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A new technique for porosity determination using seismic density

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Summary

24 sandstone samples from Singrauli coal measure basin of lower Gondwana system (M P) having a range of porosities (~4 % to 35 %), apparent densities (1.69 g/cc to 2.54 g/cc; standard deviation from the mean is 0.2 g/cc), and true densities (2.51 g/cc to 2.66 g/cc; standard deviation from the mean is 0.04 g/cc) were studied in the laboratory. Observed apparent densities were plotted against the observed true densities in the same scale, range and units on both the axes. It was found that the data points falling on the line of unit slope passing through the origin correspond to the zero porosity values. This line of unit slope was named as the zero line. By further analysis of the laboratory-observed data and their spread in the apparent versus true density plot, the region perpendicularly away and under the zero line was divided into 15 equal strips, each representing 5 % porosity value. In this way, a grid was prepared in which true density, apparent density and porosity were varying in (x), (y) and diagonal to (x-y) directions respectively. The grid was called Density-Nomogram. As the average true density is nearly constant for a particular rock, only the variation in the apparent density (also called as seismic density) in Density-Nomogram was resulted in the variation in the porosity. An empirical formula {Φ=S ($\rho_{ma}^{avg} \pm \Delta\rho_{ma} - \rho_s$); Φ=porosity; S=38.7 is an empirical constant; ρ_{ma}=matrix density; ρ_s=seismic density} was also proposed by best fitting the observed porosities with the porosity calculated from Nomogram. Large seismic density data can be easily handled using this empirical formula enabling porosity determination very easy. Porosity determination using this direct method was also tested with the laboratory-measured data of other sedimentary rocks from different stratigrphical and geographical locations, and they showed excellent correlation.

Introduction

Determination of porosity in laboratory as well as under insitu conditions is a tedious and time consuming job. It requires special care and attention in the preparation and testing of samples. Some accurate nomogram or formula is always useful to give first hand information about the rock properties.

Another vital advantage of this proposed method is in its amenability to quantification. Quantitative analysis of any petrophysical property is always more important and informative than a mere qualitative study, and is very critical while dealing with oil exploration and exploitation. The graphical or empirical relationship proposed in this paper will make the link between rock properties quantitative.

Method

Porosity determination in laboratory

Indirect method of porosity determination was used in which, porosity was determined using apparent and true density. The famous Archimedes' principle was used to find the volume of rock material and hence the density. True density is the density of a solid framework which was determined by using the crushed rock sample so as to break the pores. In this way, we avoided the effects of the pore spaces. Apparent density is the density of a rock mass which includes void spaces and was determined using solid blocks of rock samples so as to include the pores. Rock blocks used for apparent density determination were coated with wax so as to block the water to enter into pore spaces. Later on, the effect of wax was removed in the calculations. Difference in these densities resulted to the porosity. The formula used for calculations is as follows,

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Formula used

$$\rho(\text{true}) = \frac{\text{Wt of rock sample}}{\text{Wt of rock sample} + \text{Wt (Pycnometer} + \text{Water)} - \text{Wt (Pycnometer} + \text{Water} + \text{Sample)}}$$

$$\rho(\text{apparent}) = \frac{\text{Wt of rock sample}}{\text{Wt of waxed rock sample} - \frac{\text{Wt of wax}}{0.93} - \text{Wt of rock sample in water}}$$

$$\text{Porosity} = \frac{\rho(\text{true}) - \rho(\text{apparent})}{\rho(\text{true})} 100$$

Table: 1 Names and identities for the 24 samples from Singrauli, along with observed porosities, calculated porosities, and their standard deviation

