Journal of Mines, Metals and Fuels, *72(5): 439-454; 2024. DOI: 10.18311/jmmf/2024/32402*

INFORMATICS JOURNALS

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

Impact of Porosity on Underground Structure - A Review

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Abstract

Porosity is an index property that is present in all solid materials. It is used to understand the flow channel inside a material, also the pore space and matrix. The porosity of rock and soil can be divided into two types, namely, total and effective porosity. Porosity is one of the important parameters for any underground structure and rockmass which can even result in its failure with time. The primary goal of this review is to comprehend how porosity affects subsurface structures and rock mass. Although the rock and soil both have porosity, the rockmass connected to subsurface structures is the primary subject of the paper. This paper focuses on how porosity is measured, what influences porosity, and how porosity relates to other geo-mechanical parameters, this paper also discussed about the impact of changing porosity on underground constructions including tunnels, mines, underground storage, and caverns.

Keywords: *Confining Pressure, Hydraulic Conductivity, Sorting, Total Porosity*

1.0 Introduction

Porosity is an innate property of a material. In simple terms, porosity is the space inside materials. It is an index property of a material that is used in determining the hydraulic conductivity of the material. Even though porosity is not used in strength calculation, it plays a major role in a material as a basic property of like its shape, size, density[1]. These pores can be filled by fluids if they are not connected or these pores can help the flow of fluid through the pore matrix. According to the origin of materials, porosity can be divided into original and induced porosity. Original porosity is the process of development of porosity while making of the material whereas Induced porosity occurs due to the change in the material's chemical and physical composition[2].

Methods to determine the porosity depend on the type of material e.g. if the porosity is being determined for soil, then the general assumption would be that pores are connected but if the measurement is for hard material like rock, then pores may or may not be connected. Porosity has versatile roles for every branch considering engineering, material Science, and biology also. Porosity is a widely used parameter in soil mechanics, petroleum, reservoir, pharmaceuticals, geomechanics, hydrology, and so on. Porosity can be of many types varying for different materials, used in different branches to study the impact on certain parameters. The porosity can change the morphological properties of the material as well as the whole layer. It gets affected by pressure as well as temperature[1,2].

Underground structures are such structures that are situated below the ground surface like mines, tunnels, or caverns[3]. These structures rock layers as their roof and layers above this rock or roof layer are called overburden. This overburden pressure acts as a vertical load over the roof of the structure and is the main factor affecting the stability of the structure[4]. In this study, the focus is given to sedimentary rocks, because they have more pore space available as compared to igneous and metamorphic

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rocks. Thus, it can help in understanding the role of porosity more accurately. For different underground structures porosity plays different roles, the pore pressure produced by the pores can have a balancing effect or they can induce instability to the structure or if monitored carefully they can help in the stability of the structure[5,6]. The pore pressure also depends on the effective stress or pressure of the structure or rockmass which can result in an unstable structure. The instability created by porosity can lead to subsurface cavities and this can lead to trough subsidence[4].

2.0 Porosity and its Types

The definition of porosity is the pore space available in materials (Figure 1). It does not have a dimension. It is often to get confused between porosity and permeability. Porosity is the pore space available, these pores can be connected, but it is not necessary. Whereas permeability is the ability of fluid to flow through the connected pores[5]. Porosity is a very simple concept but there are many ways of determining it. For an idealized rock sample, the calculation of porosity putting mathematically is:

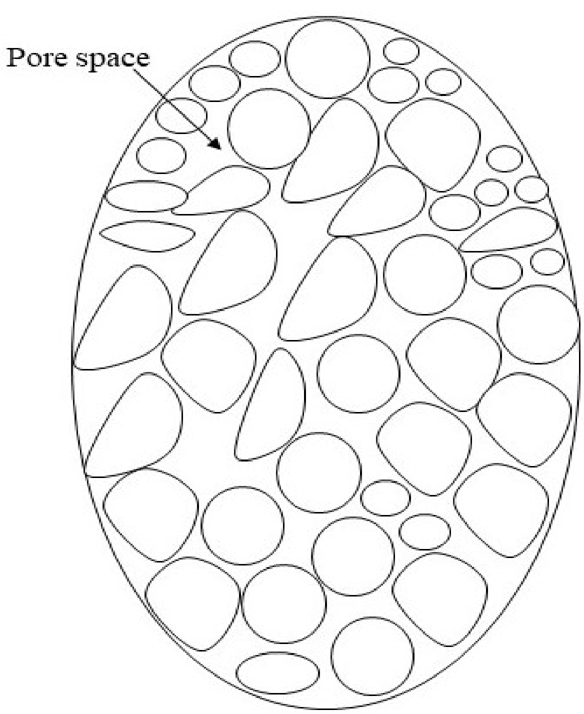

Figure 1. Porosity inside the material as pore space.

$$\Phi = (V_p/V_b) * 100$$

Where;

Φ= Porosity (in percentage or fractional value from 0 to 1)

Vp= Pore Volume or void space

Vb= Bulk volume

For the soil sample the calculation of porosity mathematically is shown

$$n = (V_v/V_b)$$

Where;

n= Porosity (shown in percentage or fractional value from 0 to 1)

Vv=volume of voids in the sample

Vb= Bulk volume of sample

Pore volume- The volume of fluid that can be stored in a volume is known as pore volume. Bulk volume- The bulk volume is the total volume of the material.

