# Empirical rock strength logging in boreholes penetrating sedimentary formations

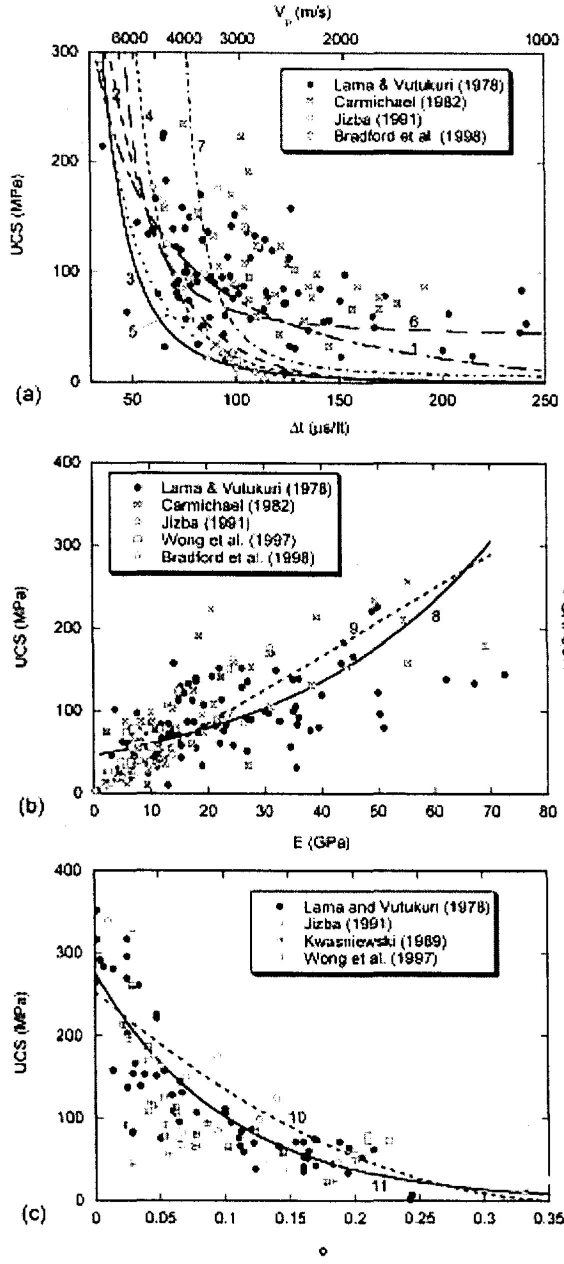
Chandong Chang

Geology and Earth Environmental Sciences, Chungnam National University cchang@cnu.ac.kr

The unconfined compressive strength (UCS) of sedimentary rocks are key parameters needed to address a range of geomechanical/geophysical problems ranging from limiting wellbore instabilities during drilling (e.g., Moos et al., 2003), to assessing sanding potential (e.g. Santarelli et al., 1989) and quantitatively constraining stress magnitudes using observations of wellbore failure (e.g. Zoback et al., 2003). UCS is typically determined from the laboratory triaxial tests on cylindrical samples that are obtained from depths of interest. In practice, however, many geomechanical problems in reservoirs must be addressed when core samples are unavailable for laboratory testing. In fact, core samples of overburden formations (where many wellbore instability problems are encountered) are almost never available for testing.

As practical approach to these problems, a number of empirical relations have been proposed that relate rock strength to parameters measurable with geophysical well logs. The use of such relations is often the only way to estimate strength in many situations due to the absence of core for laboratory tests. The basis for these relations is the fact that many of the same factors that affect rock strength also affect other physical properties such as velocity, elastic moduli and porosity. In many cases, such relationships have been suggested for sedimentary rocks mainly because the strength information is greatly demanded in reservoirs for the purpose of drilling, maintenance and depletion of wellbores.

In general, a strength-physical property relationship for a specific rock formation are developed based on calibration through laboratory tests on rock cores from the given field. If there are no core samples available for calibration, the next best thing would be to use empirical strength relations based on measurable physical properties. However, because there are multiple choices of strength models for various rock types in different geological settings, it is necessary to understand the characteristics of the models and their range of applicability prior to utilizing them.