Name of the Sample	True Density (g/cc)	Apparent Density (g/cc)	Observed Porosity (%)	Calculated Porosity from Density-Nomogram (%)	Standard Deviation (Misfit) (%)
Sandstone-1'	2.546805	2.0618	19.04366	19	0.287
Sandstone-Y	2.602837	1.912405	26.52613	27	
Sandstone-7	2.602837	2.051814	21.17009	21	
Sandstone-K	2.511041	2.068277	17.63269	17.5	
Sandstone-3'	2.555321	2.055129	19.57453	20	
Sandstone-8	2.638833	2.072357	21.46691	22	
Sandstone-4	2.603819	2.080102	20.11342	20.5	
Sandstone-3	2.637916	2.111021	19.97391	20.5	
Sandstone-9	2.619855	2.206468	15.779	16	
Sandstone-S1	2.62363	2.263875	13.71211	14	
Sandstone-S2	2.61873	2.120641	19.02025	19.5	
Sandstone-S3	2.599834	2.260281	13.06056	13	
Sandstone-S4	2.54023	2.26092	10.99545	11	
Sandstone-S5	2.586119	2.301354	11.01128	11	
Sandstone-S6	2.637885	2.264764	14.14471	14.5	
Sandstone-S7	2.642821	2.310219	12.58509	12.5	
Sandstone-S8	2.590768	2.381228	8.087959	8	
Sandstone-S9	2.664358	2.54475	4.48918	4.5	

Sandstone-Y'	2.56332	1.828826	28.654	28.5	
Sandstone-2	2.61249	1.783201	31.74324	31.5	
Sandstone-M	2.59858	1.697777	34.6652	35	
Sandstone-2'	2.532032	1.704288	32.6909	32.5	
Sandstone-5	2.53417	1.931941	23.76436	23.5	
Sandstone-5'	2.510908	1.930541	23.11384	23	

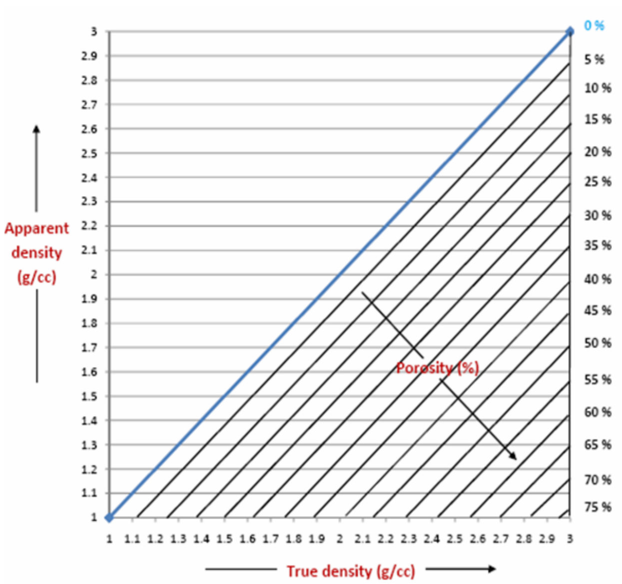

Fig. 1: Proposed Density-Nomogram.

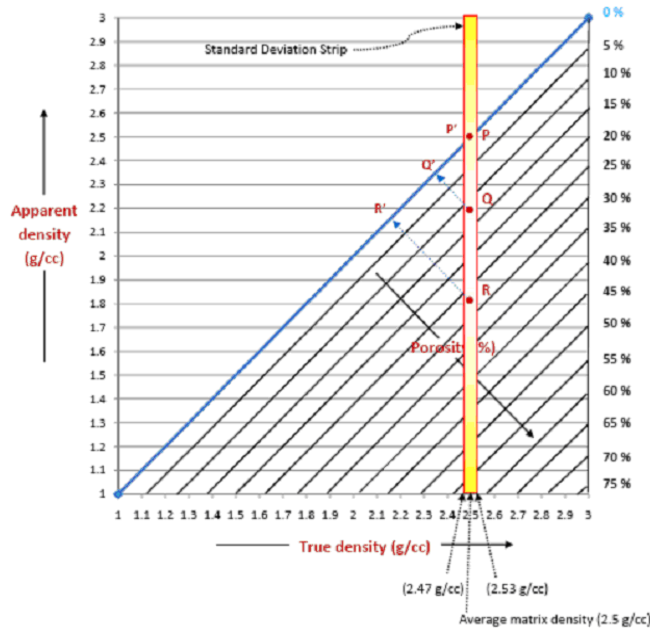

Fig. 2: Porosity determination using Density-Nomogram method.