2.1 Types of Porosity

While determining the value of porosity in a particular rock, it can divide the rock into different zones of porosity that can be called low, medium, and high porosity zone[7].

Depending on the stream, the types of porosity differ widely. For soil and rock, the types of porosity are:

2.1.1 Total Porosity

This is also known as absolute porosity. The total porosity of soil and rock can further be divided into two categories that will be

a. Primary porosity b. Secondary porosity.

The total porosity indicates all interconnected as well as non-connected pores, the brief definition is given as follows:

a. Primary Porosity

Primary porosity is the main pore space between the grains of the material that are formed during the depositional process of the material such as diagenesis and sedimentation process. Most sedimentary rocks have primary porosity. This porosity is an inherited property of the material and depends on the shape, size, grading, and packing of grains in a sedimentary rock formation. The primary porosity also depends on the initial consolidation of the layer[8,9].

b. Secondary Porosity

Secondary porosity generates from the post-depositional processsuch as solution, crystallization, weathering, fracturing, and further cementation[8]. This is an induced property of the material. Most igneous or metamorphic rocks have secondary porosity. Unlike the primary porosity, the secondary porosity is predominately nanoporous in size and shape and consists of shrinkage, fractures, and micro cracks[10]. The secondary porosity may or may not enhance the primary porosity[11-13].

For the correct evaluation of porosity, both the porosity should be known for a material, it can be determined by formation resistivity when porosities are saturated in fluid, the effective formation depends on matrix inside the material, this experiment to find both porosities conducted by Kazatchenko and Alaeksandr in 2002[14]

2.1.2. Effective Porosity

It is pore space that is interconnected to each other inside the material concerning the total bulk volume of the material. This only shows the pore space which is connected inside the material, these pores help in hydraulic conductivity or the flow of fluid inside the material. The formula to determine the effective porosity of a material is given below[7,15]:

$\Phi_{eff} = V_{interconnected}/V_b$

Where;

Φ_{eff} – Effective porosity

$V_{interconnected}$- Interconnected pore volume

2.2 Methods to Determine Porosity

For different types of material like soil or rock, the method for determining porosity variese. *eg.* Determining the porosity of sand stone (rocks mostly found in the reservoir, gas or oil reservoirs) is different from the method for determining porosity for coal. When compared to determination methods, it is difficult to find the porosity of coal than sand stone. As mentioned above the pores can be inter connected, matrix, or fractures depending on the type of porosity, shape, and size of the material. So, to overcome this many experiments were executed and three types of tests are suggested to determine the porosity in different conditions[16].

2.2.1 Direct Method

It is done by using the undisturbed core samples from the site, but practically it is not possible as the cores can be damaged by the coring process, thus no accurate determination of porosity is possible. Disturbing the core while coring cannot be avoided, but processes after that like cleaning and getting the core ready for testing can be minutely carried out[17]. The other problem with the direct methods with cores is that the sample which is loose after taking out of its stress zone needs to go back into its *in-situ* condition that is the stresses and the confining pressure should be the same as it was before so the result can be accurate. Some of the most used direct methods for determining the porosity of materials are:

a. Direct Measurement

In this method, the bulk volume and volume of the solid are determined from the samples. Then by applying simple mathematical calculations, the porosity is determined.

b. Mercury Injection

For this method, rock is evacuated and then immersed in mercury. The evacuation is done because mercury cannot enter rock pores at normal temperature and pressure. After this, the pressure is increased slowly, and injecting mercury inside the material will be continued. The mercury will gradually enter all interconnected pores with the application of increasing pressure. The amount of mercury reduced will indicate the number of pores filled by the mercury, which mathematically will give $V_{interconnected}$ for that material. After this, by calculation, the porosity of the rock can be calculated.

After this test, the sample must be disposed of very safely, because the sample can be harmful to the environment around it[17].

c. Helium porosimeter

It is a gas expansion method that strictly follows Boyle's law, also known as the ideal gas law[18-20]. A core sample of known volume is placed inside the instrument matrix cup. This matrix cup is then placed inside the core holder and the confining pressure is applied. With the help of confining pressure helium gas is inserted in the sample, and the confining pressure allows the helium gas to penetrate the smallest of pores inside the material, due to this the results are highly accurate than any other direct method[21].

Helium is used in gas expansion because it can penetrate small pores with the help of confining pressure, which other gases may not be able to do so. It is a rapid technique of determining the porosity of the material, the time will only exceed for low permeability material, as it will take more time for diffusion of helium in small pores. After this method also the sample can be further tested for other geo-mechanical properties[22,23].

d. Imbibition Method

A fluid is used for the saturation of material, which is known as imbibition. Before the process of imbibition, the weight of the sample is measured. Again, the weight is measured after the imbibition. The difference in weight is then noted[24].

For the calculation of porosity, the difference in weight and bulk volume is used. This method leaves the sample unharmed making it perfect for further testing for other properties. For different methods used for the measurement of porosity by direct method, a comprehensive table is given below as Table 1. This method is very useful for hydrocarbon reservoirs.

