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Ultrasonic pulse velocities and dynamic elastic constants of sandstones from the Semanggol Formation, Beris Dam, Kedah Darul Aman

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Abstract: The main Beris Dam is founded on a sequence of thick bedded conglomerates and pebbly to fine grained sandstones with minor mudstone mapped as the Semanggol Formation of Triassic age. Ultrasonic pulse measurements show velocities of compressional and shear waves through the sandstones to increase with decreasing grain size; the pebbly sandstone with velocities of 2.210, and 5.171, km/s, and the coarse grained sandstone with velocities of 2.477, and 5.612, km/s, respectively. The medium grained sandstones have compressional and shear wave velocities of 2.457, and 5.793, km/s and the fine grained sandstones, velocities of 2.572, and 5.867 km/s, respectively. Dynamic elastic constants computed from the ultrasonic velocities also increase in values with decreasing grain size; Poisson's ratio varying from 0.36 to 0.39, the modulus of elasticity from 35.076 to 48.210 GPa, the bulk modulus from 52.260 to 67.362 GPa and the modulus of rigidity from 12.637 to 17.468 GPa. Increasing velocities and elastic constants with decreasing grain size are considered to result from a denser arrangement of constituent grains as shown by increasing dry unit weights. Comparison with the results of an unconfined compression test on a fine grained sandstone indicate that the ultrasonic elastic constants are good approximations of static elastic constants.

Keywords: Ultrasonic pulse velocities, elastic constants, Semanggol Formation

INTRODUCTION

Properties of rock material are usually only considered from the point of view of their reaction to static stresses, i.e. the stresses to which a structure in rock would normally be subjected. However, during the construction phase of engineering projects, and possibly later if earthquakes or nuclear explosions are considered, a rock material may be subject to transient dynamic loading from the action of explosives, often exceeding by many orders of magnitude any static stress to which it may be subjected (Farmer, 1968). The way in which a rock material may accept or reject these dynamic stresses is of direct importance to the design of structures and towards this end, a knowledge of its dynamic elastic constants is extremely useful (Farmer, 1968).

Various methods are available for determination of the dynamic elastic constants of rock material; the most common laboratory method involving their calculation from measurements of the propagation velocities of compressional and shear waves (ASTM, 1976). Such a calculation procedure is possible in view of the fact that the existence and velocity of all body waves in an elastic medium is a function of its density and elasticity (Obert & Duvall, 1976). Where pulse frequencies above the audible range are used in determination of the velocities, the calculated constants are termed ultrasonic elastic constants (ASTM, 1976; AIT, 1981). It is to be noted that these ultrasonic constants, and wave velocities often do not agree with those determined by static laboratory, or *in situ* methods (ASTM, 1976). The ultrasonic method, however, has the advantage that it is a non-destructive technique and allows for preliminary prediction of the elastic properties of rock material.

A number of studies involving the ultrasonic method have been carried out in Malaysia; Raj (1996) showing compressional and shear wave velocities as well as dynamic elastic constants of igneous rocks from the Ajil area to be dependent upon inherent mineral compositions and textures. The ultrasonic method furthermore, determined a compressional wave velocity of 6.046 km/s for a porphyritic hypersthene micro-diorite from Tawau (Raj, 2004a), whilst a meta-rhyolitic tuff from the Dinding Schist was shown to be an anisotropic rock material with compressional wave velocities of 5.616, and 3.973, km/sec, parallel, and perpendicular, to foliation, respectively (Raj, 2004b).

Goh *et al*. (2016) determined the ultrasonic pulse velocities of compressional waves through some 70 granite, and 24 schist, specimens cored from samples collected at various locations in Peninsular Malaysia. Unconfined compression tests of the cores then led to proposal of two empirical relationships that were said to predict the uniaxial compressive strength from the compressional wave velocity.

Nurul Huda *et al*. (2019) determined the ultrasonic pulse velocities of compressional and shear waves through eight sandstone cores from the Kenny Hill Formation. Unconfined compression tests of the cores then allowed determination of the uniaxial compressive strengths as well as modulus of elasticity, shear modulus and bulk modulus. Regression analyses were said to yield good correlations between compressional wave velocities and static elastic constants.