<u>Porosity determination using Density-Nomogram</u>

It is well known that the average true density of a particular rock is nearly constant. The variation in the porosity is mainly because of the change in the apparent density. A minute observation was done on the density and porosity data of sandstone samples and a grid was prepared; in which the true and apparent densities were plotted on x and y axis with the same scale and same units respectively (figure 1). Blue (bold) line passing through the origin and having unit slope corresponds to the 0 % porosity values (figure 1). It is because the values of true and apparent densities are same for the rock material with zero porosity. The Lower right-angled triangle was then divided into 15 equal divisions, each having porosity difference of 5 % as shown in the figure 1.

The blue (bold) line with unit slope and passing through the origin was named as zero line. The distances perpendicularly away from the zero line referred the amount of porosity. So, porosity was calculated by fixing the true/matrix density (in a suitable range of standard deviation) on x axis, plotting corresponding apparent densities on the y axis and measuring perpendicular distances away form the zero line. The values of the perpendicular distance resulted in the porosity values. For example, if some sandstone have the average matrix density of 2.5 g/cc (Figure 2) with standard deviation from mean is 0.3 g/cc, then apparent density may be plotted in a strip (2.47 g/cc to 2.53 g/cc). This strip was named as 'standard deviation strip'. From figure 2, as the point P is having zero distance from zero line (PP'=0), so the data point P has zero porosity. Similarly, points Q and R are having distances 17 and 27 respectively (QQ'=17, RR'=27). So, the data points Q and R have porosity values as 17 % and 27 % respectively. Calculated porosities were plotted against observed porosities (Figure 3). The plot showed unit slope and excellent correlation (R^2=0.99).

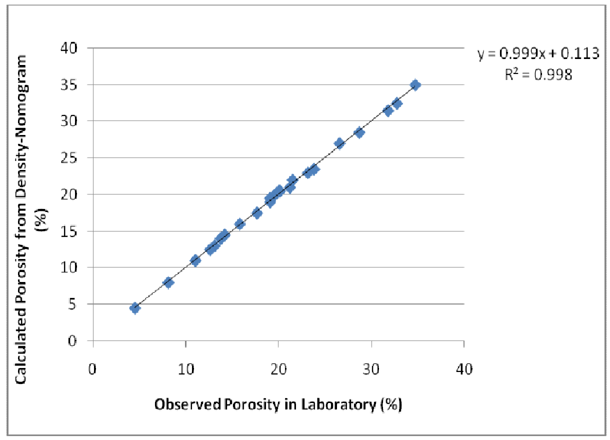

Fig. 3: Correlation between calculated porosity and observed porosity.

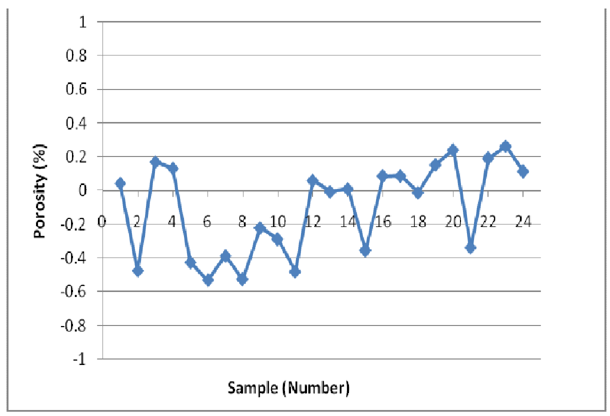

Fig. 4: Deviation of calculated porosity from the laboratory-observed porosity with a standard deviation of 0.287 % (Table 1).