2.2.2 Liquid Saturation Method

These methods are also known as laboratory methods for testing the porosity and are very economical. Some of these methods are given below:

a. Marble-Water Experiment

In this method, the porosity is determined by putting the known size of marbles in a beaker and then adding a measured quantity of water in the beaker, precisely above the marble level. Since the marble in this test represents the spherical particle in the sample which is not well packed, it gives both primary as well as secondary porosity[7]. This method is mainly used in the ceramic industry.

b. Barnes Fluid Saturation Technique

This is the most economical method of all the methods available for determining the porosity[7]. In this method, a closed flask is used. The sample will be placed inside this flask, and with the help of a vacuum pump, the flask will be vacuumed completely. After this with a high pressure of approximately 2000 *psi*, the liquid is inserted inside the flask, in this test brine is taken as the liquid. The liquid will be able to penetrate the holes because the sample is

Table1. Comprehensive table for direct method for measurement of porosity

Direct method	Conditions required	Bulk volume determination	Accuracy	The type of porosity determined
Direct measurement	Rock needs to be disaggregated.	Vernier calipers	Only for some disaggregated samples	Total porosity
Mercury Injection	Used for small irregular samples. The rock needs to be evacuated before a test.	While conducting the experiment	Very accurate	Effective Porosity
Helium porosimeter	Insensitive to mineralogy. All types of rock can be tested	Either by Vernier calipers or Archimedes' method	Highly accurate	Total Porosity and Effective porosity
Imbibition method	Rock permeability and density should be known	Either by Vernier caliper or Archimedes method	Accurate	Effective porosity

Table 2. Water saturation method for measurement of porosity

Water saturation method	Material or liquid used	Type of Porosity determines
Marble-water experiment	Uses marble	Total Porosity
Barnes fluid saturation technique	Uses saturation fluid such as Brine	Effective Porosity

completely dry and does not have air or liquid filled in pores. The sample was then taken out and pat-dried very carefully.

For the calculation, the total dry weight and saturated weight of the sample are used, divided concerning bulk volume determined by the vernier caliper. For this test, the core sample needs to be a perfect cylinder.

To understand the material or liquid used and the porosity determined by the liquid saturation method, a comprehensive table has been put together, named Table 2 is shown.

For all direct methods and the liquid saturation methods, calculating bulk volume from the same method is not possible. To calculate bulk volume different methods have been suggested and they are discussed below:

a. Vernier Calipers Method- When the sample is a perfect cylinder then by measuring its length and diameter of it, the volume of the sample can be calculated.
b. Fluid Displacement Method- The rock sample is placed in a container having fluid in it and the gradual displacement of fluid is measured. If the fluid enters the pores, it will result in an error.
c. Archimedes Method- A sample is weighed dry and then saturated in formation brine of known density. The saturated weight is then suspended in air and weighed and then weighed again in saturated brine. Then the difference between the weight of the sample suspended in air and that suspended in a fluid is calculated. There is some error in this method, but this is better in terms of accuracy than vernier caliper and fluid displacement methods.

2.2.3 Indirect Method

The most important thing about this method is that it is *in-situ* or also known as the field method[15]. Also, when the core samples from a site are very limited then used the indirect method of measurement of porosity. This method is most widely used in the petroleum industry because the liquid and gas present in the rock are very important to the industry. In the indirect method, the data from the limited core is used and by using acoustic and magnetic resonance these are tested and charts are prepared for the same[25]. The analysis of these charts and graphs was done by Baker[26]. From these tests, baker has compared the porosity and permeability of open hole logs and net pay cut-offs.

This method of determination of porosity uses a logging method that is well-logging or borehole logging[12], it is a method of recording the result and forming the graph at a particular depth or time that shows the parameters that need to be measured[27]. Well-logging also shows rock parameters as pore pressure or overburden pressure some of the popular indirect methods of porosity determination with well or borehole logging is mentioned below[28].

a. Sonic Log Method

It is mentioned in experiments that with an increase in sonic velocity the value of porosity decreases. The sonic log is a recording of interval transit time vs depth[15]. This method of determining porosity is also used in some studies to find the shale formation in the layer[29]. The transit time is the measure of how fast sound compression waves and shear waves can travel through a medium. With the determination of porosity, this method can also be used for determining confining pressure and pore pressure of the material.

The Wylie time-average equation is used in this logging method to calculate porosity. The equation is for uniformly distributed pores. The equation is given as follows[30,31]:

$$\Phi= (\Delta t_{log} - \Delta t_{ma})/(\Delta t_{f} - \Delta t_{ma})$$

Where;

Δt_{log}=Transit time reading

Δt_f =Inverse of the velocity of a sonic wave in pore fluid

Δt_{ma}=Transit time for rock material

This method is suitable for a very small length of the borehole to determine porosity. As the sound velocity of vuggy materials (materials having large cavities) depend only upon primary porosity, this method does not determine secondary porosity. This indicated that this method does not take the fractures into account[30].

b. Density Log Method

A radioactive source and detector are lowered down in the borehole, this radioactive source emits gamma rays (medium energy) into the formation. These rays interact with the electron of the formation and scatter in different ways which are noted by a distant detector, which is related to the formation's electron density. This electron density is a function of true bulk density. If the fluid density and rock matrix density is known, then the porosity of the rock can be estimated from the given formula[32]:

$$\Phi = (\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_f)$$

Where;

ρ_{ma}=Density of the rock matrix

ρ_b= Bulk density of rock from well log

ρ_f= Density of pore fluid.