In this short note, the compressional and shear wave velocities of ultrasonic pulses through sandstones from the Triassic Semanggol Formation are presented. Results of calculations of a number of dynamic elastic constants are also presented together with a discussion on the factors influencing the pulse velocities and elastic constants.

METHODOLOGY

Several boreholes were drilled during site investigation works for the main Beris Dam located in the narrow valley of Sungai Beris, some 1.6 km upstream of its confluence with Sungai Muda in Sik District in Kedah Darul Aman. A number of discontinuous rock cores from the boreholes were provided to the author for laboratory study and determination of their geotechnical properties.

One of the cores provided (borehole QR 3 at 37.50 to 38.80 m depth) was 0.7 m in length and showed graded bedding from pebbly sandstone at the base through coarse and medium grained sandstone to fine grained, laminated sandstone at the top. In order to investigate the influence of grain size on ultrasonic pulse velocities, the core was diamond sawn into several shorter specimens of differing grain size. The unit weights, densities and apparent porosities of these shorter specimens were then determined employing the saturation and buoyancy procedure of ISRM (1979). Thin-sections were prepared from representative specimens to identify their compositions and textures whilst the specific gravity of constituent mineral grains were determined with a pycnometer (GBRRL, 1952).

The tops and bottoms of the shorter cores were then finely ground before their visible textural and structural features described. The specimens were oven-dried at 105°C for 12 hours before measurement of ultrasonic pulse velocities along core lengths using an OYO Corporation Sonic Viewer (Model 5217 A). Compressional and shear wave transducers of 63 kHz, and 33 kHz, frequency were employed; the pulse rate set at 512 pps (pulses per second), a sampling range of 200 ns, and input, and output, gains of 10, and 3, respectively. For determination of the compressional wave velocities, which were carried out after measurement of the shear wave velocities, a thin film of grease was applied on the core ends to ensure good contact with the transducers.

After determination of the compressional and shear wave velocities, several dynamic elastic constants were calculated based on formulae provided in standard laboratory manuals as those of the American Society for Testing and Materials (ASTM, 1976) and the Asian Institute of Technology (AIT, 1981). It is to be noted that these formulae are based on assumption of a linear relationship between applied stress and the resulting strain; an elastic medium being one in which all strain is instantaneously and totally recoverable on removal of the applied stress (Farmer, 1968). In such a medium, the existence and velocity of all body waves is thus a function of its density (or unit weight) and elasticity; the propagation velocities of compressional, and shear, waves being related to the modulus of elasticity (E) (or Young's modulus), modulus of rigidity (G), Poisson's ratio (ν) and unit weight (or density) (Obert & Duvall, 1976).

It must be pointed out here that the formulae for calculation of the ultrasonic elastic constants have been employed in many other studies, though there are few demonstrations where these equations are truly applicable (Birch, 1966). The equations are furthermore, only valid if a material is isotropic, homogeneous and linear-elastic (Obert & Duvall, 1976). Rock material, however, is usually anisotropic, heterogeneous and behaves nonlinearly when subject to large stresses, though its behavior can be considered to be linear for sufficiently small changes in stress (Fjaer *et al*., 1992).

GEOLOGICAL SETTING OF SAMPLES

The concrete-faced rock fill main Beris Dam is located in the narrow valley of Sungai Beris, some 1.6 km upstream of its confluence with Sungai Muda in Sik District in Kedah Darul Aman (Figure 1). The dam, which is 40 m high and about 155 m long at its crest, was completed in 2004 and used to regulate flows in the Sungai Muda drainage basin to augment water available for irrigation as well as domestic and industrial water supply and other uses (DID, 2018). The dam has a catchment area of 166 km^2; the reservoir at normal pool level covering an area of 13.7 km^2 and at maximum pool level inundating an area of 16.1 km^2 (Tajul & Ismail, 2003).

