, $V_p$ is very low, only 0.23km/s, which is unusual. For S5, as expected, $V_p$ is high i.e., 5.7km/s. For W3, $V_s$ is appreciably low – only 0.25km/s; and, for S5, it is quite high as 4.0km/s. The W3 sandstone shows exceptional decrease in $V_p$ and $V_s$ values. In some samples of S3, there is slight decrease in $V_p$ and $V_s$, but not comparable with the samples of W3. $V_p$ and $V_s$ data of all the twelve variants are been shown in Fig.3.

C. Indirect tensile strength

For all the twelve variants, the representative values and minimum to maximum range of indirect tensile strength, has been shown in Fig.4. The sandstones W1, W2 and W3 have very low tensile strength of around 1.0MPa; and, for W4 sandstone, slightly higher value of 1.5MPa has been obtained. For M1, M2 and M3 representative values of indirect tensile strength are 1.4MPa, 2.0MPa & 3.1MPa respectively for moderate strength group. For strong sandstones, tensile strength of S5 is very high i.e. 14MPa – which is even higher than the representative UCS for any of the other three variants of weaker sandstones. And for S1, S2 & S4 the representative values are 10MPa, 11MPa & 12MPa respectively.
D. Shear strength parameters

The shear strength parameters of weaker, moderate and strong sandstones are shown in Table-1. These parameters have been evaluated on the basis of Triaxial Shear Test, by using Hoek’s Triaxial Cell. In weaker variants, for low confining pressures, W4 has better shear strength with shear strength parameters of 3MPa and 28° than W3 with 1.5MPa and 42° and W1 having nearby values i.e., - 1.22MPa & 50°. Thus, W3 is poorer than W4 in respect of all the three strengths evaluated here – UCS, indirect tensile strength and shear strength. All the variants of moderate sandstone group have the same value of shear strength i.e. – 9.55MPa, which is high as compared to shear strength of weaker sandstones. The S3 sandstone has higher shear strength with 12MPa cohesion and 40° among strong sandstones, whereas S2 and S4 having same values shear strength parameters i.e., - 5MPa cohesion and 55°. And S5 with 3MPa cohesion and 55° have the lowest value in stronger group.

From Fig.5, it can be inferred that weaker sandstones are decidedly lower than the moderate and stronger sandstones, while, M1 to M3 of moderate group shows higher strength than S2, S4 and S5 under compression. Moderate sandstones have better shear strength parameters than S2, S4 and S5 of stronger sandstones as-well-as all sandstones of weaker groups as usual.
E. Apparent Porosity

Amongst the twelve variants, W2 sandstone has the highest porosity (35%), and belongs to very high category of porosity, irrespective of its UCS value which is greater than that of W1. W4 with 15% and W1 with 15.67% apparent porosity are at the lower end of high porosity rocks. W3 with 5% apparent porosity is at the lower end of medium porosity rocks which is denser than the moderate sandstone with apparent porosity of 11.66% for M1 & 9.27% for M2 which is almost at the low end of high porosity rocks, whereas for M3 is 4.03% also at the lower end of low porosity rocks. And, S3 has the lowest porosity of 1.19% among strong sandstone group whereas S2, S4 & S5 2.2%, 2.0% & 2.0% porosity respectively, which also belongs to low porosity rocks (1-5%) except S1 with 7.00% porosity which belongs low end of medium porosity.

Thus, it can be inferred that as per the classification based on porosity, the twelve variants of sandstone belong to different classes – very high, high, medium and low (Carmichael, 1989) – and has no relation with its UCS. In other words, in respect of porosity, these are qualitatively different sandstones. That means, with regard to the interconnectivity of pores, or the organization of the matter, reflected by apparent porosity, there is substantial, or qualitative, difference between the four variants of sandstone. Tentatively, one looks forward to improvement in various properties and parameters, as one proceeds from left to right in Table 1, except W3, M3 & S1, whose η values are not in accordance with their respective strength groups.

F. Density – bulk (Dry/ Saturated), & Grain

As per the classification in respect of dry bulk density, W1 & W2 sandstones falls in the low density category (1800-2200 kg/m3), whereas sandstone of W4, M1, M2, M3 & S1 falls in moderate category (2200-2550 kg/m3), and W3, S2, S3, S4 and S5 falls in high density category (2550-2750 kg/m3).

On saturation, the bulk density of W1 & W2 sandstones increases by 150kg/m3 & 340kg/m3 respectively; whereas for W3, W4 35kg/m3 & 110kg/m3. For M1, M2, & M3 bulk density increases by 115kg/m3, 90kg/m3 & 35kg/m3 respectively, and for stronger sandstones, the respective increase is 60kg/m3, 12kg/m3, 10kg/m3, 12kg/m3 and 17kg/m3.

