A Laboratory Study of Strong and Weak Sandstones

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A LABORATORY STUDY OF STRONG AND WEAK SANDSTONES

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ABSTRACT

The laboratory evaluation of four sandstones from three projects, Shwezaye H.E. Project, Myanmar, Ujh H.E. Project, J&K, India (two variants) and Ken- Betwa Link Project, M.P., India, is presented here.

The study leads to three broad inferences: one, there could be very large variation between two sandstones; e.g., here, sandstone from Ken-Betwa, vis-à-vis other three (comparatively poor) sandstones, is superior in all respects (except grain density). Two, the three poor sandstones differ in respect of some – not all – properties and parameters. Three, none of the three poor sandstones is better than the other two in respect of all properties and parameters.

In respect of individual properties, the grain density of all four sandstones is similar, though their bulk densities, apparent porosity and slake durability index show great variation. The weak and strong sandstones show qualitative difference in their uniaxial compressive strength (UCS) 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.

INTRODUCTION

On the small scale, rock is composed of grains, and the form of microstructure is governed by the basic rock forming processes. Subsequent geological events may affect its mechanical properties and its susceptibility to water penetration and weathering effects.

Rock strength plays a major role in the design of structures. Mineralogy, density, water content and porosity are some of the properties that influence the behavior of rock. Sandstone is unique in behaviour amongst other variants of rock; and the sandstones may also hugely vary in respect of engineering parameters (Goodman, 1993).

The strength of sandstone is mainly a product of the diagenetic bonding. Geological nomenclature is inadequate in engineering geology, where the nature of the matrix material and descriptive information, both, are needed to describe a rock. Because of the high strength of the matrix and its completeness in filling the pores, graywackes tend to be hard, strong rock. Particles are clastic rather than crystalline.

DISCUSSION

Uniaxial compressive strength (UCS) is an important parameter, and is easy to evaluate. For four sandstone variants from three projects, Shwezaye H.E. Project, Myanmar, Ujh H.E. Project, J&K, India (two variants) and Ken-Betwa Link Project, M.P., India, (CSMRS, 2009 and CSMRS, 2012) in addition to UCS, other evaluated parameters and properties include: compression wave velocity (V_p) and shear wave velocity (V_s), in dry and saturated both states, tangent modulus (E), cohesion (c) and angle of internal friction (Ø), point load strength index ($I_{s(50)}$), under axial and diametral loading, tensile strength, bulk density (dry/ saturated), water content, apparent porosity, and slake durability index (SDI).

The recommended values for the properties – and the ranges in addition to the recommended values for parameters – are presented in Table-1 ahead. On the basis of this extract and the relevant detailed reports, correlation between different properties and parameters – of each sandstone variant, as also between the four variants of sandstones – is explored.

TABLE 1 Properties and parameters of four sandstones

Parameter / Project	Shwezaye	Ujh-1	Ujh-2	Ken- Betwa
Apparent porosity, %	35	15	5	2
Water content, %	20	6	2	0.8
Bulk density (dry), kg/m^3	1800	2490	2590	2612
Bulk density (sat), kg/m^3	2140	2600	2625	2629
Grain density, kg/m^3	2680	2640	2640	2666
SDI, I cycle, %	89	60	85	99.5
SDI, II cycle, %	79	55	75	99.2
$V_{p\ (dry)}$, km/s	1.9[1] (1.1-2.7)[2]	2.5 (2.2-3.3)	2.8 (2.7-3.0)	5.1 (4.1-6.5)
$V_{s\ (dry)}$, km/s	1.2 (0.6-1.5)	1.2 (1.1-1.7)	1.4 (1.4-1.5)	3.6 (3.2-4.8)
$V_{p\ (sat)}$, km/s	2.8 (0.9-3.2)	2.8 (1.8-4.5)	0.23 (0.18-0.30)	5.7 (4.4-6.0)
$V_{s\ (sat)}$, km/s	1.4 (0.7-1.6)	1.4 (1.1-1.7)	0.25 (0.17-0.31)	4.0 (3.7-4.7)
UCS, MPa	11 (6-15)	13 (10-25)	10 (6-21)	110 (103-149)
Tangent modulus, GPa	6 (3.5-20.0)	9 (7-23)	10 (11.0-27.0)	-
Indirect tensile strength, MPa	0.9	1.5 (1.3-3.8)	1.0 (1.1-2.1)	14 (10.9-21.1)
Cohesion, MPa	-	3	1.5	3
Ø, degrees	-	28	42	55
$I_{s(50)}$ (axial), MPa	1.8 (1.6-3.2)	0.22 (0.22-0.58)	0.15 (0.13-0.20)	10 (2.3-14.1)
$I_{s(50)}$ (diametral), MPa	1.4 (1.2-2.5)	0.15 (0.13-0.20)	0.1 (0.08-0.45)	4.8 (1.9-6.7)

