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Mutual effects of porosity–permeability and both irreducible water saturation and displacement pressure: the Törtel Formation, Hungary

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On the basis of reservoir heterogeneity in both clastic and carbonate rocks, the porosity–permeability relation of a certain reservoir zone sometimes elucidates more than one trend because of the many petrophysical factors directly or indirectly affecting such a relation. These factors tend to be interrelated to different extents.

The well known Kozeny–Carman equation and its modified version indicate that the porosity–permeability relation is mainly affected by the irreducible water saturation which is, in turn, directly related to the clay content and rock texture including grain size and clay distribution. An attempt was made to investigate the mutual effects of both irreducible water saturation and displacement pressure and total porosity, effective porosity, and laboratory measured permeability data of the clastic interval belonging to the Törtel Formation encountered in the Algyő oil and gas field.

Some significant linear relations have been obtained indicating that the mutual effect between the irreducible water saturation, porosity and permeability is more efficient than that of the same combination with the estimated displacement pressure. The calculated permeability based on the modified Kozeny–Carman equation reveals reliable relationships with strong correlations with the effective and total porosity data and even laboratory measured permeability. The calculated regression line equations, characterized by high correlation coefficients, give an order of magnitude greater accuracy in permeability assessment based on effective porosity and/or total porosity measured data of the sandstone of the Törtel Formation.

Keywords: porosity, permeability, saturation, Törtel Formation

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1. Introduction

Numerous experimental data obtained in major rock physics laboratories suggest that there exists a relatively simple relation between porosity and permeability and such important other parameters as irreducible water saturation, specific surface area, pore space framework, and clay content [EL SAYED 1981, VERNIK 1994].

The relationship between the absolute permeability and porosity has been extensively addressed from both theoretical [CARMAN 1937, SCHEIDEGGER 1974] and experimental [e.g. TIMUR 1968, EL SAYED 1981, HERRON 1987, ADLER et al. 1990, CHILINGRIAN et al. 1990, EHRENBERG 1990] perspectives. The well known Kozeny–Carman equation [SCHEIDEGGER 1974] has been expressed as

$$k=\left(A\phi^{3}\right)\Big/\left\{s^{2}(1-\phi)^{2}\right\} \tag{1}$$

where s is the specific surface area, A is an empirical constant, and k is the absolute permeability in millidarcies. This equation is limited in application because (1) it strictly applies only on loose sand, and (2) the surface area is difficult to estimate in consolidated rock formations and is not directly measurable by logging. TIMUR [1968] developed a modified version of the original Kozeny equation as follows,

$$k=\left\{0.136\left(\phi^{4.4}/S_{wi}^{2}\right)\right\}\cdot 10^{5} \tag{2}$$

where k is the absolute permeability in millidarcies, and S_{wi} is the irreducible water saturation. This equation was successfully tested on 155 sandstone samples related to three different sedimentary basins [VERNIK 1994]. The porosity exponent (n) in the above equation ranges from 4 to 5 [ADLER et al. 1990].

It is mentioned that in some sedimentary facies (especially clean arenite sandstone defined by VERNIK and NUR 1992), the irreducible water saturation is almost independent of porosity in a wide range from ϕ = 6 up to 36 % and average S_{wi} = 10 to 5 % [VERNIK 1994]. Therefore the irreducible water saturation–porosity relation ($S_{wi}=f\phi$) should be developed for each sedimentary facies or even reservoir zone instead of the generalized expressions theoretically assumed in order to predict absolute permeability based on porosity measured data using the Kozeny modified version.

In the present work, using experimental measurements of 52 core samples from the Törtel Formation encountered in the Algyő oil and gas field

(Hungary), the relationship between both porosity and permeability and irreducible water saturation and displacement pressure have been studied. The Törtel Formation (comprising number of sandstone reservoirs) of the Great Hungarian Plain is penetrated by more than 900 holes drilled in the Algyő field. The aims of the present study are: (1) to investigate the mutual relations between porosity, permeability, irreducible water saturation, and displacement pressure; (2) to develop some specific relations to allow permeability prediction based on porosity measurements; and (3) to test the relationship between calculated permeability [TIMUR 1968] and the laboratory measured permeability.