This method does not differentiate between total and effective porosity if clay or shale is present in the formation the result obtained may need some calibration.

c. Neutron Log Method

This method uses the amount of hydrogen present in the strata to determine the porosity. Hydrogen is present in all types of hydrocarbons (oil, petroleum), and water[22]. By the determination of hydrogen, this method identifies the fluid pressure present in pores and finally gives the porosity of the material. But to give the porosity, the pores must have fluid that contains hydrogen. There are mainly three types of neutrons logs available, they are Gamma-ray Neutron Tool (GNT), Sidewall Neutron Porosity (SNP), and Compensated Neutron Log (CNP)[33].

This method uses elastic collision in all types of neutron logs, the mechanics of elastic collision predicts that when two equal mass collides then the maximum energy is generated. Therefore, the hydrogen atom can slow down the neutron the most as they have almost equal masses. This can directly link it to the porosity of the material.

The neutron density method gives a low porosity value as it only gives the value for the pores with fluids present, so this method is always used in combination with the density log method.

There are several other methods to determine the porosity of rock one of them is Image Analysis[23]. In image analysis with good resolution images are used because it uses the software which transforms the image into the binary signal as gray scale. Once this is done the software determines the distance shape and other parameters inside the material which is present in the image. From

Table 3. A Comprehensive table to discriminate the accuracy and requirement for different indirect methods

Indirect method	Conditions required	Accuracy	Type of porosity determines
Sonic log method	The lithology should be known. Type of rock should be known.	Accurate	Primary porosity
Density log method	Rock matrix and pore fluid should be known. Rock composition should be Monominrolic.	Very accurate	Total Porosity
Neutron log method	The pores should be filled with oil, gas, or water (any fluid that contains hydrogen)	Very accurate	Effective porosity

these results it is possible to give porosity in percentage by the relation shown.

Φ= (Pores area/total area) *100

These are the few methods to determine the porosity in the lab as well as on the field. According to the type of porosity required one can choose between these methods. A comprehensive table has been put together for indirect method; Table 3 as shown.

The direct method of porosity calculation is the most accurate measurement but if the samples are limited then the indirect method also gives accurate results if the condition for different methods satisfies the requirement of the method.

3.0 Factors Affecting Porosity

The types of porosity of different materials depend on many factors, which major factors are mentioned below:

3.1 Particle Sphericity and Angularity

The porosity majorly depends on the shape of the grain inside a material. The meaning of sphericity of a particle is its form in three dimensions or very close to the sphere and the angularity of a particle is the opposite of the roundness of the particle. It has been observed in many experiments that with an increase in sphericity porosity also increases whereas, with an increase in angularity, porosity decreases due to less space between particles as they lock each other more accurately in angular particle arrangement[34]. To show the effect of angularity on the porosity of porous material, hydraulic conductivity has been used in some studies[34].

3.2 Size of Grain

The other important factor with shape is the size of grains. For sedimentary rocks, it has been observed that the porosity only becomes significant if the size is lower than 100 µm[35]. The porosity over this limit does not change and the change can only occur if the process is reversed *i.e.* the compaction of the material takes place. It has been observed that heterogeneity introduced by the different grain sizes directly affects the peak strength of the material[36].

3.3 Sorting and Packing

Sorting and packing are the terms usually applied to sedimentary rocks. Sorting is the uniformity of grains and packing is the distribution of grains in a material. It has the most important effect on porosity[37]. The sorting can be well-sorted and poorly sorted. These two also can have combined with the shape of grains, which also decides the porosity of a material.

a. Well sorted- It is sediment that will have a uniform size of particles distributed in a systematic manner making uniform areas for pores.

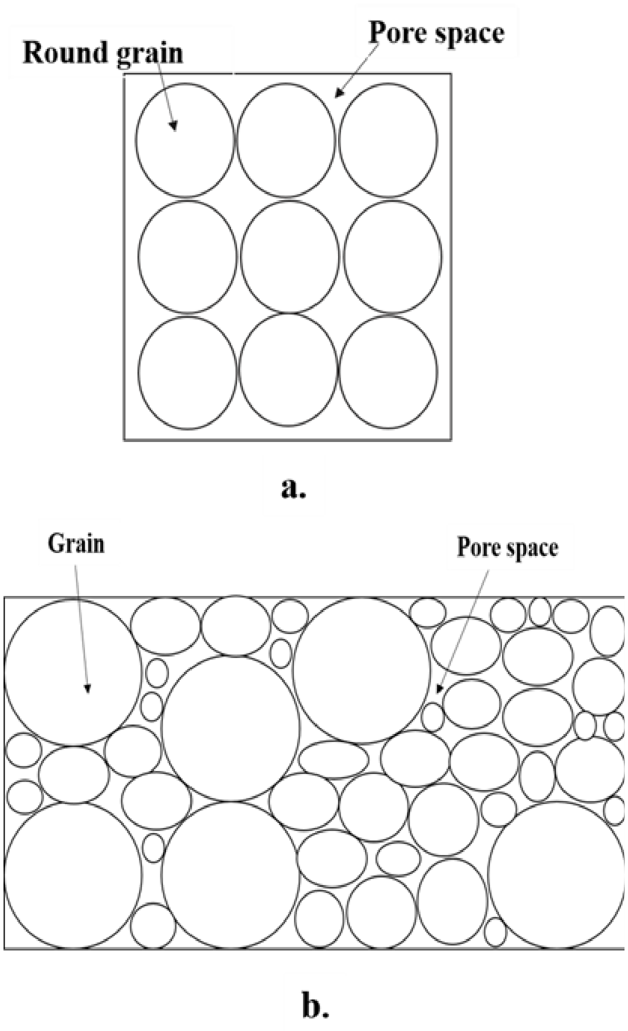

Figure 2. (**a**) Well-sorted packing of grains showing more pore space and (**b**) Poorly sorted packing of grain showing less pore space.