The main Beris Dam and its spillway are founded on a sequence of massive to thick bedded conglomerate and gritstone with some sandstone and mudstone that is mapped as the Semanggol Formation of Triassic age (Teoh, 1992). Conglomerate predominates at the right abutment and underneath the dam, whilst at the left abutment and spillway, the conglomerate is inter-bedded with gritstone and coarse sandstone (Tajul & Ismail, 2003).

The matrix-supported, polymict conglomerate contains gravel to pebble-sized clasts of black to dark

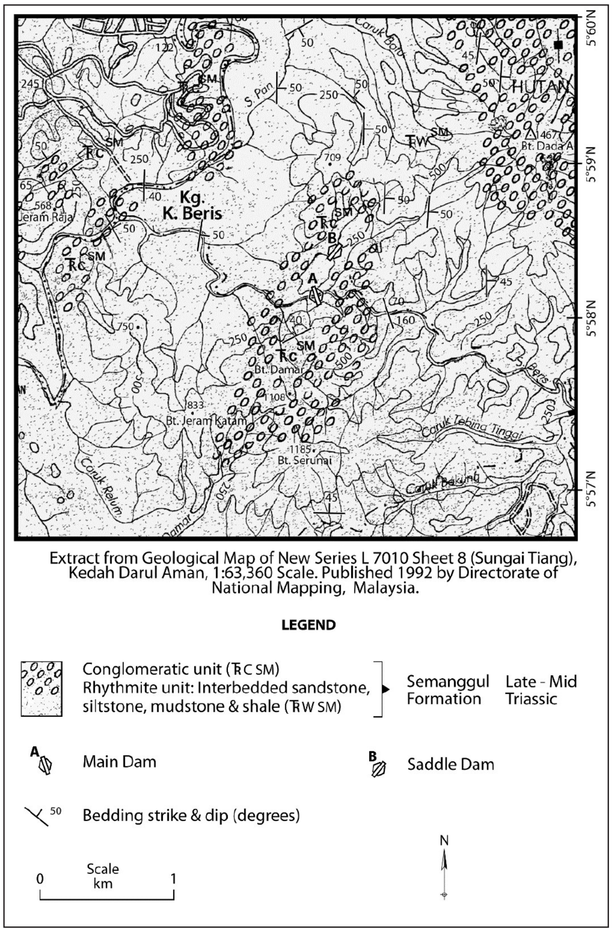

Figure 1: Geological setting of the Beris main and saddle Dams.

slate and mudstone, chert, quartz and other rock fragments, whilst the matrix comprises coarse sandy to gritty materials of quartz, feldspar and rock fragments. The rocks were said to be generally hard, compact and well indurated; requiring several blows of the geological hammer to collect samples (Tajul & Ismail, 2003).

The gritstones are transitional between the conglomerate and sandstone, and composed of fine gravel to coarse sand grains of quartz, quartzite, sandstone, chert and mudstone as well as other rock fragments. They are grey and hard and occur as inter-beds in the conglomerate and sandstone. The sandstone is generally a light grey, fine to coarse-grained, hard, compact and well indurated rock. In places, the thick sandstone beds contain shale/ mudstone partings (Tajul & Ismail, 2003).

The bedding planes are often not clearly defined due to the thick to massive bedding. At the right abutment, however, bedding planes strike about west to west-southwest with dips of 15° to 30° towards north. At the left abutment, the bedding strikes about east-west with dips of 45° to 52° towards south. The rocks are intensely faulted and jointed with a total of 5 to 6 major joint sets having been identified (Tajul & Ismail, 2003).

RESULTS

Petrography of investigated sandstones

The pebbly sandstones are seen in thin-section to be poorly to moderately sorted with clasts of chert, quartz and rock fragments in a finer grained matrix of similar composition. The clasts are 1 to 4 mm in size, whilst grains in the matrix are 0.13 to 0.25 mm in size. The clasts are sub-angular to angular in shape with the rock fragments including quartz-mica schist, siltstone and sandstone. Both mono-crystalline and poly-crystalline quartz clasts are present with some grains being well rounded.

