International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2022 | Issue 51 | Volume 14 | Number 2 | Pages 160-166

ON THE INFLUENCE OF POROSITY ON MECHANICAL PROPERTIES OF MATERIALS

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Abstract- Natural materials as soils, rocks, woods, leathers, bons, soft tissue of organisms and artificial materials as concrete, brick, ceramics and others can be attributed to porous bodies. The soil that forms the basis of agriculture is also a porous body. These examples show how porous bodies play an important role in human life. A characteristic feature of all these materials is that they collect liquid and allow them to move under the action of extracted from the pours of deposits located at great depths. Oil and gas accumulated in these porous deposits are extracted based on the filtration law that makes the filtration theory one of the most important theories.

Keywords: Porous Materials, Skeleton, Neutron, Electric Charge, Endurance, Embrittlement of a Material.

1. INTRODUCTION

In recent years, porous materials have attracted great interest as a new class of construction materials. For example, ceramic materials were able to withstand higher temperatures and aggressive media longer than metals and macro molecular components. These properties allow to use ceramics as a heat-insulating and filtering material in oilfield equipment. At present a porous ceramic is successfully used in the design of filters and dispensers for letting drugs out [21].

Under strong physical influences, non-porous materials also behave like porous materials. One of these physical actions is high temperature. Under high temperature, the distance between atoms and molecules increases and non-porous bodies turn into porous bodies. Therefore, even steels under high temperature behave themselves not like elastic bodies, but like viscous-elastic bodies [7, 17]. Neutron irradiation can be shown as the second physical action. Neutrons have no electric charge. Therefore, the electrical energy [11]. It should be noted that although neutron irradiation itself leads to embrittlement of the material, the high temperature arising from the amount of the released heat increases plastic properties of the material.

If should also be noted that under neutron irradiation, pores in the material are formed not only due external forces. This liquid can flow in the porous biomaterial of a living organism. The movement of moisture in the soil also plays an important role. In the end, it is the liquid that moves in the soil, delivers the nutrients to the plant and leads to the nutrition of the entire living world as a whole. Finally, the main source of energy of the XXI century, oil and gas are neutrons with high speeds can penetrate deep into the material. When fast neutrons collide with atomic nuclei, they knock atoms out of their places. The knocked-out atoms in their turn knock out other atoms from their places. After several collisions, the atoms are embedded between other atoms. The empty places of the knocked-out atoms are called vacancy, an atom stuck between other atoms is called an instilment.

The process of formation of vacancy-instilment is called dislocation. After some time, the empty places are occupied by another atoms and the number of vacancies equals the number of instilments and saturation occurs. Over time, as a result of dislocations, the material becomes brittle, its endurance limits, proportionality and elasticity increase the plasticity decreases. For example, the modern tanks that receive a dose of 10^{20} neutrons/cm^2 collapse as a glass when it starts moving [3, 10, 12]. It should be noted that neutron irradiation is not always harmful. It is known that in cyclic processes the material can be destroyed due to fatigue under stresses much lower than elasticity limit. If the structural element in the cyclic process works only in tension or only in compression, then due to neutron radiation, by increasing the endurance limit of the material, we can increase the number of cycles needed to destroy the element. During neutron irradiation, when neutrons collide with the nuclei of other atoms, a huge amount of heat is released. Just this heat is used in nuclear reactors to get the formation of a vacancy, they are also formed due to high temperature [1, 2, 17].

The pores are interconnected by capillary tubes [9]. When a porous body is in a wetting liquid, the liquid rises through the capillary tube to the height h, determined by the formula $h = 2\sigma(\rho g r)$, where σ is a surface tension coefficient, ρ is the wetting liquid density, g is acceleration of gravity, r is a capillary tube radius. The height h may be rather large due to the small radius of the capillary tube. Then the pressure $P = \rho g h = 2\sigma / r$ formed in the capillary tube will also be rather great [4, 5, 16, 22].