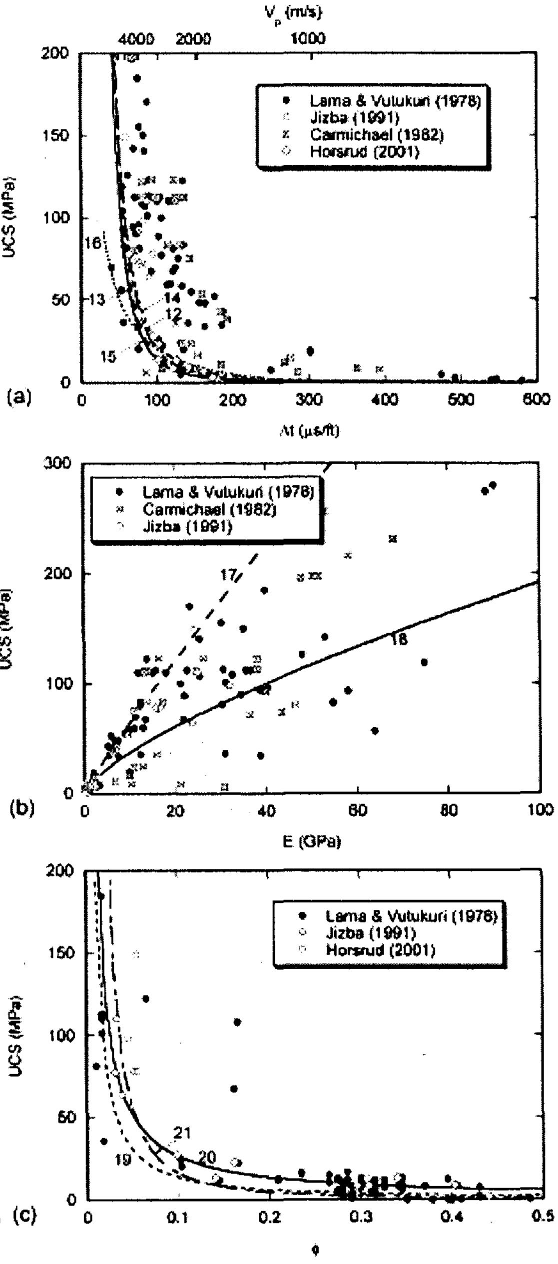


Figure 1. Comparison between different empirical equations for the dependence of the strength of 260 sandstones on (a) interval transit time (or equivalently P-wave velocity), (b) Young's modulus, and (c) porosity.

Figure 2. Comparison between differen empirical equations for the dependence o the strength of 100 shales on (a) interva transit time (or equivalently P-wav velocity), (b) Young's modulus, and (c porosity.

Nearly all proposed formulae for determination of rock strength from geophysical logs utilize one (or more) of the following parameters: P-wave velocity (Vp=Δt-1)which is directly measured, Young's modulus (E) which is derived from velocity and density measurements, or Porosity (ϕ) which is usually derived from density measurements assuming rock matrix and fluid densities. Conceptually, the justification for the empirical relations is the general correlation between these parameters and unconfined compressive strength. These general correlations are seen in the laboratory data presented in Figures 1 and 2 for sandstone and shale, respectively. The rock strength and physical property data presented in these figures were compiled from the literature (Lama and Vutukuri, 1978; Carmichael, 1982; Kwasniewski, 1989; Jizba, 1991; Wong et al., 1997; Bradford et al., 1998; Horsrud, 2001). Despite the considerable scatter in the data, for each rock type, there is a marked decrease in strength with Δt and ϕ, and an increase in strength with E.

A number of relationships in common practice (both published and proprietary) for estimating the unconfined compressive strength of sandstones and shales from geophysical logging data are presented in Figures 1 and 2. These relations were derived for case studies carried out for markedly different rocks in markedly different geological settings, around the world. The first impression one gets from seeing the fit between the measured strength and velocity data in the lab with the seven empirical relations appropriate for the UCS-Vp domain in Figure 1a is that the scatter is remarkably large a roughly ~100 MPa variation of strength at any given Δt. It is noteworthy that except for equations (1) and (6) (derived for relatively strong rocks), all of the relations appear to badly underpredict the strength data for very low velocities (Vp<3000 m/s). Such velocities are characteristic of very weak sandstones such as found in the Gulf of Mexico (GOM), but one needs to keep in mind that there are essentially no very weak sands represented in most of the strength data available. Similarly, for fast, high strength rocks, equation (3) (derived for low strength rocks) does a particularly poor job of fitting the data.