The Törtel Formation (Pannonian s.l.) conformably overlies the Algyő Formation and underlies the Zagyva Formation. It is interpreted as deltaic sandstone of three major deltaic rock genetic types: (1) distributary channel, (2) barrier bar, and (3) deltaic fringes [EL SAYED 1981, BÁN, EL SAYED 1986, JUHÁSZ 1991]. On the other hand, the intercorrelation of capillary pressure derived parameters of this formation has been studied by EL SAYED[1993 and 1994] to enhance methods for reservoir development.

2. Methodology

The gas permeability of the samples that were studied was measured using the Ruska gas permeameter. The measuring technique is outlined by EL SAYED [1981]. Mercury porosimetery is used to approximate reservoir conditions and to allow accurate determination of both effective and total porosity of the sandstone of the Törtel Formation. Capillary pressure measurements using a Carlo Erba porometer were performed to calculate the irreducible water saturation and displacement pressure. Capillary pressure is defined as the pressure difference across the curved interface between two immissible fluid phases jointly occupying the interstices of a rock, while it is due to the tension of the interfacial surface. The capillary pressure formula modified by WARDLAW[1976] from WASHBURN[1921] and BERG [1975] is:

$$P_c = 2\gamma \cos\theta / r \tag{3}$$

where P_c is the capillary pressure (kPa), γ is the surface tension of Hg (485 mN/m), θ is the contact angle (140°) and r is the radius of pore aperture for a cylindrical pore; thus, r (μm) = $741.9/P_c$ (kPa).

The 52 samples taken from the Törtel Formation were mainly of calcareous and argillaceous sandstones and siltstones. The displacement pressure was determined graphically from the mercury pressure injection curves as the pressure at 10% mercury saturation [SCHOWALTER 1979]. The irreducible water saturation was calculated graphically on the mercury capillary injection curves as the corresponding water saturation while the curve is almost parallel to the pressure axis.

3. Results and discussions

From the standpoint of reservoir rock physics, the obtained relationships for the sandstone of the Törtel Formation (Algyő field) gave considerable information about the mutual effects between either irreducible water or displacement pressure and both porosity and permeability, which are the most important reservoir parameters. The significance of the permeability prediction from either total and/or effective porosity is also investigated as discussed below.

Irreducible water saturation versus porosity

The total porosity versus irreducible water saturation relation (*Fig. 1A*) elucidates the intermediate correlation coefficient (r=-0.69), the calculated linear regression equation is represented as

$$S_{wi} = 64.05 - 2.12\phi_t \qquad (4)$$

where S_{wi} is the irreducible water saturation (%), and ϕ_t is the total porosity (%). On the other hand, the relationship between effective porosity and the irreducible water saturation exhibits (*Fig. 1B*) a relatively high correlation coefficient (r=- 0.80) and is represented by a linear equation:

$$S_{wi} = 53.5 - 1.937\phi_e \qquad (5)$$

where ϕ_e is the effective porosity (%) and S_{wi} is the irreducible water saturation (%).

The irreducible water saturation (Fig.1B) shows a stronger dependence on the effective porosity than the total porosity. This may be due to the existence of stagnant pore spaces (precluding saturation) which are mainly filled earlier by gases and therefore do not share in reservoir capacity.