[1] – The recommended values are outside the parenthesis. To account for variability, these are lesser than the representative values.
[2] – The range (minimum-maximum value) is given in parenthesis.

The investigated projects pertain to water resources sector; and, therefore, all the engineering parameters are evaluated in saturated state. However, the waves' velocities are assessed in dry, and in saturated, both, states, because of two reasons. One, the evaluation of waves' velocities is the only non destructive method of assessment, and therefore it is feasible to determine waves' velocities in dry and saturated both states for the same specimens; and, two, because the variation in waves' velocities – on saturation – reveals a lot about the involved rock variant.

In Table 1 above, the four different variants of sandstone rock, drawn from three different projects, are arranged according to descending order of apparent porosity, as pore spaces are considered crucial for comparative strength of different variants of a given rock type such as sandstone. That is so because the interconnected voids facilitate the formation of the failure plane. The decreasing apparent porosity also matches with the increasing bulk density – dry and saturated, both.

Apparent porosity

Amongst the four variants, Shwezaye sandstone has highest porosity at 35%, and belongs to very high category. Ujh-1 with 15% apparent porosity is at the low end of high porosity rocks. Ujh-2 with 5% apparent porosity is at the low-end of medium porosity rocks. And, Ken-Betwa has the lowest porosity of 2%, and belongs to low porosity rocks (1-5%).

Thus we note that as per the classification based on porosity, the four variants of sandstone belong to different classes – very high, high, medium and low (Carmichael, 1989). In other words, in respect of porosity, these are qualitatively different sandstones. That means, with regard to the interconnectivity of pores, or the organisation 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 above.

Density – bulk (dry/ saturated), and grain

The dry bulk density is rather low (1800 kg/m^3) for Shwezaye sandstone, but high for Ujh-1(2490kg/m^3), Ujh-2 (2590kg/m^3), and Ken-Betwa (2612kg/m^3). And as per classification in respect of dry bulk density (BIS codes), Shwezaye sandstone falls in the low density category (1800-2200 kg/m^3), whereas sandstone of Ujh-1 falls in moderate category (2200-2550 kg/m^3), and that of Ujh-2 and Ken-Betwa falls in high density category (2550-2750 kg/m^3).

In terms of dry bulk density, Ujh-2 and Ken-Betwa sandstones are quantitatively different, but these are qualitatively same; whereas, these sandstone variants are qualitatively different in respect of apparent porosity. That suggests, the apparent porosity criterion is more sensitive, and that selection of apparent porosity as the fundamental criterion to organise the data in Table 1 is correct.

Increasing apparent porosity and decreasing dry bulk density for the four variants also suggest that the material is probably of similar density; and it is basically the organisation of matter that is different in the four variants.

On saturation, the bulk density of Shwezaye sandstone increases by 340kg/m^3; whereas for Ujh-1, Ujh-2 and Ken-Betwa sandstones, the respective increase is 110, 35, and 17kg/m^3. And, the latter three sandstones have similar saturated bulk density values – 2600, 2625 and 2629kg/m^3 – and, it is appreciably higher than Shwezaye sandstone (2140kg/m^3).