In order to use this technique for a large scale seismic density (apparent density) data, a best fit empirical formula have also been proposed from the Density-Nomogram with a standard deviation in porosity of 0.32 %.

Proposed formula

Apparent density (seismic density) is the density of a rock mass which includes pore spaces while the true density is the density in which the pore spaces are excluded. Thus, porosity may be defined as the function of difference in the true and apparent density. Hence, we can write it as:

$$\Phi = f\left(\rho_{ma} - \rho_{app}\right)$$

Where, Φ= Porosity

ρ_{ma} = Matrix density or true density and

ρ_{app} =Apparent density.

By observing the laboratory data, it was found that the porosity is linearly related and directly proportional to the difference between true density and apparent density. So, a constant of proportionality S was introduced to remove the sign of proportionality. The value of the constant S was determined from the Density-Nomogram by best fitting the observed and calculated data. Different values of S were tested and a suitable one with least standard deviation was chosen. Thus,

$$\Phi = S\left(\rho_{ma} - \rho_{app}\right)$$

Where, S= 38.7; a constant derived from the Density-Nomogram.

Replacing ρ_{ma} by ρ_{ma}^{avg} (average matrix density) because matrix density for a rock type is constant. Hence, Φ can be written as:

$$\Phi = 38.7\left(\rho_{ma}^{avg} - \rho_{app}\right)$$

If there is some deviation in true density (standard deviation strip; Fig. 2), then a separate deviation term i.e. $\Delta\rho_{ma}$ can be used to have more accurate results. In that case the formula will become:

$$\Phi = 38.7\left(\rho_{ma}^{avg} \pm \Delta\rho_{ma} - \rho_{app}\right)$$

$$\boxed{\Phi = 38.7\left(\rho_{ma}^{avg} \pm \Delta\rho_{ma} - \rho_{s}\right)}$$

Where, ρ_{ma}^{avg} = Average matrix density, $\Delta\rho_{ma}$ = Standard deviation from mean matrix density, and ρ_s = Seismic density

Discussion

The Density-Nomogram and the proposed formula have been tested for different sedimentary rock types of different origin and from different areas. To test and verify the authenticity of the proposed method, some of the data were taken from the work done in laboratory (Landslide risk analysis in and around Luhri area, Lower Himalaya, Himanchal Pradesh, India; Sarkar K. 2009; unpublished PhD Thesis). 3 rock types of 4 data sets were used for the validation as well as the use of Density-Nomogram in porosity determination.

Table: 2 Data sets, their classes and corresponding geological locations.

Data Sets	Rock type	Rock Class	Geological Location
Data Set-1	Sandstone	Sedimentary	Jayant Open Cast Mine, Gondwana Basin
Data Set-2	Shale	Sedimentary	Jayant Open Cast Mine, Gondwana Basin
Date Set-3	Limestone	Sedimentary	Luhri, Siwalik, Himanchal Pradesh

Data Set-1 (Sandstone)

No. of samples: 16; Average true density (ρ_{ma}^{avg})=2.506 g/cc; Standard deviation from the mean ($\Delta\rho_{ma}$)=0.014 g/cc; Calculated Porosity =38.7 ($\rho_{ma}^{avg} - \rho_s$); Calculated (+) =38.7 ($\rho_{ma}^{avg} + \Delta\rho_{ma} - \rho_s$); Calculated (-) =38.7 ($\rho_{ma}^{avg} - \Delta\rho_{ma} - \rho_s$)

