Effect of pore attribute on pore complexity and its impact on rock quality

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Abstract. Several studies have shown that pore complexity of rock is the main factor causing establishment of rock units with certain dynamic behaviors that are different from each other (rock type). Generally, modified of Kozeny-Carmen equations supported by petrographic data are used to identify the rock units. However, petrographic data is not always available, so another approach is needed to explain the pore complexity of rock. This study is intended to obtain another approach that can be used to describe the effect of pore complexity on rock quality (HFU). The pore complexity of the rock is expressed in the form of combination of shape factor with tortuosity ($F_s \tau$) and the specific surface area ($S$). This study uses 120 carbonate rock samples data. These data include porosity and permeability obtained from routine core analysis. By using the method of hydraulic flow unit, rock samples can be grouped into several HFU where each HFU has its own porosity and permeability relationship. This study shows that 1 HFU defined by the hydraulic flow unit is characterized by a unique value of specific surface area but has a wide range of $F_s \tau$. It can be concluded that the specific surface area is the dominant factor that distinguishes 1 hydraulic flow unit to another.

Keyword: Pore Complexity, Rock Type, HFU, Tortuosity, Specific Surface Area

1. Introduction
It is widely known that rock quality is strongly influenced by the pore complexity of rock. In relation to the petrophysical properties of rock, the pore complexity can be represented by the parameters such as tortuosity $\tau$, shape factor $F_s$, and specific surface area $S$. As demonstrated by Leverett J-Function, capillary pressure curves can be used to group the rock according to the lithology [1]. The J-function curve represents the specific lithology of the formations that are different from the others. In relation to the pore complexity of the rock, the J-function curve represents the pore size distribution of the rock [2]. Thus the J-function curve states specific unit of rocks of a certain quality characterized by certain values of $S_{wc}$ and tortuosity which differ from one another [3].

Amaefule indicates that the hydraulic quality of rock is controlled by pore geometry which is a function of mineralogy (type, amount, morphology and position relative to pore throat) and texture (grain size, grain shape, uniformity of grain size and grain arrangement) [4]. Weger showed that the relationship between porosity and permeability is affected by the pore network complexity [5]. Large and simple pores size have low micro-porosity compared to small pores with complex arrangements so
that in simple and large pores will have a low perimeter over area. Wibowo and Permadi state the complexity of the pore system can be expressed by a combination of reservoir parameters of porosity and permeability [6]. The pore geometry is expressed as \((k/\phi)^{0.5}\) and the pore structure \(k/\phi\). One rock type will have similarity of pore architecture in which the similarity of pore architecture can be shown in the presence of similarity microscopic geological feature.

This study is intended to understand the dominant pore attributes that affect the quality of the rocks. Rock quality is identified by hydraulic flow unit method as shown by Amaefule. It can be shown that the specific surface area is the dominant factor affecting the quality of hydraulic flow unit (HFU) and distinguish one HFU from another.

2. Data and Method

2.1. Data Used

The study used 120 samples of carbonate rocks from several locations in Middle East, Southeast Asia, and Australia published by Weger [5]. All samples are carbonate and dolomite rocks with non-carbonate material less than 2%. Texture of rock samples are ranging from coarse grained packstones with interparticle to vuggy porosity to fine grained wackestone dominated by interparticle to micromoldic porosity. The available data include the petrophysical properties of rocks such as porosity and permeability. The pore space parameter data is obtained by digital image analysis (DIA) method which includes two-dimensional pore size (DomSize), aspect ratio (AR), and pore network complexity (PoA) [5]. DomSize represents the range of pore sizes that dominate the sample. Aspect ratio (AR) is defined as the ratio between the major axis and the minor axis of pores space. AR describes ellipsoid elongation of pore space. While the perimeter over area (PoA) is the ratio between the total area of pore space in the thin section and the total perimeter that encloses the pore space.