Table 4. Different types of packing with theoretical value of maximum porosity

Name of Packing	The Theoretical Value of Maximum Porosity
Cubic Packing	48%
Orthorhombic Packing	39%
Tetragonal Packing	31%
Tetrarhombic Packing	26%
Random	Less than or equal to 39%, depending upon the packing.

b. Poorly sorted- It is sediment that will have a non-uniform size of the particle and their distribution is not systematic, it decreases the value of porosity as it decreases the number of pores. Figure 2 shows a pictorial view of well sorted and poorly sorted packing.

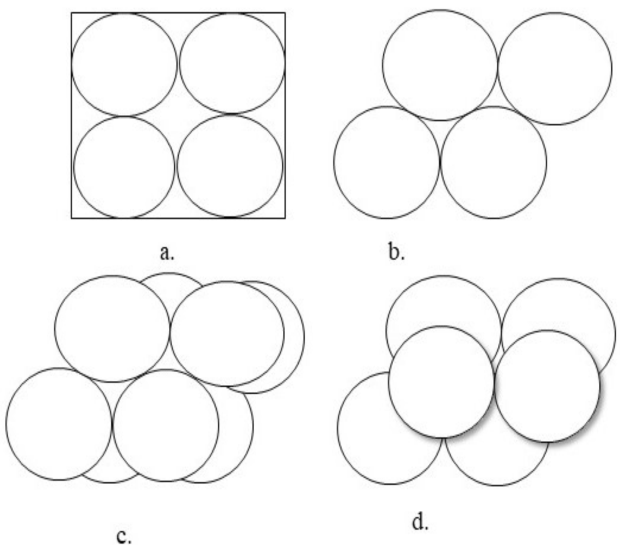

Figure 3. **(a)** Different types of packing in 2D form (a) Cubic, **(b)** Orthorhombic, **(c)** Tetragonal, **(d)** Tetrarhombic.

The grain packing in rocks plays a major role in porosity, if the grains are tightly packed with poorly sorted particles, it decreases the value of porosity. The value of grain packing varies from 30% to 75%[10].

Different types of packing have different values (approximate) of porosity, some names of packing and approximate porosity values are given in the Figure 3 and Table 4 shows different types of packing of grains.

4.0 Discussion

To understand the relation between porosity and stability of structure, one needs to understand the dynamics between the index properties and physio-mechanical parameters. It can be understood in two points, considering porosity in storage underground structure such as caverns, reservoirs, and porosity as a parameter for stability of the underground structure and rockmass.

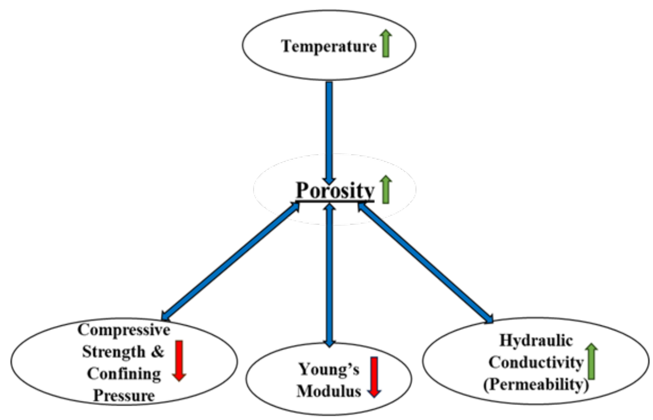

Figure 4. Porosity and its relation with other parameters.

A tentative image of the discussion is shown in Figure 4. The figure's double-sided arrows illustrate how porosity and other factors like as hydraulic conductivity, young's modulus, compressive strength, and confining pressure relate to one another.

4.1 Relation Between Temperature and Porosity

The temperature effect plays a vital role in the increment and decrement of the porosity of the material as shown by