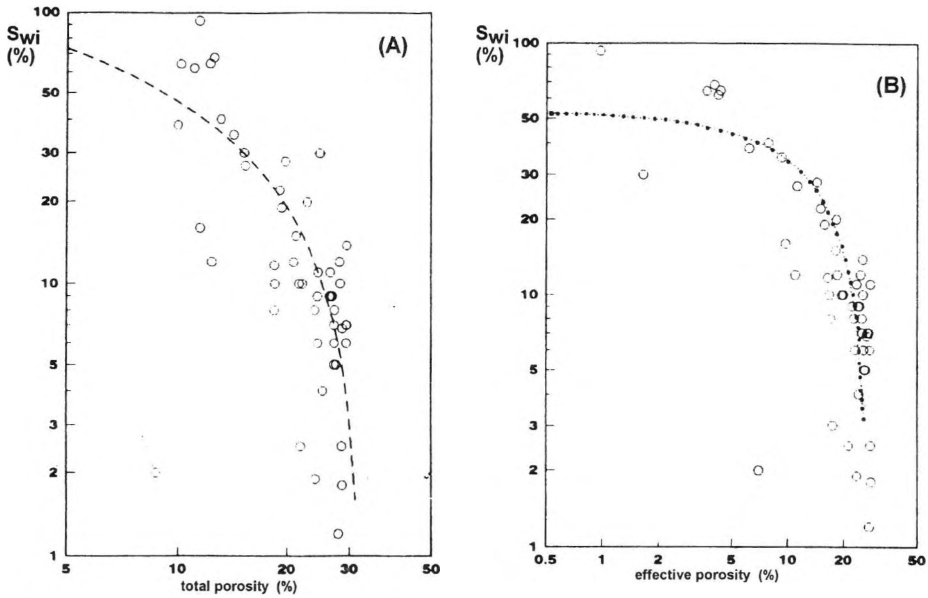


Fig. 1. Irreducible water saturation versus total (A) and effective porosity (B)
1. ábra. A vissza nem állítható viztelítettség a teljes (A) és az effektív (B) porozitás függvényében

Displacement pressure versus porosity

Displacement pressure data were plotted against total and effective porosity (*Figs. 2A, 2B*) . These plots show weak correlation while the majority of samples were characterized by displacement pressure values range from 5 kPa up to 400 kPa. The scattering of the data points may indicate weak dependence of displacement pressure on either total or effective porosity. However, at least two sample groups (A&B) could be determined while each of them has a certain characteristic pore space history. They suffered from post depositional cycles of different nature of diagenesis by which different pore geometries were created. Therefore, we can conclude in general, that the effect of porosity on the displacement pressure is sometimes unequal and can give misleading relations.

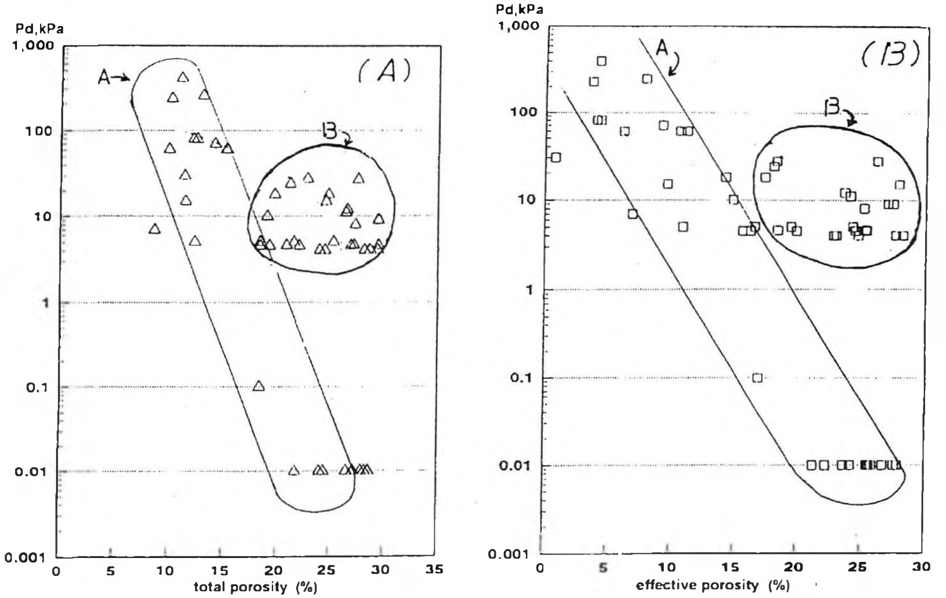


Fig. 2. Displacement pressure versus total (A) and effective porosity (B)
2. ábra. Az elmozdulási nyomás a totális (A) és az effektív (B) porozitás függvényében

Irreducible water saturation versus permeability

The measured gas permeability versus irreducible water saturation has been constructed (*Fig. 3A*). This figure reveals an intermediate correlation between the two investigated parameters while the exponential equation representing this relation is

$$k_m = 192.65\mathrm{e}^{-0.092} S_{wi} \tag{6}$$

where k_m is the measured permeability (μm^2), and S_{wi} is the irreducible water saturation (%). The calculated correlation coefficient for the relationships between the irreducible water saturation and both porosity and permeability shows that it is strongly dependent on porosity rather than the reservoir permeability.