2.2. Hydraulic Flow Unit Concept

Amaefule developed a method of identification and characterization of a hydraulic flow unit within a geological facies based on the Kozeny-Carman concept and mean hydraulic radius corresponding to the specific surface area per unit grain volume \((S_g)\) and effective porosity \((\phi_e)\) [4]. Variations of these geological attributes indicate the presence of rock units with the similarity of pore throat. The general equation of Kozeny-Carman can be written as follows:

\[
k = \frac{\phi^3}{(1-\phi)^2} \left[ \frac{1}{F_s \tau^2 S_g} \right]
\]

Equation 1 can be arranged into:

\[
\sqrt{k} = \frac{\phi}{(1-\phi)} \left[ \frac{1}{\sqrt{F_s \tau^2 S_g}} \right]
\]

where reservoir quality index \(RQI\) is a function of porosity and permeability and can be written as follows:

\[
RQI = \sqrt{\frac{k}{\phi}}
\]

whereas the ratio between pore volume and grain volume \(\phi_e\) is defined as follows:

\[
\phi_e = \left( \frac{\phi}{1-\phi} \right)
\]

and flow zone indicator \(FZI\) are:
\[ FZI = \frac{1}{\sqrt{F_s \tau S_{gv}}} \]

Thus equation 1 can be arranged in logarithmic form as follows:

\[ \log RQI = \log \phi_z + \log FZI \] (6)

Log-log plot reservoir quality index \((RQI)\) vs \(\phi\) of all samples having a similar value of the flow zone indicator \((FZI)\) will fall in a straight line with the same slope. All data falling on the same line has a pore throat similarity called hydraulic flow unit \((HFU)\). \(FZI\) is a function of shape factor \((F_s)\), tortuosity \((\tau)\) and specific grain surface \((S_{gv})\) so that in one hydraulic flow unit \((HFU)\) it has similarity shape factor \((F_s)\), tortuosity \((\tau)\) and specific grain surface area \((S_{gv})\).

3. Results And Discussion

3.1. Hydraulic Flow Unit \((HFU)\) Identification

To study the effect of pore attribute on rock quality, starting with grouping of samples using hydraulic unit method as shown by Amaefule. The plot between \(\phi\) and \(RQI\) for each group of data that has a similarity of pore attribute will form a straight line with 45 degree of slope [4]. Based on the plot between \(\phi\) and \(RQI\), the data can be grouped into 8 \(HFU\) (Figure 1.). \(HFU\) is then used as a basis analysis in studying the effect of pore attribute on rock quality. Good quality \(HFU\) are characterized by large \(RQI\) values and denoted by small \(HFU\) numbers. In contrast, low quality \(HFU\) is denoted by a large \(HFU\) number and is characterized by a low \(RQI\) value. \(RQI\) is a function of porosity and permeability expressed by \((k/\phi)^{0.5}\). Equation 3 shows that \(RQI\) is directly proportional to permeability so that \(RQI\) value describes the quality of rock.

![Figure 1. Grouping of rock samples based on hydraulic flow unit concept](image-url)

Amaefule states that each \(HFU\) has a similar flow zone indicator \((FZI)\) and will form a straight line with the same slope where the data falling on the same line has a similar pore throat. \(FZI\) is a function of the shape factor \((F_s)\), tortuosity \((\tau)\) and specific grain surface \((S_{gv})\) so that in a hydraulic flow unit \((HFU)\) has similarity of shape factor \((F_s)\), tortuosity \((\tau)\) and specific grain surface \((S_{gv})\). Figure 2 shows that the data can be grouped into several \(HFU\) where each \(HFU\) has its own porosity and permeability relationship.
3.2. The Relationship of Perimeter Over Area (PoA), Dominant Pore Size (DomeSize), and Aspect Ratio (AR) with Reservoir Quality Index (RQI)

The effect of some pore parameters on the reservoir quality index (RQI) was observed. These parameters include perimeter over area (PoA), Dominant pore size (DomeSize), aspect ratio (AR), and specific surface area (S). Reservoir quality index is a function of porosity and permeability. The porosity and permeability is influenced by the sedimentation process and diagenesis so that the porosity and permeability will be greatly influenced by the pore attributes.