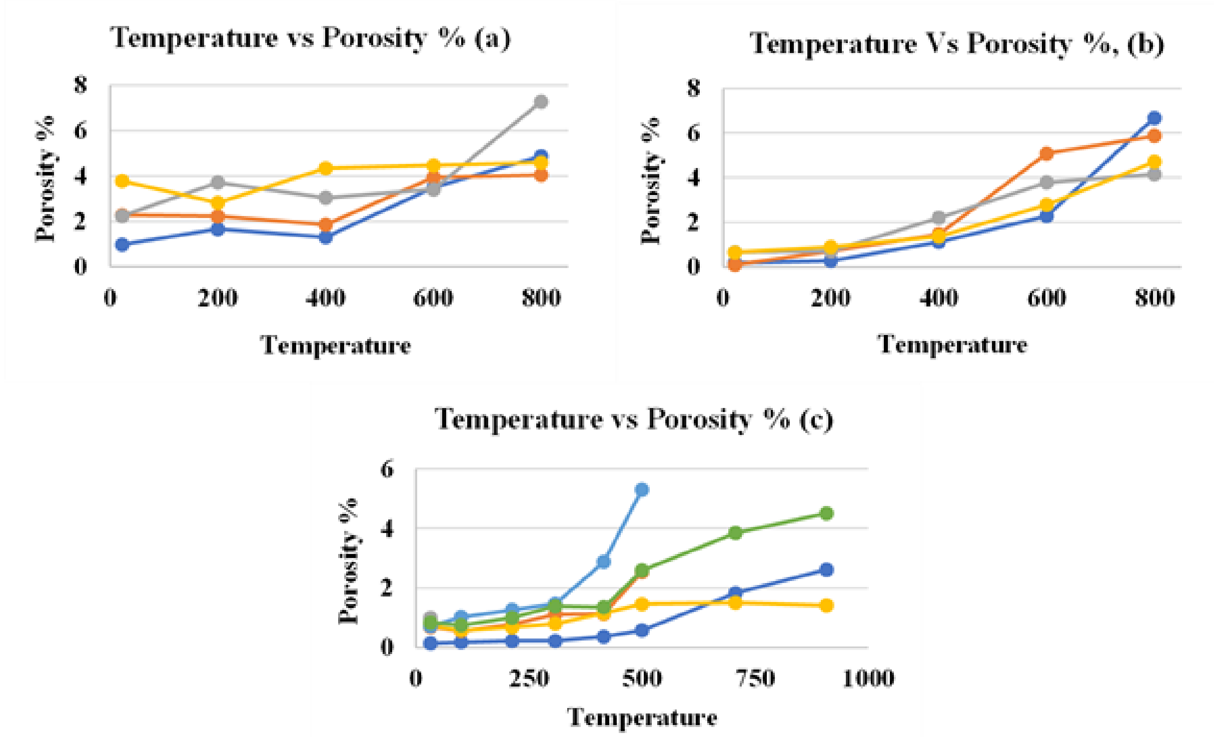

Figure 5. Rate of change in porosity with respect to temperature **(a), (b)** modified from Ozguven and Ozalik and **(c)** modified from Mombou)[39,40]**.**

Hassanzandegan. The porosity increases with an increase in temperature with low effective porosity and decreases with a rise in temperature with high effective porosity[38].

Hassanzandegan studied the effect of static and dynamic elastic moduli with porosity variation by performing a triaxial test under different temperature of 25, 60, 90, 120 and 140. The effect of porosity was also studied for an indirect method of determining the cracks and rate of deterioration for the in-situ rocks. It was found that when testing with P-wave and S-wave the microcrack porosity does not affect the results but the fluid in these microcracks does. By these studies it was made evident that the increase in temperature always increases porosity as the pore space, grain size and spatial distribution changes.

The change in porosity with increasing temperature were studied by Ozguven and Ozelik, the samples contained sedimentary rocks (limestones) and metamorphic rocks (marbles), from this study it was observed that the change in rate of change of porosity in sedimentary rock is less than the rate of change in porosity in the metamorphic rocks. The rate increased after the temperature is increased from 400˚C shown in Figure 5 (a) and (b)[39]. In the review article Mombou *et al*, showed the rate of change of porosity in hard rocks (granite), the temperature was varied for different studies, it was observed that the rate increases suddenly after the temperature rises to 500˚C. from these studies it was clear that the less cementitious material goes through constant increase in porosity with lesser cracks initiation, whereas in hard rocks the rate of change of porosity is sudden and higher after a certain temperature and generation of cracks[40].

4.2 Porosity with Confining Pressure, Consolidation, and Uniaxial Compressive Strength

It is the one of the most important relationships to understand while studying the impact of porosity on underground structures. Confining pressure is the stress that is exerted on a layer of rock by its over lying structure.

The over lying structure or Overburden has a high impact on porosity, with an increase in compaction the confining pressure increases, and the porosity of the structure or rock mass decreases[41]. Overburden plays a major role in the compressibility or consolidation of a material or rock layer, as it is the major vertical load acting in the direction of gravity over the roof of the structure. Over burden can also be the external load applied vertically on the original ground level of the sub-surface structure. As the depth increases the compaction increases with burial, and the porosity decreases[42], but from studies, it has been found that with the increase in depth, the rate of change of porosity decreases. The damage due to compaction was studied and it states that due to compaction porosity and water retention changes[43]. It is shown by many studies that if the material is well compacted or consolidated the value of porosity decreases and after a certain depth, the porosity becomes constant and further porosity only changes if hydrostatic pressure or any external pressure is specifically applied on that layer[41]. The rock layer will be stable when it is in hydrostatic equilibrium, if the hydrostatic pressure is less than local pressure then the layer is said to be in over pressure condition and if the local pressure is less than the layer is said to be under pressure condition. The effect of over burden pressure can be negligible in consolidated rocks but it also depends on the type of consolidated rocks. The major effect of the relation between confining pressure and porosity is that it can make the material brittle with time and it will eventually become very poor in strength which leads to failure of the material because the brittleness in the material causes cataclastic flow[44]. But if the confining pressure is increasing the pore fluid pressure will decrease with it which can make the material ductile with time and can lead to a creep effect in the material layer, if the layer is assumed as a cantilever beam or fixed beam. There will be bending moment generation due to the increase in load and increase in confining pressure, which will decrease the porosity which will decrease the resistance provided by the pore fluid pressure to the confining pressure which makes the layer stable in its place[45].