2. PROBLEM STATEMENT

Determining the given mechanical properties of the material. When porous materials come into contact with liquid, the liquid penetrate deep into the materials resulting in a two-phase medium. Saying liquid, we mean liquid and gas. A part of porous materials consisting of partitions between the couples is called a skeleton. The pores in porous materials are interconnected by capillary tubes. Under the action of external influences, the skeleton of the polymer is deformed resulting in a change in pore volume [13, 14, 15]. And this process takes place over time. Therefore, in structural elements made of porous materials the internal pressure formed by external influences are distributed unevenly and over time through capillary tubes the liquid filling the pores move from higher pressure pores to lower pressure pores [19, 20].

As the volume of the pore's changes, the mass of the liquid in the pores also changes. Thus, over time there appear time-dependent deformations. Such deformations when reversible, are called viscous deformations [6, 7, 8, 23].

3. PROBLEM SOLUTION

The following parameters are considered in the analysis:

V, Volume of the porous body

V_s, Volume of the skeleton

V_m, Volume of liquid in pores

m_s, Mass of the skeleton

m, The mass of the material of the construction with liquid-filled pores

m_m, Mass of liquid in pores

ρ_s, Density of the skeleton

ρ, Density of the material of the construction with liquid-filled pores

ρ_m, Density of liquid in pores

Three of these quantities, V, m_m and m_s can be measured directly, two of them, ρ_m and ρ_s become known. The rest of the quantities can be determined by means of these three quantities as follows:

$$m_m = m - m_s \tag{1}$$

$$m_m = \frac{V_m}{\rho_m} - \frac{V - V_S}{\rho_m} \tag{2}$$

$$V_S = V - V_m \tag{3}$$

$$\rho_S = \frac{m_S}{V_C} = \frac{m_C}{V - V_m} \tag{4}$$

From (1) we obtain: $m_m + m_s = m$, therefore,

$$\frac{m_m}{m} + \frac{m_S}{m} = 1 \tag{5}$$

We now obtain an expression for the reduced young modulus of the material of the construction with liquid-filled pores. In the uniaxial traction, as is known the Hooke law is as follows:

$$\varepsilon = \frac{\sigma}{E} \tag{6}$$

where, E is young modulus, σ is tensile stress, ε is aspect ratio which is obtained from Equation (6).

$$E_s = \frac{F}{\frac{m_s}{m} S\varepsilon} = \frac{m}{m_S}\frac{F}{S\varepsilon} = \frac{m}{m_S}E \tag{7}$$

therefore, the pores of the young modulus of the skeleton are $\frac{m}{m_s}$ times different from the young modulus of the material of the construction with liquid-filled pores.

When the bar is compressed, the compression deformations in its skeleton and liquid column in pores equal to each other, i.e., $\varepsilon_s = \varepsilon_m$, then,

$$\frac{T_s}{S_s E_s} = \frac{T_m}{S_m E_m} \tag{8}$$

where, T_s and T_m are compressive forces, whose cross section acts on the skeleton and porous parts, respectively, and S_s, E_s and S_m, E_m is a cross-section of the skeleton and liquid and young modulus, respectively.

On the other hand, compressions both of the skeleton, liquid column and common element are equal, i.e.,

$$\frac{T_s}{S_s E_s} = \frac{T_m}{S_m E_m} = \frac{T_s + T_m}{(S_s + S_m)E_g}$$

where, E_g is a reduced young modulus. From the last equality

$$E_g = \frac{m_s E_s + M_m E_m}{M} \tag{9}$$

Similarly, for the reduced shear modulus G, the Poisson ratio v_g, yield point σ_g, creeping kernel K_g, relaxation kernel Γ_g we obtain the following expressions.

$$G_g = \frac{m_s G_s + m_m G_m}{m} \tag{10}$$

$$V_g = \frac{m_s V_s + m_m V_m}{m} \tag{11}$$

$$\sigma_g = \frac{m_s \sigma_{sa} + m_m \sigma_{ma}}{m} \tag{12}$$

$$K_g = \frac{m_s K_s + m_m K_m}{m} \tag{13}$$

$$\Gamma_g = \frac{m_s \Gamma_s + m_m \Gamma_m}{m} \tag{14}$$

In Equations (9)-(13), the s index belongs to the skeleton, and the m index refers to liquid. Since the liquid and gases take the shape of the container in which they are poured, the shear module of liquid and gases can be assumed to be zero. Then the Equation (10) takes the following form.