The medium and coarse grained sandstones are seen in thin-section to be well sorted with angular to sub-angular, and more rarely, rounded, grains of quartz, chert and rock fragments. In the coarse grained sandstone, the grains are some 0.15 to 1.5 mm in size with a mean value of about 0.35 mm, whist in the medium grained sandstone, the grains are 0.1 to 1.5 mm in size with a mean value of 0.25 mm. Opaque, and heavy, minerals including tourmaline and zircon are sometimes seen in the thin-sections.

The fine grained sandstones are seen in thin-section to be distinctly laminated and well sorted with sub-angular to rounded grains of quartz, chert and rock fragments as well as mica flakes. The grains are some 0.06 to 0.5 mm in size with a mean value of 0.15 mm. A few heavy minerals including tourmaline and zircon are sometimes seen in the thin-sections.

Physical properties of investigated sandstones

Bulk and dry unit weights show some variation with grain size; the pebbly sandstone with a dry unit weight of 25.35 kN/m^3, whilst the coarse, and medium, grained sandstones have dry unit weights of 25.33, and 25.36, kN/m^3, and the fine grained sandstone, a dry unit weight of 25.81 kN/m^3 (Table 1). Values of dry density mirror those of the dry unit weight; the pebbly sandstone with a dry density of 2,585 kg/m^3, the coarse, and medium, grained sandstones with dry densities of 2,583, and 2,586, kg/m^3, respectively, and the fine gained sandstone with a dry density of 2,632 kg/m^3 (Table 1). The fine grained sandstones are thus the densest rock material investigated with the maximum values of unit weight and density.

Apparent porosities reflect to some extent differences in grain size with the pebbly sandstone having an average porosity of 3.9%, whilst the fine grained sandstone has a value of 2.2%. The coarse and medium grained sandstones, however, have a similar porosity value of 3.8% (Table 1).

The specific gravity of mineral grains in the different sandstones shows little variation and ranges between 2.62 and 2.64 (Table 1). This limited variation is not unexpected in view of the closely similar composition of the mineral grains present.

Compressional and shear wave velocities

Compressional wave velocities show a distinct decrease with increasing grain size; the fine grained sandstone having a velocity of 5.867 km/s, whilst the medium, and coarse, grained sandstones have velocities of 5.793, and 5.612 km/s, respectively, and the pebbly sandstone, a velocity of 5.171 km/s (Table 2). Shear wave velocities show a less distinct decrease with increasing grain size; the fine grained sandstone having a velocity of 2.572 km/s, whilst the medium, and coarse, grained sandstones, have velocities of 2.457, and 2.477, km/s, respectively, and the pebbly sandstone, a velocity of 2.210 km/s (Table 2).

Table 1: Physical properties of sandstones from the Semanggol Formation.

Sample Number	Bulk Unit Weight (kN/m^3)	Dry Unit Weight (kN/m^3)	Apparent Porosity (%)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)	Specific Gravity Grains
Pebbly Sandstone						
PS 1	26.02	25.73	3.0	2,653	2,624	2.63
PS 2	25.44	24.97	4.8	2,594	2,546	2.62
Average	25.73	25.35	3.9	2,624	2,585	2.62
Coarse grained Sandstone						
CS 1	25.69	25.32	3.7	2,619	2,582	2.62
CS 2	25.71	25.34	3.8	2,622	2,584	2.62
Average	25.70	25.33	3.8	2,621	2,583	2.62
Medium grained Sandstone						
MS 1	25.83	25.46	3.7	2,634	2,597	2.63
MS 2	25.64	25.26	3.9	2,615	2,576	2.62
Average	25.74	25.36	3.8	2,624	2,586	2.62
Fine grained Sandstone						
FS 1	25.96	25.72	2.4	2,647	2,622	2.64
FS 2	26.10	25.91	2.0	2,662	2,642	2.63
Average	26.03	25.81	2.2	2,654	2,632	2.63

Table 2: Ultrasonic pulse velocities and dynamic elastic constants of sandstones from the Semanggol Formation.