Contrary to normal expectation, notwithstanding markedly low bulk density (dry and saturated, both) for Shwezaye sandstone, it has highest grain density. However, broadly, all four sandstones have similar grain density values (2680, 2640, 2640, and 2666kg/m^3) in order of Shwezaye (Sh), Ujh-1 (U1), Ujh-2 (U2) and Ken-Betwa (KB).

Slake durability index

The degradability of rock is very important in soft rocks – like weak sandstone and shale. To assess the degradability of rock, Franklin (1972) suggested slake durability index test. The loss of weight, as a result of the procedure suggested by him, is a measure of susceptibility of rock to combined action of slaking and mechanical erosion.

It is to be noted that Shwezaye sandstone has lowest dry bulk density amongst four 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).

Ujh-1 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 Ujh-2 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 Shwezaye and Ujh-2 sandstones have more in common, whereas Ujh-1 had excessive (40%) loss in the first cycle; but, in the second cycle, the loss is half compared to Shwezaye and Ujh-1 (5% against 10%). Perhaps the third cycle would be appropriate to categorise the rock near correctly.

The Ken-Betwa sandstone has a very high durability – 99.5% in the first cycle and 99.2% in the second cycle. That means, further loss in second cycle (i.e., with respect to the first cycle) is only 0.3%. This clearly differentiates the KB rock from other variants of sandstones.

Wave velocity – compression/ shear

For Shwezaye, Ujh-1, Ujh-2 and Ken-Betwa, the recommended $V_{p(dry)}$ values are 1.9, 2.5, 2.8 and 5.1km/s respectively. That means the less porosity, or more bulk density, has helped wave propagate faster.

The respective recommended values of $V_{s(dry)}$ are 1.2, 1.2, 1.4 and 3.6km/s. Like $V_{p(dry)}$, in case of $V_{s(dry)}$ also, an increasing trend is observed for the same sandstones.

In case of the sandstones from Shwezaye and Ujh-1, the recommended $V_{s(dry)}$, $V_{p(sat)}$ and $V_{s(sat)}$ are 1.2, 2.8 and 1.4km/sec respectively. However, in all three cases, the range for the two sandstones is different.

$V_{s(dry)}$ for Shwezaye ranges from 0.6 to 1.5km/s, but for Ujh-1 it is 1.1 to 1.7km/s. The ranges for $V_{p(sat)}$ for Shwezaye and Ujh-1 are 0.9-3.2km/s and 1.8-4.5km/s respectively. And, the ranges for $V_{s(sat)}$ are 0.7-1.6km/s and 1.1-1.7 km/s respectively for Shwezaye and Ujh-1.

The foregoing ranges show that notwithstanding the recommended values for Shwezaye and Ujh-1 being same, a more conservative value is recommended for Ujh-1, because of other considerations.

For Ujh-2, $V_{p(sat)}$ is very low, only 0.23km/s, which is unusual. For Ken-Betwa, as expected, $V_{p(sat)}$ is high (5.7km/s).

For Ujh-2, $V_{s(sat)}$ is appreciably low – only 0.25km/s; and, for Ken-Betwa, it is quite high (4.0km/s).

On saturation, the Ujh-2 sandstone shows exceptional decrease in V_p and V_s values. In some samples of Ujh-1, there is slight decrease in V_p and V_s on saturation, but not comparable with the samples of Ujh-2. For all the four variants, the variation of '$V_{s\ (dry)}$ with $V_{p(dry)}$' and '$V_{s\ (sat)}$ with $V_{p(sat)}$', both, has been shown in Fig.1.