Displacement pressure versus permeability

The gas permeability versus displacement pressure relation (Fig. 3B) reveals two groups of data points confirming the same groups obtained with

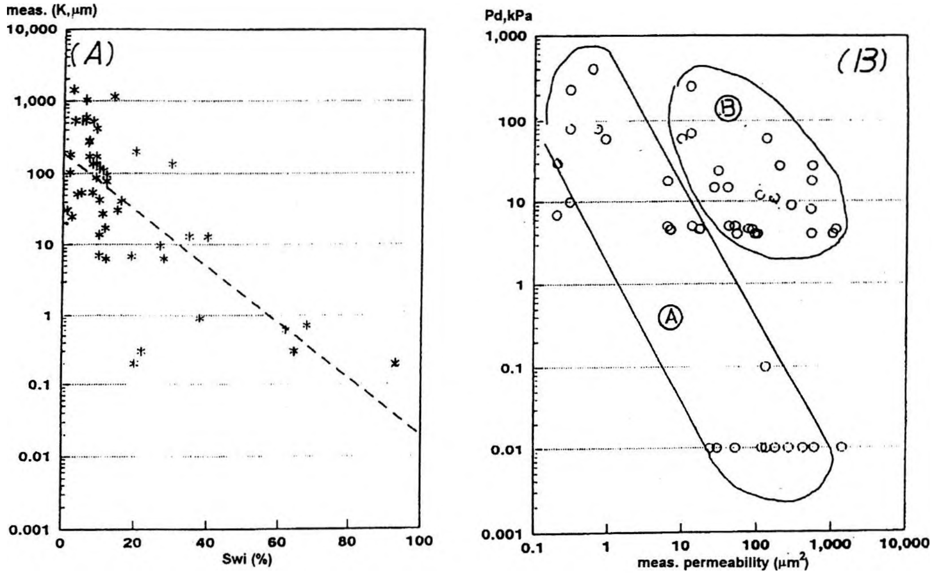


Fig. 3. Measured permeability versus irreducible water saturation (A) and displacement pressure (B)

3. ábra. A mért permeabilitás a vissza nem állítható víztelítettség(A) és az elmozdulási nyomás (B) függvényében

porosity data, while the same interpretation previously mentioned for porosity should be adequate. It is clear that the displacement pressure could be dependent on more than one formation parameter; it does not directly depend on either porosity or permeability.

Porosity versus measured permeability

The relationship between porosity and permeability is unequal for different reservoir rocks depending on other petrophysical factors such as clay content, rock texture and pore space framework. The prediction of permeability based on porosity data is commonly done in practice using least squares regression analysis. It is appreciated that the relationship between the dependent and independent variables may be expressed in other forms using other means [Chapman 1983, Chork et al. 1994]. The statistical approach performs well if the two variables concerned are strongly correlated. In the event that they are poorly correlated, other forms of equations involving additional independent variables such as pore size, specific surface area, displacement pressure, and residual water saturation may have to be used to give reliable results.

Figure 4A &B, show the porosity-measured permeability relations for the sandstones of the Törtel Formation. On the basis of our knowledge, the correlation coefficient controlling the relation (Fig. 4A) between the measured permeability and total porosity (r=0.82) is slightly higher than that obtained for the same relation with the effective porosity (r=0.8). The linear regression equations representing these relations (Figs. 4A&B) are,