Sample Number	S Wave Velocity (km/s)	P Wave Velocity (km/s)	Poisson's Ratio	Modulus of Elasticity (GPa)	Bulk Modulus (GPa)	Modulus of Rigidity (GPa)
Pebbly Sandstone						
PS 1	2.111	5.033	0.393	32.570	50.882	11.688
PS 2	2.310	5.308	0.383	37.583	53.637	13.585
Average	2.210	5.171	0.388	35.076	52.260	12.637
Coarse grained Sandstone						
CS 1	2.470	5.575	0.378	43.415	59.229	15.755
CS 2	2.483	5.650	0.380	43.984	61.256	15.933
Average	2.477	5.612	0.379	43.700	60.243	15.844
Medium grained Sandstone						
MS 1	2.503	5.859	0.388	45.164	67.448	16.265
MS 2	2.410	5.726	0.392	41.668	64.508	14.963
Average	2.457	5.793	0.390	43.416	65.978	15.614
Fine grained Sandstone						
FS 1	2.443	5.751	0.390	45.503	65.871	15.650
FS 2	2.702	5.983	0.372	52.917	68.853	19.286
Average	2.572	5.867	0.381	48.210	67.292	17.468

It is to be noted that the propagation of ultrasonic pulse velocities in the investigated specimens is at an angle of about 15° to inherent bedding planes. Bedding planes, however, are only clearly seen in the laminated, fine grained sandstones and not in the medium, to coarse, gained, and pebbly, sandstones.

Dynamic elastic constants

Dynamic elastic constants computed from the ultrasonic pulse velocities show variations with grain size, except for Poisson's ratio (**ν**), which is a measure of the compressibility of material perpendicular to the applied stress, and has limited variation, ranging from 0.372 to 0.393 (Table 2).

The modulus of elasticity (or Young's modulus) (*E*) refers to the ratio of longitudinal normal stress to longitudinal normal strain and shows a general decrease with increasing grain size (Table 2). The fine grained sandstone has a modulus of elasticity of 48.210 GPa whilst the medium and coarse grained sandstones have values of 43.416, and 43.700, GPa, respectively, and the pebbly sandstone, a modulus of 35.076 GPa (Table 2).

The bulk modulus *(K*) defines the resistance of material to elastic compression and shows a clear decrease with increasing grain size (Table 2). The fine grained sandstone has a bulk modulus of 67.292 GPa, whilst the medium, and coarse, grained sandstones have values of 65.978, and 60.243, GPa, respectively, and the pebbly sandstone, a value of 52.260 GPa (Table 2).

The modulus of rigidity (*G*), or shear modulus, defines the ratio of shear stress to shear strain and shows a general decrease with increasing grain size (Table 2). The fine grained sandstone has a modulus of rigidity of 17.468 GPa, whilst the medium and coarse grained sandstones have values of 15.614, and 15.844, GPa, respectively, and the pebbly sandstone, a value of 12.637 GPa (Table 2).

DISCUSSION

Compressional and shear wave velocities

Compressional wave velocities have been shown to decrease with increasing grain size, though the shear wave velocities show a less distinct trend (Table 2). Plots of wave velocities versus dry unit weights furthermore, show a positive trend with rather low, squared correlation coefficients for both compressional (R^2=0.0693) and shear (R^2=0.0622) waves (Figure 2). Plots of wave velocities versus apparent porosity, however, show a negative trend with low squared correlation coefficients for compressional (R^2=0.1371) and shear (R^2=0.1332) waves (Figure 3).

The increase in velocities with increasing dry unit weights is an expected phenomena as several studies have shown that there is such an increase in rock materials with an increase in density (Lama & Vutukri, 1978). In the case of the investigated sandstones, the increase in pulse velocities with an increase in dry weights would thus be indicative of an increase in density with a decrease in grain size (Figure 2). The decrease in ultrasonic pulse velocities with an increase in apparent porosity is furthermore, reflective of the decrease in density with an increase in grain size (Figure 3).