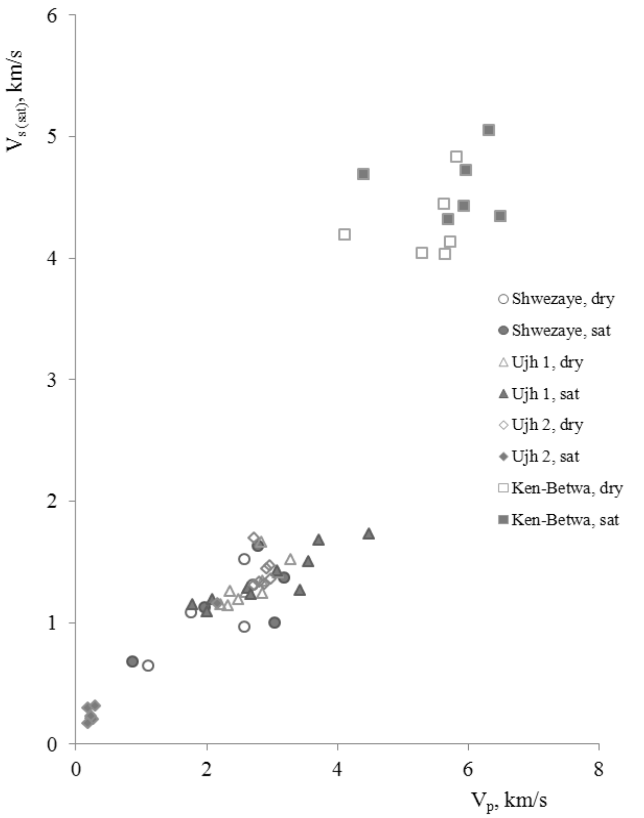

Fig. 1. V_s v/s V_p for sandstones

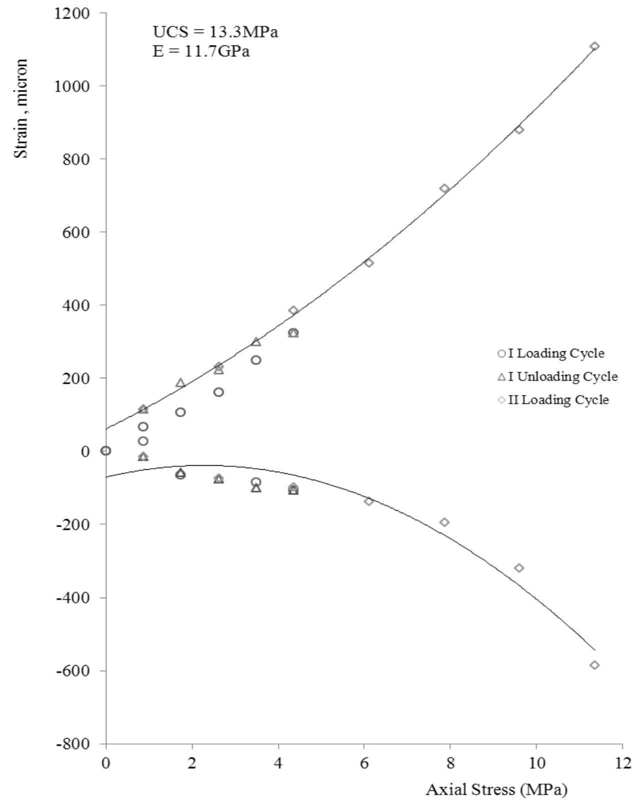

Fig.2. Strain v/s Stress (Shwezaye sample)