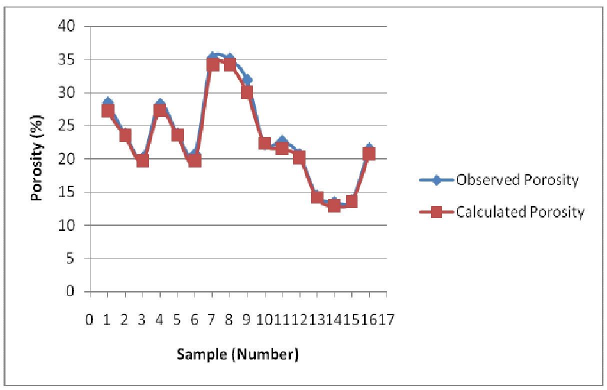

Fig.5: Observed porosity and calculated porosity plotted against the different samples numbered.

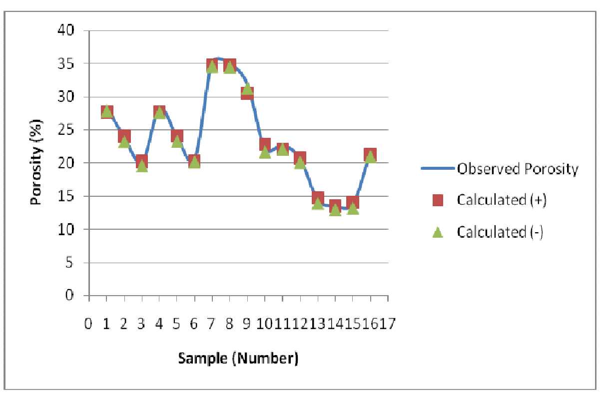

Fig.6: Observed porosity plotted along with the calculated porosity with positive standard deviation i.e. Calculated (+) as well as the calculated porosity with negative standard deviation i.e. Calculated (-); all plotted against the samples numbered.

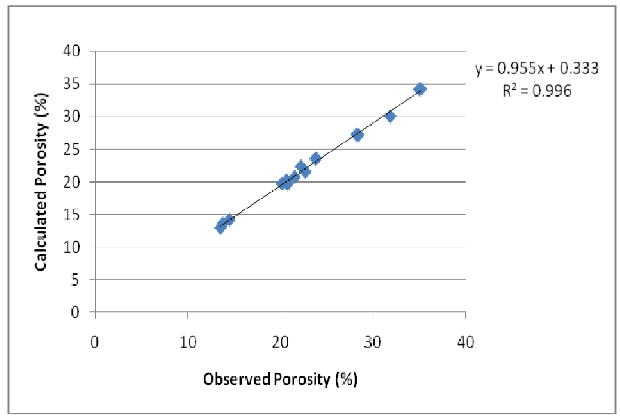

Fig.7: Observed porosity plotted against the calculated porosity. Slope is very close to unity and the observed porosity is closely matching with the calculated porosity by high value of correlation coefficient.

Table: 3 Table showing the correlation between observed porosities and calculated porosities.

Data Set	Rock type	Slope*	r^2 (r=Correlation coefficient)	Standard deviation ** (%)
Data Set-1	Sandstone	0.955	0.996	0.857
Data Set-2	Shale	0.937	0.989	0.291
Data Set-3	Limestone	0.988	0.995	0.180

- * Slope of the regression relation between observed and calculated porosities.
- ** Standard deviation between observed and calculated porosities

Conclusion

All the data sets examined, showing an excellent correlation between the observed and the calculated porosity. For all the data sets, the observed porosity values are lying very close to calculated (+) and calculated (-) porosity values. Regression lines between observed and calculated also reveal very good correlation (r^2 ~0.99). Standard deviation (Misfit) between observed and calculated porosity values is far less (ranging from 0.18 % to 0.85 %). From the laboratory tests and validation, it can be concluded that the Density-Nomogram and proposed formula provide good results for sedimentary rocks. This method will not only be useful for petroleum reservoir studies but also for civil and mining engineering projects. It will be heartening if the described technique finds favor as a universal too in mass scale determinations of porosity in varied engineering projects.

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