Increasing velocities of compressional and shear waves with decreasing grain size are thus considered to reflect increasing densities that result from a more dense arrangement (or closer packing) of constituent particles in the investigated sandstones.

Published local data of relevance is limited to the compressional and shear wave velocities of 4.679 to 5.210 km/s, and 2.177 to 3.413 km/s, respectively, determined on 'hard' sandstones from the Kenny Hill Formation (Nurul Huda *et al.*, 2019). The shear wave velocities are comparable with those of the present study, though the compressional wave velocities are lower. The 'hard' sandstones of the Kenny Hill Formation with unit weights of between 29.62 and 30.42 kN/m³ furthermore, appear to be denser than those of the Semanggol Formation.

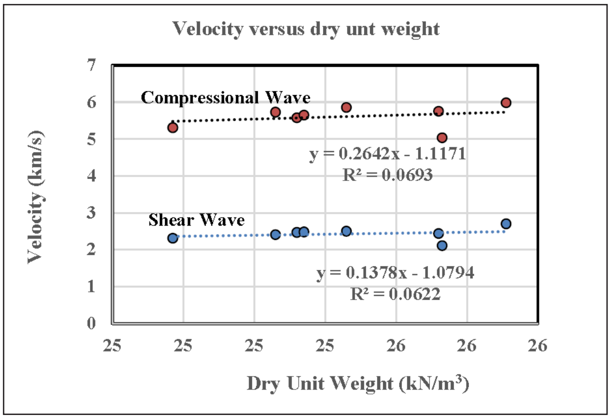

Figure 2: Compressional and shear wave velocities versus dry unit weight.

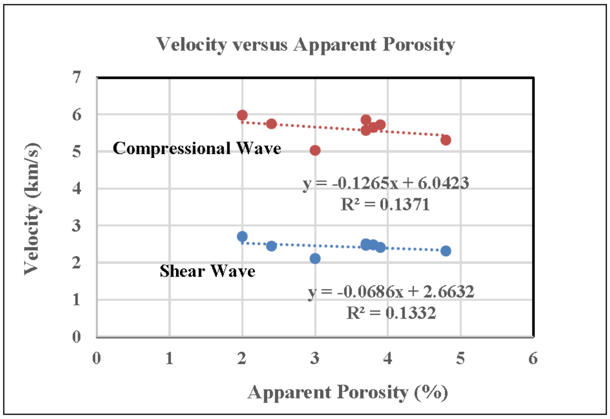

Figure 3: Compressional and shear wave velocities versus apparent porosity.

A number of empirical relationships have been proposed in Peninsular Malaysia to correlate ultrasonic pulse velocities with the strength of rock materials. Goh *et al*. (2016) for instance, proposed two empirical relationships that could be used to predict the unconfined compressive strength of granites and schists from the compressional wave velocity. No attempt, however, is made in the present study to correlate ultrasonic pulse velocities with published point load strength indices [$Is_{(50)}$] as the pulse velocities were measured at an angle (about 15°) to inherent bedding, whilst the point load tests were carried out parallel to bedding (Raj, 2019).

Dynamic elastic constants

Dynamic elastic constants, calculated from the measured velocities, have been shown to increase in values with a decrease in grain size (Table 2). Plots of the modulus of elasticity versus dry unit weights furthermore, show a positive trend with a low squared correlation coefficient (R^2=0.1549) (Figure 4). Plots of the bulk modulus, and modulus of rigidity, versus dry unit weights also show positive trends with low squared correlation coefficients of R^2=0.1372, and R^2=0.1271, respectively (Figures 5 and 6).

It is to be noted that the increase in values of elastic constants with an increase in dry unit weights is very similar to that shown by the compressional and shear wave velocities (Figure 3). It can therefore, be inferred that increasing values of the dynamic elastic constants with decreasing grain size reflect increasing densities that result from a more dense arrangement (or closer packing) of constituent particles in the investigated sandstones.