Pores inside the material have two usages first is that connected pores will always help the inflow of liquid and gas, if the pores are not connected, they are used for storage of gas and liquid. It has been reported by many studies that if pores are connected then with an increase in confining pressure the permeability decreases due to the decrease in porosity[46]. The non-connected pores will have more fluid pressure. The high pore fluid pressure tends to promote the brittle behavior of materials. The fluid in these non-connected pores promote does not work as a lubricant, it reduces the normal stress that develops inside the rock. The effect of porosity on confining pressure is not instant but it is a time-dependent effect.

To understand the effect of overburden pressure further formation factor was analyzed using Archie's equation. It was found that with two different methods of determining porosity direct method(imbibition method) and indirect method (electrical resistivity)) the cementation factor was high for low porosity samples and low for high porosity samples[47].

Related to confining pressure and overburden, Uniaxial Compressive Strength (UCS) is important strength parameter for rock mass. From various studies, it was established that the increase in porosity is decrease in UCS[48].

4.3 Porosity and Young's Modulus

The relation between porosity and young's modulus can only be defined by the indirect method of testing for porosity *i.e.* by well logging of the core sample. The grain size and shape, pore size and pore shape are responsible for the change in Young's modulus due to porosity[41,49]. The relationship between elastic moduli and porosity cannot be defined completely because the relationship between them is dependent on the effective poisson's ratio[5,35]. But some data suggests that the increase in porosity shows a decrease in elastic moduli[50]. At critical porosity 0.2, the effective poisson's ratio is free of porosity so the dependence of young's modulus on porosity is nonlinear. To describe the relationship between elastic moduli and porosity GMR (Generalized Mixture Rule) is used for different types of rocks[5,51,52]. Study's by Choren shows that there cannot be any clear relationship between the pore bodies and young's modulus despite the research of 60 years. But if pore structures are altered then the mechanical properties such as young's modulus can be changed[53].

As Phani and Niyogi, stated that the relation between young's modulus and porosity is in reverse order for brittle solid materials, that is when the porosity increases the value of young's modulus decreases because stiffness decrease because of pore space. A semi empirical equation was derived from the original equation given by Spriggs

$$E = E_0(1 - aP)^n$$

Where E and E_0 are the Young's moduli corresponding to the values of porosity from 0 to P, a is packing geometry factor from 1 to 3.85 and n depends on the grain morphology[54]. The pore spaces initially become tightened with an increase in elastic deformation but at the point of inflection this decrease becomes more compliant, and an increase in compaction is noticed, then after sometime with continuous loading the grains get crushed and the porosity decreases completely[44]. The change in porosity for young's modulus and vice-versa also depends on the loading, if cyclic loading is on the structure, then with every cycle the strain value changes and it changes the pore pressure inside the material[55].

The work of Hadrigan and Nakhla shows that the elastic moduli decrease with the change in porosity[45]. They prepared a 2D FEM model to show the change in elastic modulus for the change in porosity of a material. The study was conducted for a beam, then further adding to this study made a 3D model of the same and it further provides the result that the amount of porosity, its concentration location in a layer affects the young's modulus of the layer. Young's modulus of material gives a brief idea about the load a structure can bear and if it decreases with an increase in porosity then it does impact the structure[53].

4.4 Porosity and Hydraulic Conductivity

The relation between porosity and hydraulic conductivity is very important. It is called permeability for soil and hydraulic conductivity for hard materials. Permeability and porosity are also very important indicators of various types of rocks. The connected pores inside a material provide the fluid conduit to the material, which helps in fluid flow inside the material in the direction of hydraulic gradient, these pores are known as open pores (effective porosity). Hydraulic conductivity is used in Darcy's law which follows the laminar flow of fluid[56]. This relation is used in an underground structure like a cavern for the stability of the roof[6]. Hydraulic conductivity also indicates the water retention potential of the rock, the fragments are the main component for that, and the use of this is mainly in agriculture[57].

With a significant decrease in hydraulic conductivity, it may accompany the compaction of material[44,58,59]. This

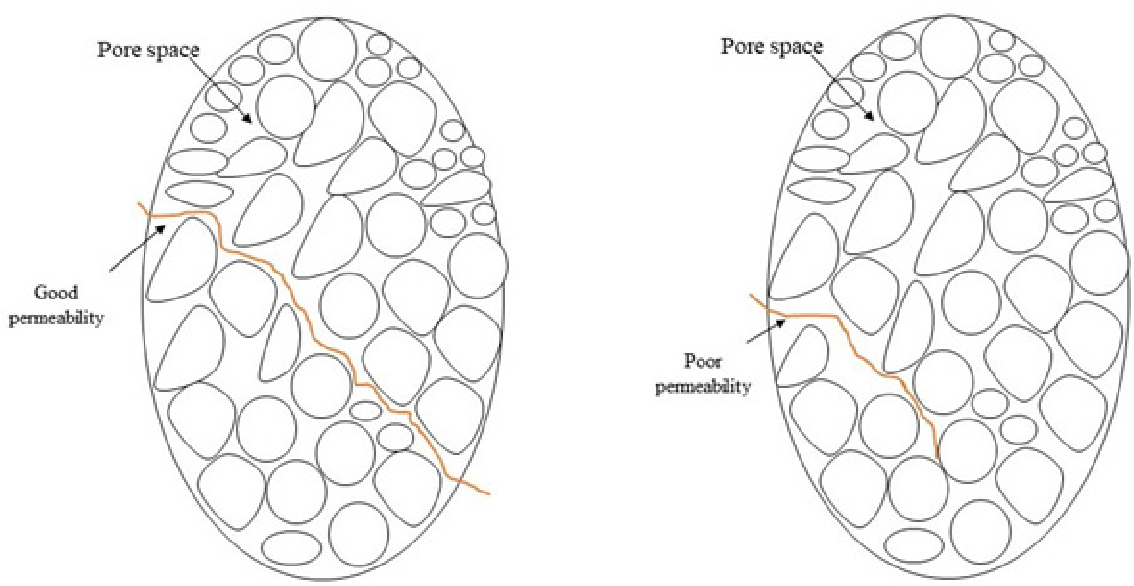

Figure 6. Porosity and permeability- a pictorial representation.