Contrary to normal expectation, notwithstanding markedly low bulk density (dry and saturated, both) for W1 & W2 sandstones, it has highest grain density. However, broadly, all sandstones have similar grain density values (2615, 2625 and 2620 kg/m3) - W1 to W4, (2615, 2625 and 2620 kg/m3) – M1 to M3 and (2590, 2724, 2686, 2816 & 2666kg/m3) – S1 to S5 in order of Weaker, Moderate and Stronger Sandstone Groups.

G. Slake Durability Index

Assessment of weathering resistance in case of weak sandstones, shales, mudstones, siltstones and other clay-bearing rocks is important. SDI test measures the resistance of a rock sample to weakening and disintegration resulting from a standard cycle of drying and wetting [Franklin 1972].

It is to be noted that W2 sandstone has lowest dry bulk density amongst all variants of rock under consideration. But, it’s loss in mass (in the first cycle is 11% (89% SDI) and that places it in the category of high durability variety. In the second cycle, there is 10% further loss (79% SDI).

W4 sandstone is in the low durability category, as mass loss is 40% in the first cycle (60% SDI); but in the second cycle, the loss in mass is only 5% (55% SDI). The W3 sandstone has 85% SDI in the first cycle and 75% durability in the second cycle. Here, from 15% in the first cycle, the loss in mass reduces to 10% in the second cycle.

The foregoing suggests that with regard to SDI, the W2 and W3 sandstones have more in common, whereas W4 had excessive (40%) loss in the first cycle; but, in the second cycle, the loss is half compared to W2 and W3 (5% against 10%). Perhaps the third cycle would be appropriate to categories the rock near correctly.

The strong sandstones have very high durability in bot first and second cycles. Also, further loss in second cycle (i.e., with respect to the first cycle) is only 0.5% maximum. This clearly differentiates the strong sandstone rocks from other variants of sandstones. Whereas, slake durability data for W1, M1, M2 and M3 is not available for comparative study.

IV. CORRELATIONS OF PROPERTIES & PARAMETERS

Figures 6 and 7 show the variation of UCS values of each and every sample of all the twelve sandstones with respect to $V_p$ and $V_s$, respectively. It can easily be inferred from the graphs that there is no direct one to one correlation between the two parameters. However, broadly, it can be seen that the UCS values increases with the increase of $V_p$ and $V_s$.

In view of the broad direct correlation between these parameters (UCS and $V_p/V_s$), the representative values of UCS have been correlated with the representative values of both $V_p$ and $V_s$ (shown in Figure 8). Using regression analysis, the UCS has been correlated with $V_p$ and $V_s$. And, it is observed that both $V_p$ and $V_s$ is exponentially correlated with UCS and the coefficients of regression are 0.92 and 0.95, respectively.
Similar to UCS, the representative values of $E$ have also been correlated with the representative values of $V_p$ and $V_s$ (Figure 9). Similarly, using regression analysis, the $E$ has also been correlated with $V_p$ and $V_s$. It is observed that both $V_p$ and $V_s$ is correlated with $E$ using a power trend line, which shows that the $E$ increases at a specific rate with the increase in both $V_p$ and $V_s$. And, the coefficients of regression are 0.89 and 0.91, respectively.
The variation of UCS with indirect tensile strength for the eleven sandstones is given in Fig. 10. Figure 10 shows that weaker and stronger sandstones are directly proportional, whereas moderate sandstones do not follow the trend of other two sets of sandstones.

The variation of UCS with Bulk density (sat) for the twelve sandstones is given in Fig. 11. And, it shows that the two weaker sandstones i.e. W3 & W4 have higher values with low UCS, as quantity of fissures & irregularities were different in the specimens of UCS and physical properties which at times may have resulted in the lower strength despite having higher density.

Fig. 10: UCS v/s Indirect tensile strength ‘σt’ for sandstones

Fig. 11: UCS v/s Bulk Density ‘ϒsat’ for sandstones

Fig. 12: ‘ϒ’ (dry & Grain), ‘W.C.’ and ‘η’ for sandstones

Fig. 12, showing bulk density (dry), grain density, apparent porosity and water content. Increasing apparent porosity and decreasing dry bulk density also suggest that the material is probably of similar density; except W3 & W4 and it is basically the organization of matter that is different in these variants. Density of W1 > W2 & W3 > W4, while apparent porosity of W2 > W1 & W4 > W3, which infers density, porosity and UCS have no correlation.

The apparent porosity – and also the densities – gives no clue with regard to engineering parameters, such as strength. And, virtually, in respect of all engineering parameters, W3 turned out to be inferior to W4 sandstone, except; in respect of physical properties and also slake durability index.
V. CONCLUSION

The study demonstrates that there is no one-to-one correspondence between any two properties and parameters. However, there is a diffused and/or qualitative relationship between different properties and parameters, in the form of representative values.

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