$$k_m = 0.12 \times 10^{-5}(\phi_t)^{5.69} \qquad r = 0.82, \tag{7}$$

and

$$k_m = 0.019(\phi_e)^{2.73} \qquad r = 0.8 \tag{8}$$

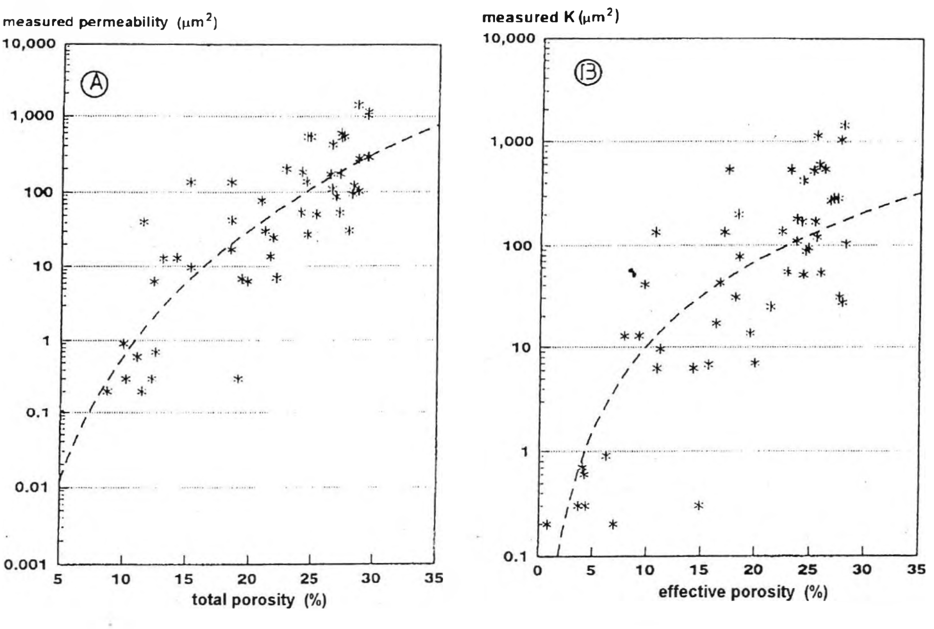


Fig. 4. Measured permeability versus total (A) and effective porosity (B)

4. ábra. A mért permeabilitás a totális (A) és az effektív (B) porozitás függvényében *where* k_m is the laboratory measured permeability (μm^2), ϕ_t is the total porosity (%), and ϕ_e is the effective porosity (%).

Measured permeability vs. calculated permeability

The permeability of the samples was calculated using the modified Kozeny equation [TIMUR 1968] while the porosity exponent was equal to 4.5 [ADLER et al. 1990]. *Figure 5A* shows a relatively strong correlation between the measured and calculated permeability. The correlation coefficient characterizing this relation (r=0.81) is sufficiently reliable, while the relation is represented by

$$k_{cal} = 5.33(k_m)^{0.647} \tag{9}$$

where k_{cal} is the calculated permeability in μm^2. Therefore, the above equation is successfully applicable to the sandstone of the Törtel Formation thereby enabling one to predict either permeability or irreducible water saturation using the effective porosity.

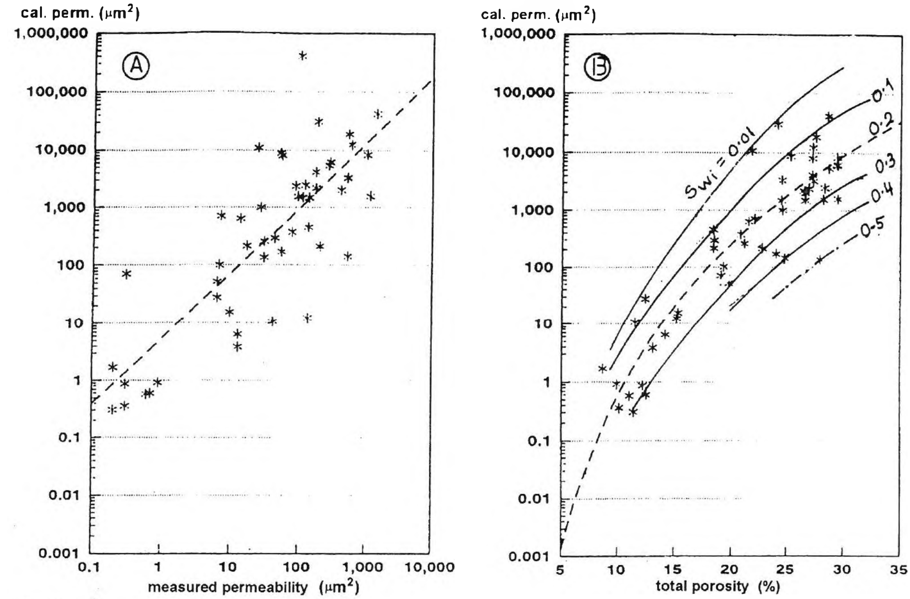
Permeability prediction

An attempt was made to relate the calculated permeability to both total and effective porosity (*Figs. 5B&C*). Figure 5B reveals the calculated permeability–total porosity relationship, showing a strong correlation. A few data points are scattered above and below the best fit line especially at high sample porosity. This may be due to the effect of the irreducible water saturation. The values of the irreducible water saturation have been plotted and contoured, while their trends seem to be parallel to the fitting line (general curve trend). The values of the irreducible water saturation decrease while the permeability increases.