It is worth noting that the estimated strengths from equations (2)-(5) and (7) are very similar to one another for high travel time (Δt higher than about 120 s/ft) sandstones (Figure 1a) as most of these equations are derived for the GOM or Gulf Coast sandstone. The variation of rock strength estimated using these relations is within 10 MPa. These suggest that the rock strength of very weak sandstones from the GOM, the North Sea, and probably other sedimentary basins are characterized by a similar strength-velocity trend.

The use of Young's modulus for estimating UCS is less straightforward than that of velocity, because it generally requires the static-dynamic conversion or frequency correction. Equations (8) and (9) derived using Young's modulus fit the available data shown in Figure 1b reasonably well in the lower E range.

With respect to porosity, both of the porosity relations seem to generally overestimate strength, except for the very lowest porosities. An extremely wide range of UCS (a range of ~300 MPa) is observed in the data at $\phi<0.05$ (Figure 1c). This suggests that porosity alone is not a good indicator for strength of low porosity sandstone. Such a wide scatter in rock strength can be attributed to different diagenetic processes (e.g. quartz vs. calcite cement, etc.) as sandstones are compacted.

Overall, it is probably fair to say that none of the empirical equations do a very good job of fitting the data in Figure 1. That said, it is important to keep in mind that the validity of any of these relations is best judged in terms of how well it would work for the rocks for which they were originally derived. Thus, calibration is extremely important before utilizing any of the relations shown. Equation (5), for example, seems to systematically underpredict most of the data in Figure 1a, yet worked very well for the relatively clean sands from the North Sea (Bradford et al., 1998) since it was derived for an equivalently clean coarse-grained sandstone (Moos et al., 1999).

The empirical relations for the strength of shale in Figure 2 are based on model calibration for unconsolidated porous shales of Tertiary, or younger age except for equations (18) and (19) developed for rather strong shales. Equations (12)-(15), principally utilizing $\Delta t$ for UCS estimation, are expressed in the same form of power law function, providing a lower bound of the data (Figure 2a). As mentioned above, it is prudent to underestimate strength to be conservative for applications to wellbore stability. However, the difference between these relations and the measured strengths is quite marked for fast velocity rocks. For slower rocks ($\Delta t$ >100), these equations fit about 30-35% of data within 10 MPa. Still almost all data are located above the model predictions, implying that the UCS-$\Delta t$ relationships provide only a lower bound of UCS of shale. It should be noted that equations (12)-(16) were calibrated for samples collected from the North Sea and Gulf of Mexico where high porosity, unconsolidated Tertiary or younger shales are dominant, while the majority of rock strength data presented in Figure 2a came from shales that underwent a higher degree of diagenesis except for the North Sea shale (Horsrud, 2001). Thus, the use of the empirical equations leads to significant misfits in most cases, while estimating the North Sea shale data fairly well. The strengths of the majority of slow, weak shales are either fit well, or underestimated by relations (12)-(16). Hence, such relations form a useful, if perhaps overly conservative, means for estimating shale strength in weak formations.

The two relations (Equations (17) and (18)) that utilize Young's modulus for estimating UCS show a remarkable difference in their general trends (Figure 2b). This is because the two equations were developed based on markedly different rock types: equation (17) was developed for high porosity North Sea

shale and equation (18) from relatively strong compacted shale.

Equations (19)-(21) that utilize porosity are in a similar form of power law function and exhibit a similar decreasing trend of UCS as a function of $\phi$ (Figure 2c). Unlike the case for sandstones, porosity appears to be a good parameter that can be used to estimate UCS of shale, especially for high porosities (>0.1). The three equations (19)-(21) all predict shale strength fairly well, fitting 90 % of available data within 10 MPa. This is a very useful result since the weak shales are major constituents of most sedimentary basins and reservoir that often cause major wellbore stability problems. Their strength can be relatively well constrained with empirical relations that utilize porosity as a constitutive parameter. While equations (19) and (21) estimate nearly the same UCS, equation (20) predicts slightly higher UCS (by 4 to 10 MPa) than the other two. In the lower porosity range (<0.1), the fit is not as good but there are only a limited number of available data. Statistically, however, equation (19) appears to do a better job than the other two, which supports the fact that the former equation was developed based on low porosity and high strength shale.