For purposes of comparison, the results of an unconfined compression test (with measurement of axial and circumferential strain) on one of the fine grained sandstone cores is presented in Table 3 (Raj, in prep). The said sandstone has an unconfined compressive strength of 136.2 MPa and overall, average values of 0.1072 for Poisson's ratio, 46.392 GPa for the modulus of elasticity, and 20.823 GPa for the modulus of rigidity (Table 3). A detailed analysis furthermore, shows that values of Poisson's ratio and modulus of elasticity vary with the compressive stress (Table 4). Poisson's ratio is low (<0.17) for low to moderate stresses (<130 MPa) and only reaches a value of 0.324 close to failure (130 to 135 MPa) (Table 4). The static modulus of elasticity, however, shows large values (>50 GPa) at low stresses (<20 MPa) and somewhat low values (<48 GPa) at high stresses (20 to 130 MPa) (Table 4).

Computed dynamic Poisson's ratios for the sandstones show a limited variability (Table 2) and thus indicate that the sandstones, although composed of particles of different size, would compress in a similar manner under applied stress. The unconfined compression test on the fine grained sandstone furthermore, shows that only close to failure does Poisson's ratio have the relatively large value of 0.324; this value being close to the calculated value of 0.381 (Tables 2 and 4). Values of the dynamic Poisson's ratio calculated from ultrasonic pulse velocities are therefore, only likely to be applicable under high compressive stresses (Birch, 1966).

Values of the dynamic modulus of elasticity (*E*) are seen to decrease with increasing grain size and range from

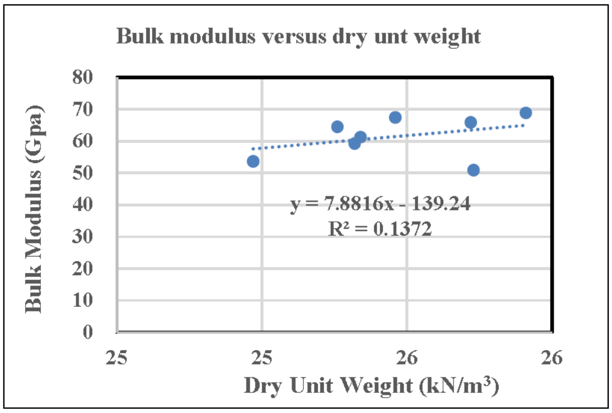

Figure 5: Dynamic bulk modulus versus dry unit weight.

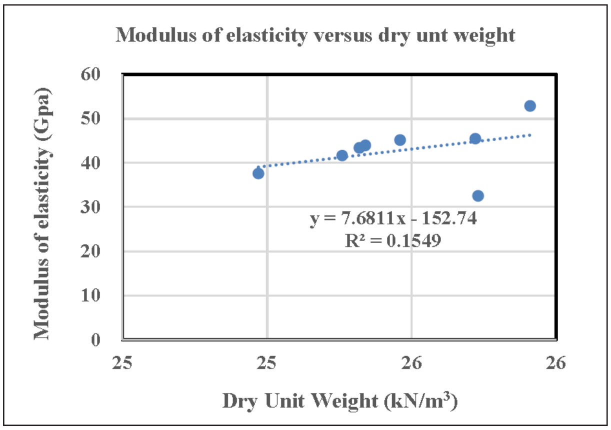

Figure 4: Dynamic modulus of elasticity versus dry unit weight.

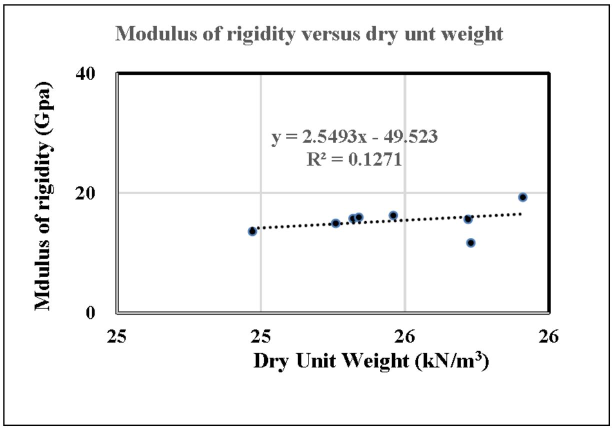

Figure 6: Dynamic modulus of rigidity versus dry unit weight.