Figure 3 below is a plot between PoA against RQI. RQI is reservoir quality index defined by Amaefule [4] whereas PoA is defined as the ratio between the total pore space area in the thin section and the total perimeter that encloses the pore space [5]. PoA is equivalent to the specific surface area that expresses the ratio between the pore volume and the pore surface. Generally, the smaller the PoA value indicates simple pore geometry. The greater the value of the PoA indicates greater pore complexity. Although it looks scatter but it can be observed a trend where the better HFU quality is indicated by a large RQI and low PoA. The low PoA value represents simple pore geometry so that the pore complexity of the rock is lower. Thus it can be concluded that a large RQI is formed due to simple pore geometry resulting in rocks with low pore complexity.
Figure 3. The Relationship of perimeter over area with RQI.

This is supported by the relationship between $S$ with $RQI$ (Figure 4). The $S$ is the specific surface area per unit of bulk volume estimated using Kozeny equation. Figure 4 shows that the quality of HFU is strongly influenced by the specific surface area. Good quality HFU is characterized by large $RQI$ and low $S$ values. In the previous paragraph it has been discussed that the high $RQI$ is caused by simple pore geometry which is indicated by low $PoA$ values where $PoA$ is proportional to the specific surface area $S$. Thus, the better the HFU quality indicates the simpler pore structure that can be observed with the lower of specific surface area $S$. Conversely, the lower the HFU quality is indicated by the larger value of $S$.

Assumed the porous medium is a straight capillary tube with diameter $d$, then the Kozeny equation can be written as follows [7]:

$$k = \frac{\phi d^2}{32} \tag{7}$$

or

$$d = 5.66 \left( \frac{k}{\phi} \right)^{0.5} \tag{8}$$

As for the straight capillary tube model, the specific surface area per unit of bulk volume can be written as function of porosity and pore diameter $d$ as follows:

$$S = \frac{4\phi}{d} \tag{9}$$

The large $S$ indicates a more complex pore arrangement and small pore diameter (Eq. 9). Equation 9 shows that $S$ is inversely proportional to pore diameter $d$. The larger the pore diameter the lower the $S$ and the smaller the pore diameter $d$ the greater the $S$ value.
DomSize is a pore attribute that describes the dominant pore size of rock [5]. The pore size and complexity of the pore arrangement will certainly determine the RQI and the quality of the HFU. In general, Figure 5 shows that pore size greatly affects RQI. The greater the RQI is indicated by the larger pore size of the rock. Based on Figure 5 it can be seen that good quality HFU tends to be composed by rock samples dominated by larger dominant pore sizes (PoA). In contrast, low quality HFU tend to be dominated by relatively smaller pore sizes. RQI is proportional to \((k/\phi)^{0.5}\) so that RQI represents the pore diameter (Eq. 8). Thus a large RQI value is proportional to the large pore diameter.

Figure 4. The Relationship of specific surface area with RQI.

Figure 5. The Relationship of DomSize with RQI of each hydraulic flow unit.
The relationship of aspect ratio $AR$ with $RQI$ is shown in Figure 6. Aspect ratio $AR$ expresses the ratio of the major and the minor axis of pore space [5]. Thus the aspect ratio $AR$ will affect the shape of the pore space of rock. The lower the aspect ratio value then the pore shape is getting rounded. Figure 6 shows that the $RQI$ value is not sensitive to aspect ratio. Thus by taking the discussion from the previous section can conclude that the complexity of pore arrangement and pore size is the dominant factor affecting $RQI$.