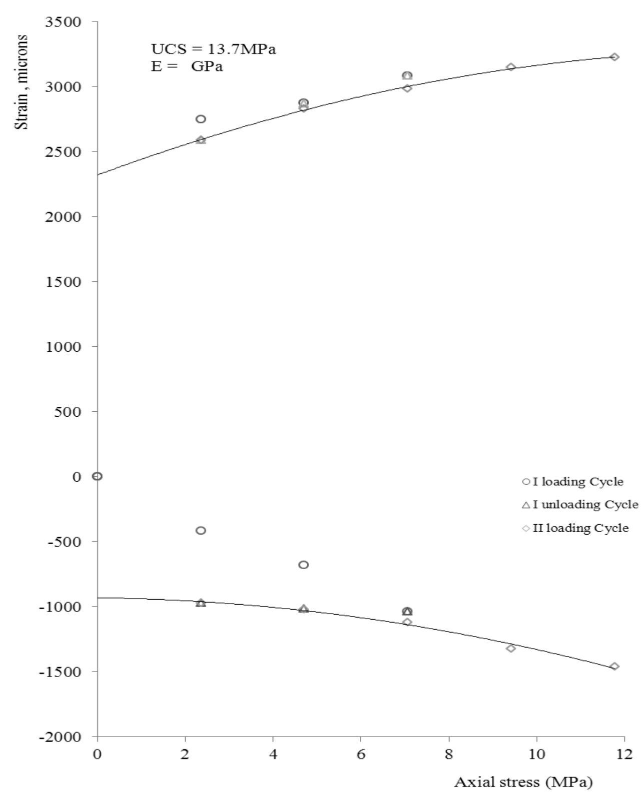

Fig.3. Strain v/s Stress (Ujh-2sample)

UCS and tangent modulus

Shwezaye, Ujh-1 and Ujh-2 all have low UCS – 11MPa, 13MPa and 10MPa respectively, i.e., all these variants fall under low strength category (ISRM classification). Ken-Betwa sandstone has a high UCS of 110MPa – and thus belongs to high strength category.

The UCS for Shwezaye, Ujh-1 and Ujh-2 sandstones varies from 6 to 15, 10 to 25, and 6 to 21MPa, whereas for Ken-Betwa, variation is from 103 to 149MPa. In percentage terms, the Ken-Betwa samples have lowest variability

The recommended modulus (E) values for are 6, 9 and 10GPa for Shwezaye, Ujh-1 and Ujh-2. The UCS and E values are low for the three sandstones; but there is marginal variation, and there is no correlation between the two.

The Typical strain v/s stress curves for Shwezaye and Ujh-2 sandstone samples are shown in Figures 2 and 3. As can be seen from these figures, the Ujh-2 samples undergo large initial deformation.

Figures 4, 5 and 6 show the variation of ‘UCS with $V_{p(sat)}$’ ‘UCS with $V_{s(sat)}$’ and ‘E with $V_{s(sat)}$’ respectively. It reveals that UCS has a better correlation with $V_{s(sat)}$ than with $V_{p(sat)}$. The modulus of elasticity (E) also has reasonable correlation with $V_{s(sat)}$.