The relationship (Fig. 5B) is characterized by a high correlation coefficient (r=0.9) allowing one to estimate reliable values of calculated permeability using the total porosity data. The relationship is represented by a regression line equation as

$$k_{cal} = 0.01e^{0.48\phi_t} \tag{10}$$

On the other hand, Figure 5C, exhibits a reliable and applicable relationship between calculated permeability and effective porosity. This relation is characterized by a strong correlation coefficient (r=0.94) thereby



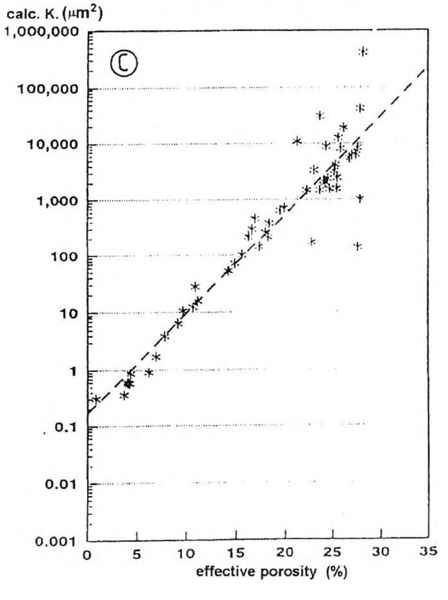


Fig. 5. Calculated permeability versus measured permeability (A), total porosity (B), and effective porosity (C)

5. ábra. A számított pemeabilitás a mért permeabilitás(A), a teljes porozitás (B) és az effektív porozitás (C) függvényében

allowing one to predict a calculated permeability value from the effective porosity data. The relationship is represented by a regression line equation as

$$k_{cal} = 0.169e^{0.403\phi_e} \tag{11}$$

where ϕ_e is the effective porosity (%), and k_{cal} is the calculated permeability (μm^2).

4. Conclusions

— The irreducible water saturation significantly affects porosity; however, the effective porosity seems to be more sensitively affected than the total porosity.

— The effect of both porosity and permeability on the displacement pressure could not be cancelled while the constructed relations indicate weak correlation between displacement pressure and effective porosity.

— The laboratory measured permeability seems to be greatly affected by the irreducible water saturation.

— The estimated permeability using Timur's equation gives reliable relationships using the laboratory measured permeability, total porosity, and effective porosity. The effective porosity could be considered as the most important parameter for permeability prediction for the studied sandstone samples of the Törtel Formation.

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A permeabilitás, a porozitás, a vissza nem állítható víztelítettség és elmozdulási nyomás kölcsönatása a Törtel formációban (Magyarország)

Abdel Moktader A. El Sayed

A törmelékes és karbonátos kőzetekben lévő tározók is heterogének. Egy adott zónában a porozitás és permeabilitás közti összefüggés vizsgálata rávilágít arra, hogy ezt a kapcsolatot sok kőzetfizikai tényező befolyásolhatja, közvetve vagy közvetlenül, és ezek a tényezők egymástól is függenek.

A jól ismert Kozeny–Carman egyenlet és ennek egy módosított változata azt jelzi, hogy a porozitás és permeabilitás közötti kapcsolatot főként a helyre nem állítható víztelítettség befolyásolja. Ez ugyanis közvetlen kapcsolatban van az agyagtartalommal és a kőzet szövetével, amely viszont magában foglalja a szemcseméretet és az agyag eloszlását is. Megkíséreltük meghatározni a vissza nem állítható víztelítettség és az elmozdulási nyomás hatását a porozitásra, az effektív porozitásra és a laboratóriumban mért permeabilitásra a Törtel formáció (algyői olaj- és gázmező) törmelékes kőzeteinek egy adott intervallumában. Néhány olyan lineáris kapcsolatot sikerült feltárni, amelyek azt jelzik, hogy a vissza nem állítható víztelítettség, a porozitás és a permeabilitás között sokkal szorosabb a kapcsolat mint ugyanezen paraméterek és a becsült elmozdulási nyomás között. A módosított Kozeny–Carman egyenlet alapján számított permeabilitás jól korrelál mind az effektív, mind a teljes porozitással és a laboratóriumban mért permeabilitással is. A regresszió korrelációs együtthatója nagy és az effektív és/vagy teljes porozitáson alapuló permeabilitás becslés pontossága jelentősen javul a Törtel formáció homokkövei esetében.