inelastic compaction can result in the deformation of the whole layer[60]. Such deformation can result in surface deformation[61,62]. It is also seen that during combustion of coal the permeability goes down drastically, increases suddenly and then decreases, as the pore volume and permeability is inter connected[63]. To show the difference between porosity and permeability a pictorial representation is shown in Figure 6.

To better understand the relationship between porosity and permeability, studies have been conducted under cyclic loading. It was discovered that as confining pressure increases, the rock's porosity, and permeability decrease[64], rises with each loading cycle. The porosity and permeability in the unloading process are typically lower than in the loading process under the same confining pressure because of permanent rock deformation during the loading phase. The sandstone's porosity and permeability are sensitive to stress in different ways. Particularly at low confining pressures, the permeability is more responsive to variations in the confining pressure than the porosity. Because of the relationship between the rock's porosity and permeability, even a slight change in porosity can have a significant impact on permeability. This study also states that porosity and permeability follow a power law relationship given as,

$$K = K_0\left(\frac{\Phi}{\Phi_0}\right)^c = K_0\left(\frac{1}{\Phi_0}\right)^c \times \Phi^c = a\Phi^c$$

Where K and Φ are permeability and porosity respectively. a and c are fitting parameters for the power law curve. This relationship stands better under confining pressure of 30 Mpa[65].

To understand the effect of porosity and permeability with effect of increased overburden pressure was studied for sandstones, the fracture capacity shown by the samples were same, this response to overburden pressure was significant for determining the storage capacity of the rocks. A relationship for the same was made for the condition:

$$C_p = \frac{1}{d_p}\frac{dV_p}{V_p}$$

Where C_p is compressibility, d_p is net overburden pressure, dV_p and V_p is change in pore volume and pore volume, from this equation it was clear that within a smallrange of change in overburden pressure, no change in pore compressibility occurred[66].

4.5 Porosity and Underground Structures

With change in temperature the porosity changes, with change in chemical conditions pore matrix changes the porosity. While the construction of any mining tunnel, the pathway for water creates very easily due to the connected pores, the permeability continuously increases due to increase in pores[67]. This affects the construction and strength of the structure. This was studied by Ma *et. al.,* that the change in properties of the rock mass such as porosity occurs non-linearly, with increase in porosity UCS decreases exponentially[68]. This was studied with the help of indirect test for determining porosity. As shown in work of Chimanni and Lokhande, the water curtaining in the caverns works effectively due to the pore pressure generated through the pores over the crown of the structure, this helps in stability of the structure by balancing the effective stress coming from the overburden[6]. For the abandoned underground coal mines, the refilling of the excavated area is important. This can be done through various methods, but as the residual coal expands due to exposure, the porosity decreases, which makes the adsorption of the methane gas difficult[69]. Another underground structure nowadays is hydrogen storages, Tarowski *et al.* studied barrier for underground storage and it was found that the dissolution of mineral due to formation of CH4 increases because of the presence of hydrogen, which increases porosity and it can activate faults in the region with time. This phenomenon led to the weakening of the rock mass of the underground storage[70]. The cement backfills, also called Paste Cement Backfill (PCB) is used in backfilling of the excavated areas in metal mines, the pores developed can be damaging or multi damaging to the structure upto 4% and 7% of the total volume respectively. Higher percentage of these can lead to decrease in UCS which can lead to the instability of the structures[71].

5.0 Conclusions

The stability of a structure is the most crucial consideration during construction. One such parameter is covered in this paper, it addresses the origin of a material's porosity, how it changes over time, and which factor causes changes in porosity along with the methods for evaluating porosity and which ones are most appropriate for *in-situ* use. Since porosity shows a rock layer's resilience over time, it has a significant effect on subsurface structures. The temperature impact can alter this via affecting the material's UCS, confining pressure, Young's modulus, and hydraulic conductivity. The strength of rockmass structures is significantly influenced by these characteristics, with porosity having the substantial impact. The relationship or influence is not linear; rather, it varies according to the burial depth and the pressure exerted by overburden above the structure's roof, also it changes with grain size and chemical reactions. The indirect approach of porosity determination, which can demonstrate the influence of porosity and is the most effective way to ascertain the association between these variables which can eventually cause structural instability. The underground structures constructed or excavated for various purpose such as mining, storage caverns, tunnels and foundation rocks can be heavily affected during and after the completion of the procedure due to change in porosity of rock mass.

6.0 Acknowledgments

The authors are thankful to the Head of the Department, Mining Engineering, and Director VNIT, Nagpur for providing the necessary support and permission to conduct this study and publish this research work. Special thanks to Ruchika Mange and Aparna Unnikrishnan who helped with editing and other support for this paper. The views expressed in this paper are of the authors and not necessarily of the organization they represent. This paper forms a part of the M. Tech dissertation work of the first author.

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