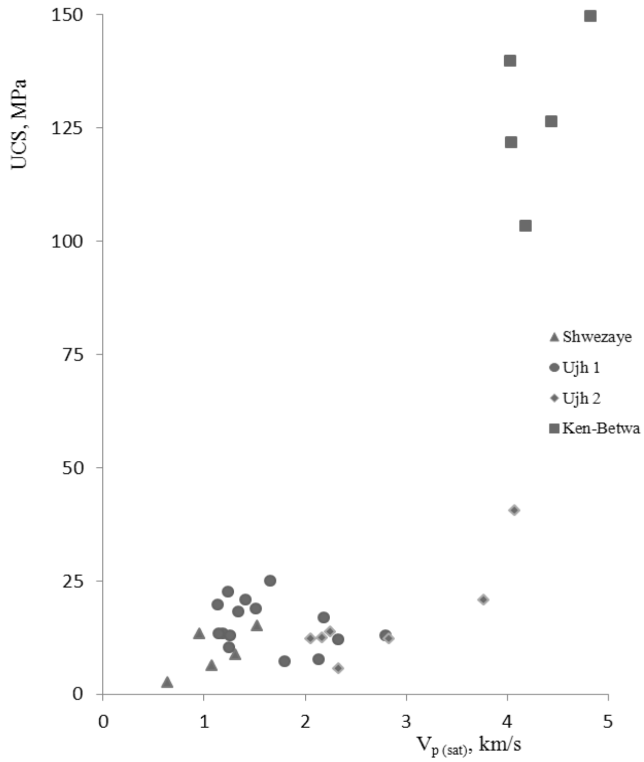

Fig.4. UCS v/s $V_{p(sat)}$

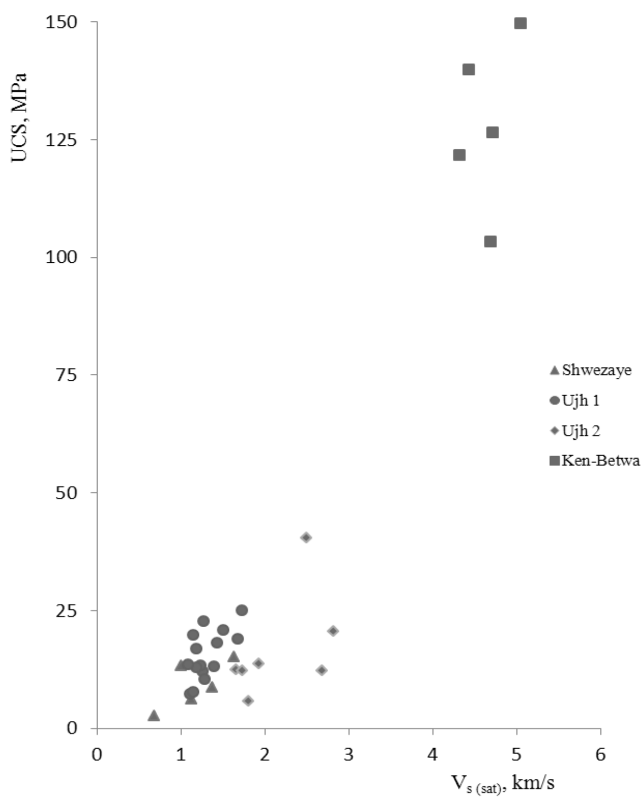

Fig.5. UCS v/s $V_{s(sat)}$

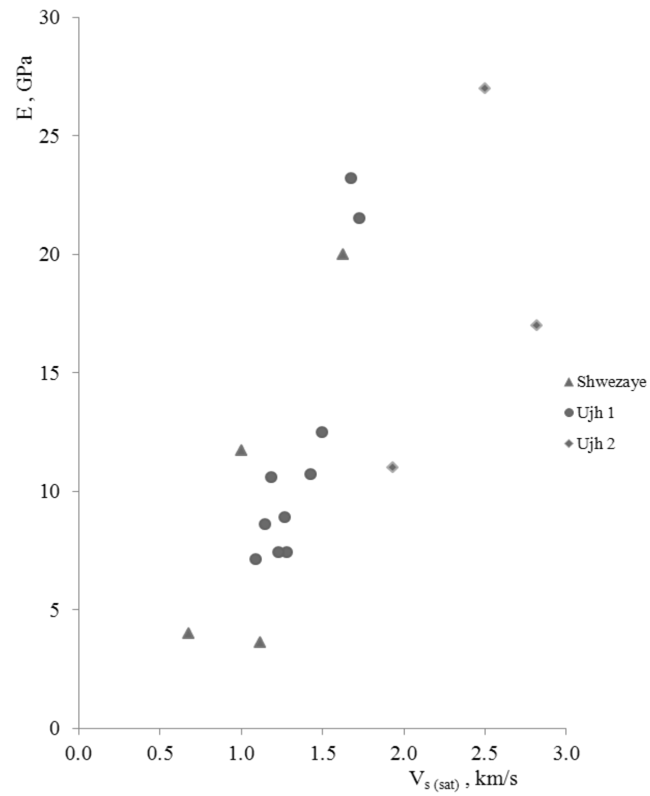

Fig.6. E v/s $V_{s(sat)}$

<u>Indirect tensile strength</u>

The tensile strength is evaluated indirectly, using Brazilian method (Brown, 1978). The Shwezaye and Ujh-2 sandstones have very low tensile strength of around 1.0MPa; and, for Ujh-1 sandstone, slightly higher value of 1.5MPa is recommended.

Ken-Betwa sandstone has a very high tensile strength of 14MPa – which is even higher than the recommended UCS for any of the other three variants of sandstone.