It is clear that a few of the empirical relations discussed above appear to work fairly well for some subsets of the rocks tested in the laboratory. For example, as far as relatively weak rocks are concerned which are of most interest in cases of wellbore stability, use of $\Delta t$ with equations (3) and (5) seem to provide a reasonable fit to the strength of weak sands. In addition, equation (11) allows one to utilize porosity measurements to estimate weak sand strength when porosity is relatively high $\phi$ (>0.1). With weak shales, equation (15) seems to work well when using $\Delta t$ and equations (20) and (21) seem to work well at relatively high porosity ($\phi$>0.15).

While most of other relations do a poor job in fitting measured data for the reasons discussed above, it should not be forgotten that these relations were originally proposed because they fit some subset of data. Therefore, they do work, but not necessarily for the data represented by the published studies available in the present study. Moreover, a number of the strength-physical property correlations are especially useful in applications related to wellbore stability by providing a lower bound estimate of in situ rock strength. These relations may provide a good first approximation of the lower strength bound when no other information on rock strength is available. It is somewhat obvious, however, that calibration of empirical relations between strength and physical properties is generally required for any correlation to be used with some degree of confidence.

## References

Bradford, I.D.R., Fuller, J., Thompson, P.J., and Walsgrove, T.R., 1998, Benefits of assessing the solids production risk in a North Sea reservoir using elastoplastic modeling. SPE/ISRM 47360, papers presented at the SPE/ISRM Eurock '98 held in Trondheim, Norway, 261-269

Carmichael, R. S., 1982, CRC Handbook of Physical Properties of Rocks, Vol. II, CRC Press, Inc., Boca Raton.

Horsrud, P., 2001, Estimating mechanical properties of shale from empirical correlations.

SPE Drilling & Completion, 16, 68-73.

Jizba, D., 1991, Mechanical and Acoustical Properties of Sandstones and Shales, Ph.D. thesis, Stanford University.

Kwasniewski, M., 1989, Laws of brittle failure and of B-D transition in sandstones. In Rock at Great Depth, edited by Maury, V. and Fourmaintraux, D.,A.A.Balkema, Brookfield, Vt., 45-58.

Lama, R.D. and Vutukuri, V.S., 1978, Handbook on Mechanical Properties of Rocks, Vol. II, Trans Tech Publications, Clausthal, Germany.

Moos D., Zoback, M.D. and Bailey, L. 1999, Feasibility study of the stability of openhole multilaterals, Cook Inlet, Alaska, presentation at the 1999 SPE Mid-Continent Operations Symposium held in Oklahoma City, Oklahoma, 2831 March 1999, SPE 52186

Moos, D., P. Peska, T. Finkbeiner and M. D. Zoback, 2003, Comprehensive wellbore stability analysis utilizing quantitative risk assessment, Journal of Petroleum Science and Engineering, Special Issue on Borehole Stability, edited by Aadnoy, B.S. and Ong, S., 38, 97-110.

Santarelli, F.J., Detienne, J.L., and Zundel, J.P., 1989, Determination of the mechanical properties of deep reservoir sandstones to assess the likelihood of sand production. In Rock at Great Depth, edited by Maury, V. and Fourmaintraux, D.,A.A.Balkema, Brookfield, Vt., 779-787.

Wong, T.-F., David, C.and Zhu, W., 1997, The transition from brittle faulting to cataclastic flow in porous sandstones: mechanical deformation. J. Geophys. Res., 102, 3009-3025.

Zoback, M.D., Barton, C.A., Brudy, M.,Castillo, D.A., Finkbeiner, T., Grollimund, B.R., Moos, D.B., Peska, P., Ward, C.D., and Wiprut, D.J., 2003, Determination of stress orientation and magnitude in deep wells. Int. J. Rock Mech. Mining Sci., 40, 1049-1076