$$G_g = \frac{m_s G_s}{m} \tag{15}$$

where, $M = m_s + m_m$, and taking into account

$$G_s = \frac{E_s}{2(1+V_s)},\ G_g = \frac{m_s}{m_s+m_m} \times \frac{E_s}{2(1+V_s)}$$

As can be seen from this formula, as the mass of the liquid increases, the shear modulus decreases, but the shear modulus is independent on mechanical properties of liquid or gas filling the pores, it depends only on mechanical properties of the skeleton.

In Equation (9) taking into account $m = m_s + m_m$ for E_g, we obtain,

$$E_g = \frac{m_s E_s + m_m E_m}{(m_s+m_m)^2} \tag{16}$$

Since in the deformation time the volume of the skeleton changes little, but the volume of pores changes a lot, we consider in (16) m_m as a variable quantity and taking a derivative from E_g with respect to m_m

$$E_g' = \frac{m_s\left(E_m - E_s\right)}{(m_s+m_m)^2} \tag{17}$$

As can be seen from (15) for $E_m > E_s$, E_g' is positive, for $E_m < E_s$, E_g' is negative. This means that regardless the mass of liquid in pores, when the young modulus of the liquid is greater than the young modulus of the skeleton, increasing the mass of the liquid the reduced young modulus increases and vice versa, if the young modulus of the liquid is less than of the skeleton it decreases.

If the liquid in the pores of construction material is incompressible, then $v_m = 0.5$. In this case, from (16)

$$E_g' = \frac{m_s V_s + 0.5 m_m}{m_s + m_m} \tag{18}$$

From the physical properties of the material, the thermal expansion coefficient α and specific heat capacity c are determined as follows.

$$\alpha_g = \frac{m_s\alpha_s + m_m\alpha_m}{m_s+m_m} \tag{19}$$

$$c_g = \frac{m_s c_s + m_m c_m}{m_s+m_m} \tag{20}$$

It should be noted that as when deformed the volume of the skeleton changes very little than the volume of liquid, it is necessary to adopt a fixed specific heat capacity for the skeleton.

Since for liquids in pores, both volume and pressure change, a specific heat capacity in constant pressure should be adopted.

The experiments were carried out in the unit AIMA-5-2, as Figure 1.

3.1. Geometrical Characteristics of Test Samples

a) cylindrical sample: diameter d = 10 mm, calculated length l = 100 mm, fastening form groove head M12.
b) cylindrical sample: diameter d = 5 mm, calculated length l = 25 mm, fastening form groove head M12.
c) Plane sample: thickness h = 2 mm, width b = 20 mm, calculated length l = 25 mm, tie shape, finger combination.

Figure 1. Electrical equipment installation of AIMA-5-2

3.2. Methods for Measuring the Elongation of Test Samples

a) Cylindrical sample: a sample 25 mm grooved M12, measuring instrument a scale ruler, 100 mm grooved M18, measuring instrument tensimeter with 2 indicators and whose scale is 0.001 mm.
b) plane sample: a sample 25 mm grooved M12, measuring instrument- a scale ruler, 100 mm grooved M18, tensimeter with 2 indicators and whose scale is 0.001 mm.

Composite materials have been widely used in engineering. The use of natural composite materials dates back to the Middle Ages when ancient builders used straw to make bricks and mud strong in constructions. At present, composite materials with special properties are being developed. For example, radiotransparent and absorbent materials, composite materials for thermal protection of space craft, composite materials with little thermal linear expansion, high-strength materials etc.

There are many areas of application of composite materials: space aviation, rockets and so on. Furthermore, composite materials are successfully used in power engineering, machine-building, in the chemical industry for engine parts, in oil and gas industry for manufacturing various equipment's and others.

Composite materials consist of two or more phases. Usually, one of the phases consists of discrete solid elements. The less rigid phase is called a matrix. The composites can be divided into three groups: polymer-matrix, metal matrix and ceramic matrix composites. Recently, the production of super hybrid composites has already begun.