The variation of UCS with indirect tensile strength for the four sandstones is given in Fig. 7. And, it shows that the two strengths are directly proportional.

<u>Shear strength parameters</u>

The shear strength parameters of Ujh-1, Ujh-2 and Ken-Betwa have been evaluated. The Ken-Betwa sandstone has better shear strength with 3MPa cohesion and 55^o Ø. And, for low confining pressures, Ujh-1 has better shear strength with shear strength parameters of 3MPa and 28^o than Ujh-1 with 1.5MPa and 42^0. Thus, Ujh-2 is poorer than Ujh-1 in respect of all the three strengths evaluated here – UCS, indirect tensile strength and shear strength.

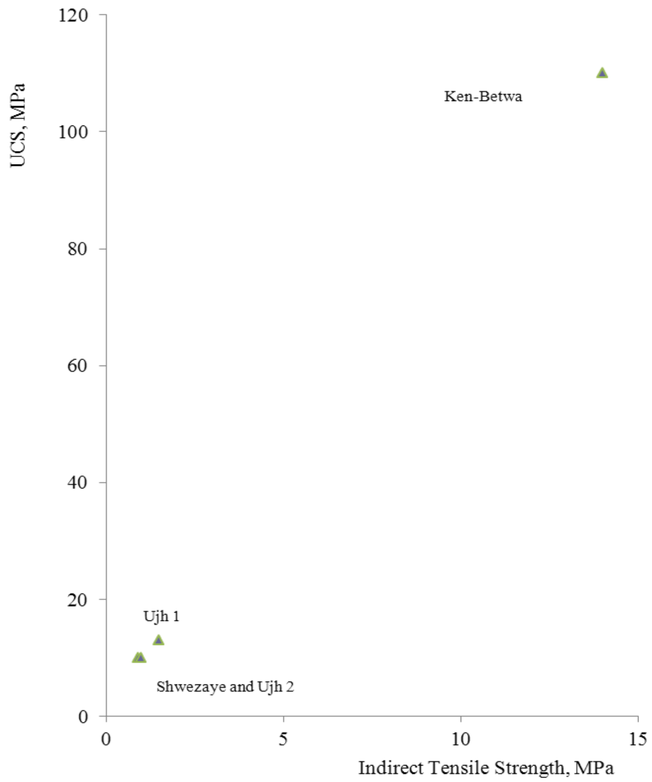

Fig.7. UCS v/s Indirect tensile strength

Point load strength index

The recommended point load strength index (axial) for Shwezaye sandstone is 1.8MPa, whereas for the sandstones from Ujh-1 and Ujh-2 it is just 0.22 and 0.15MPa respectively. In diametral loading, $I_{s(50)}$ is 1.4MPa for Shwezaye but 0.15 and 0.1MPa for Ujh-1 and Ujh-2. Though in UCS and indirect tensile strength, both, Shwezaye sandstone is poorer than Ujh-1 and Ujh-2, but it's $I_{s(50)}$ (axial and diametral, both) is much higher than Ujh-1 and Ujh-2.

In case of Ken-Betwa, $I_{s(50)}$, under axial and diametral loading, is 4.8 and 14MPa respectively; and that is quite high compared to the three weak sandstones.

CONCLUSIONS

The physical properties of apparent porosity – and also the densities – give no clue with regard to engineering parameters, such as strength. Ujh-2 sandstone showed peculiar behaviour in respect of waves' velocities on saturation. And, virtually, in respect of all engineering parameters, Ujh-2 turned out to be inferior to Ujh-1 sandstone; though it was quite superior to Ujh-1 sandstone in respect of physical properties and also slake durability index.

The point load strength index value does not reflect any correlation with either UCS or indirect tensile strength.

In case of qualitative difference in the uniaxial compressive strength, the wave velocity (compression and shear, both) also shows marked change; and the UCS is better correlated with $V_{s(sat)}$.

The study 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 properties and parameters.

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