![Figure 6. The Relationship of Aspect Ratio with RQI.](image)

### 3.3. The Influence of Pore attribute to the rock quality

In Section 3.2 it has been shown that pore attributes have a dominant impact on rock quality. To obtain the main factor that distinguishes every HFU is done by studying the influence of pore attributes such as shape factor $F_s$, tortuosity $\tau$, and specific surface area $S$ toward flow zone indicator and reservoir quality index. The pore attribute of shape factor $F_s$ and tortuosity $\tau$ is expressed in the form of a combination $F_s\tau$. $F_s\tau$ is widely known as kozeny constant which is a combination of shape factor and tortuosity. The $S$ is the specific surface area per unit of bulk volume estimated using Kozeny equation. Amaefule states that one HFU has a similarity of shape factor $F_s$ and tortuosity $\tau$. In this study the influence of the shape factor $F_s$ and tortuosity $\tau$ is observed in the form of a combination of $F_s\tau$ which is known as Kozeny constant $c$. Mortensen shows that Konzeny constant can be expressed as function of porosity [8]. Mortensen developed an approach for estimating the value of $c$ based on porosity using a simple 3D model of interrelated linear tubes and Poiseuille equations. Based on this approach, Mortensen derive the equation of $c$ as function of porosity as follows:

$$c = \left(4 \cos \left(\frac{1}{3} \arccos \left(\frac{8}{\pi^2} - 1\right) + \frac{4}{3} \pi \right) + 4\right)^{-1}$$

(10)

The effect of the pore attribute $F_s\tau$ on quality of $HFU$ is shown in Figure 7. One HFU is characterized by the similarity of $FZI$. It has been discussed earlier that $FZI$ is a function of the shape factor ($F_s$), tortuosity ($\tau$) and specific grain surface ($S_{gv}$). One hydraulic flow unit should have a similarity of shape factor ($F_s$), tortuosity ($\tau$) and specific grain surface ($S_{gv}$) values. However, Figure 7 shows that each $HFU$ has a similar $FZI$ value but has a wide range of $c$ values.
Figure 7. The Relationship of FZI with $c$ of each hydraulic flow unit.

The same pattern is also shown by the relationship between $c$ and $RQI$. It is generally seen that each HFU has a linear relationship between $c$ and $RQI$. Each HFU has a wide and relatively equal range of $c$ values making it difficult to separate one HFU from another.

Figure 8. The Relationship of $c$ with $RQI$ of each hydraulic flow unit.

Figure 7 and 8 show that the pores attribute $F_{S\tau}$ does not significantly affect the quality of the HFU. Another pore attribute that affects FZI is the specific surface area $S$ (Figure 9 and 10). The relationship between FZI and $S$ indicates that each HFU has specific value of FZI and $S$. The HFU can be clearly separated based on the specific range of FZI and $S$ value (Figure 9). The better the quality of HFU is
characterized by the low value of specific surface area. The low value of specific surface area is caused by simple pore geometry and relatively large pore size (Fig. 5).

![Figure 9](image1.png)

Figure 9. The Relationship of specific surface area with FZI of each hydraulic flow unit.

Figure 10 shows that each HFU can be clearly separated by the value of specific surface area. Figure 10 confirms that the internal pore characteristics of the specific surface area $S$ have a dominant role that distinguishes one HFU from the other compared to the influence of shape factor and Tortuosity.

![Figure 10](image2.png)

Figure 10. The Relationship of specific surface area with $c$ of each hydraulic flow unit.

4. Conclusion
The study of 120 carbonate rock samples shows that pore attribute is a major factor affecting the complexity of pore arrangement and rock quality. By grouping rock samples into HFU can be explained the influence of each pore attribute on the rock quality. This study shows that the pore
attribute such as shape factor and tortuosity ($F_{\text{t}}$) does not significantly affect the quality of HFU. Each HFU is characterized by a unique value of specific surface area that differentiates one HFU from another. Specific surface areas are the dominant factors that affect the quality of HFU and differentiate one HFU from another.

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