Table 3: Results of unconfined compression test on fine grained, laminated sandstone (Raj, in prep.).

Parameter	Value	Comments
Unconfined compressive strength (UCS)	136.2 MPa	
Poisson's ratio	0.1072	Stress range: 4.3 to 78.5 MPa
Modulus of elasticity (E) (GPa)	46.392 GPa	
Modulus of Rigidity (G) (GPa)	20.823 GPa	

Table 4: Static elastic constants from unconfined compression test on fine grained, laminated sandstone (Raj, in prep.)

Compressive Stress	5-10 MPa	10-20 MPa	20-30 MPa	30-40 MPa	40-60 MPa	60-80 MPa	80-100 MPa	100-125 MPa	125-130 MPa	130-135 MPa
Poisson's Ratio	0.068	0.059	0.059	0.071	0.087	0.104	0.126	0.151	0.172	0.324
Modulus of Elasticity	64.53 GPa	52.72 GPa	47.00 GPa	47.74 GPa	46.91 GPa	46.40 GPa	46.61 GPa	44.90 GPa	42.86 GPa	32.82 GPa

32.570 to 52.917 GPa (Table 2). These calculated moduli are considered to be good approximations of static moduli of elasticity for the unconfined compression test on the fine grained sandstone yielded an overall static modulus of elasticity of 46.392 GPa; a value that is close to the calculated modulus of 48.210 GPa (Tables 3 and 2).

Values of the dynamic bulk modulus *(K*) are seen to decrease with increasing grain size and range from 50.882 to 68.853 GPa (Table 2). As the bulk modulus defines the resistance of a material to elastic compression, it is expected that the investigated clastic rocks will require large loads (or stresses) for any volume change.

Values of the dynamic modulus of rigidity (*G*) are seen to generally decrease with increasing grain size and range from 19.286 to 11.688 GPa (Table 2). These calculated moduli are considered to be good approximations of static moduli of rigidity for the the unconfined compression test on the fine grained sandstone yielded an overall modulus of rigidity of 20.823 GPa; a value close to the calculated dynamic modulus of 17.468 GPa (Tables 3 and 2).

Relevant published data in Peninsular Malaysia is only limited to the study by Nurul Huda *et al*. (2019) on 'hard' sandstones from the Kenny Hill Formation. Unconfined compression tests yielded static moduli of elasticity ranging from 8.98 to 24.80 GPa, bulk moduli of 10.85 to 23.07 GPa, and shear moduli of 3.30 to 10.89 GPa. The dynamic elastic constants determined in the present study are, however, of much larger values and indicate that sandstones form the Semanggol Formation are not as easily deformed as those from the Kenny Hill Formation.

CONCLUSIONS

Ultrasonic pulse measurements have shown that velocities of compressional and shear waves through sandstones of the Semanggol Formation increase with decreasing grain size. Pebbly sandstone has compressional and shear wave velocities of 2.210, and 5.171, km/s, whilst coarse grained sandstone has velocities of 2.477, and 5.612, km/s, respectively. Medium grained sandstone has compressional and shear wave velocities of 2.457, and 5.793, km/s and fine grained sandstones, velocities of 2.572, and 5.867 km/s, respectively. Dynamic elastic constants computed from the ultrasonic velocities also increase in values with decreasing grain size; Poisson's ratio ranging from 0.37 to 0.39, the modulus of elasticity from 35.076 to 48.210 GPa, the bulk modulus from 52.260 to 67.292 GPa and the modulus of rigidity from 12.637 to 17.468 GPa. Increasing velocities and elastic constants with decreasing grain size are considered to result from a more dense arrangement of constituent grains as shown by increasing dry unit weights. Comparison with the results of an unconfined compression test on a fine grained sandstone indicate that the ultrasonic elastic constants are good approximations of static elastic constants.

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