The properties of composites depend on the properties of their components, arrangement density of elements and their geometrical displacements. Composite materials have unusual advantages compared to homogeneous materials, i.e., the composites have high strength, density, sufficient longevity, low compression. But some composite materials have some negative properties as high price, anisotropic feature, high scientific demand for production, etc.

Our goal is to find stresses arising because of stretching from the samples made of composite materials under higher temperature and build their diagrams. A new approach is used for estimating the strength of numerous composite materials. Strength of a layer does not determine strength of an entire composite material.

In order to analyze strength of numerous composite materials we take into account following additional factors:

- Difference of location of fibers in various layers
- Change of the strength of the layer of the composite along the coordinate axes
- Sequence of location of layers influencing on bending and mutual strength
- Polymerization condition influencing on stress values of a layer.

The samples are given in the following form Figure 2.

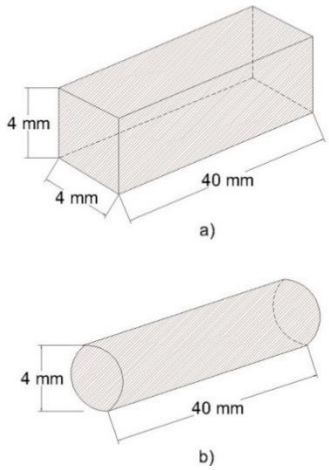

Figure 2. Geometrical shapes and sizes of samples

We tested these samples for stretching and bending at high temperature. The test of the applied samples for creeping for a long period, is implemented under the action of traction force at constant temperature. Strength analysis of this material differs from previous one by the fact that the sample is reduced to the failure limit. A long-term ultimate strength of the composite material is determined in experiments. For shear and long-term strength analysis of the composite material the AIMA 5-2 is used. The samples to be tested are fixed by a fixator from both sides and from above it is affected by the mechanism. The machine enables to test the samples in 50-400 N boarding mode. The machine operates in both automatic and manual modes. The machine is equipped with an electric oven which heats samples to 1000 ˚C.

The essence of the method is that loading of the samples of bent material on the cross-section and reducing it until its failure (when determining long-term ultimate strength) or depending on the loading time of residual deformation to a certain value, in the test period loading and temperature remain constant.

The test is carried out in AIMA-5-2 installation. This installation was designed to apply shear processes of the material samples at fixed temperature and to determine certain shear characteristics: the ultimate shear and period of continuation of hardness limit.

AIMA-5-2 installation was designed only for tension testing of material samples. For bending testing of material sample the installation is equipped with a special accessory Figure 3. Its overall dimensions are restricted with the dimensions of the heating chamber. To establish the shear curve, the maximum stress and maximum linear deformation are determined in the sample.

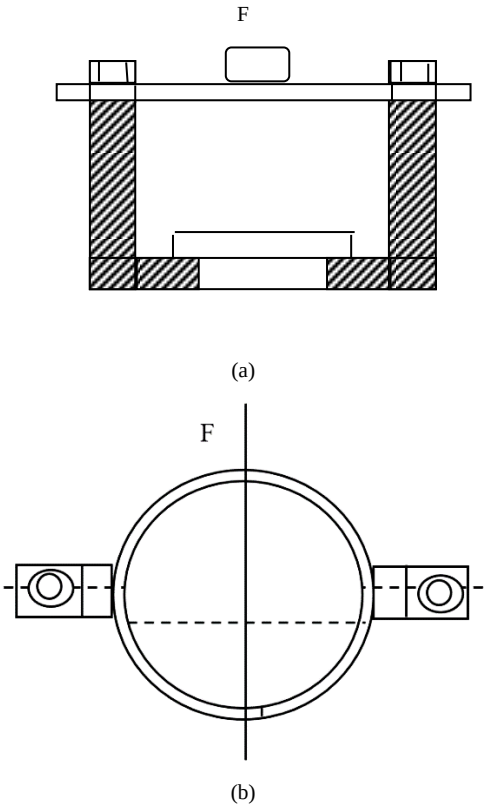

Figure 3. An installation for bending test

The maximum stress in the sample:

$$\sigma_{\max} = \frac{Fl_0}{4W_k} \tag{21}$$

Resistance moment for annular cross-section of the sample

$$W_v = \frac{\pi {d_0}^3}{32} \tag{22}$$

For a square cross-section sample

$$W_v = \frac{a_0^3}{32} \tag{23}$$

where, d_0 and a_0 one the diameters of annular cross-section of the sample and the side of the square before testing (initial), respectively. Taking into account formulas (22) and (23) in (21) for the annular cross-section sample we get:

$$\sigma_{\max} = \frac{2.546Fl_0}{d_0^3} \tag{24}$$

For a square cross-section sample

$$\sigma_{\max} = \frac{1.5}{d_0^3} \tag{25}$$

Maximum linear deformation occurs in the edge fiber of the cross-section. Here the greatest bending moment affects. To determine the bending moment the bent axis during pure bending is accepted in the form of circumference arc

$$(1/2)^2 + (p-y)^2 = p^2 \quad (26)$$

hence, we determine the dependence between the curvature radius of the bent axis and maximum bending:

$$p = l^2/8y \quad (27)$$

For annular cross-section samples with maximum deformation in edge fibers

$$\frac{\varepsilon_{\max} d_0}{2p} = \frac{4d_0 y}{l^2} \quad (28)$$

For square cross-section samples

$$\varepsilon = \frac{4a_0 y}{l^2} \quad (29)$$

The test program combiners 2 types of tests: short-term and long-term tests. The short-term test is considered for determining the dependence of the strength and characteristics of the material on t^0. Each sample, starting at constant t^0 from 0 is tested at various values of loading for destructive loading and for building deformation curvature, it is calculated by the formulas (24), (25), (28) and (29) in $\sigma_{\max}$ and $\varepsilon_{\max}$ coordinates. The samples were tested:

- first test T = 18-20 °C
- second test T = 500 °C
- third test T = 700 °C
- fourth test T = 900 °C

A long-term test was carried out to determine the shear characteristics of the test sample (was considered for long-term ultimate strength limit and shear limit). Each sample was tested at constant loading and fixing the time at constant t^0 and at various moments of deformation time. Then the shear curvature was built in linear deformation time coordinates. Depending on the given $\sigma_{\max}$ for each sample, the required load is determined by formulas (24) and (25) for annular samples.

$$F = \frac{\sigma_{\max} d_0^{\,3}}{2.546\pi l_0} \quad (30)$$

$$F = \frac{\sigma_{\max} a_0^{\,3}}{5l_0} \quad (31)$$

The 6 samples are tested:

- the first test T = 500 °C; $\sigma_{\max} = 0.9\,\sigma_a$
- the second test T = 500 °C; $\sigma_{\max} = 0.7\,\sigma_a$
- the third test T = 700 °C; $\sigma_{\max} = 0.7\,\sigma_a$
- the fourth test T = 700 °C; $\sigma_{\max} = 0.5\,\sigma_a$
- the fifth test T=900 °C; $\sigma_{\max} = 0.7\,\sigma_a$
- the sixth test T = 900 °C; $\sigma_{\max}$ =0.7 σ_a

where, σ_a is a yield point of the material with t^0 obtained a result of short-term testing.

The long-term ultimate strength is determined as a result of long-term testing, where σ_{mh} is the conditional of the long-term strength limit, t_p is time to destruction, and T is the t^0 of the testing. The dependence between long term strength limit and the time to destruction of material is accepted as follows:

$$\sigma_{mh}^m t_p = C \quad (32)$$

where, σ_{mh} is a long-term ultimate strength (for certain temperature); t_p is time to failure, m and c are characteristics of the material. The parameters m and c are determined as a result of testing of two samples.

$$m = \frac{t_p(2)/t_p(1)}{\log \sigma_{mh}(1)/\sigma_{mh}(2)}$$
$$C = \sigma_{mh}^b(1) \log t_p(2) \quad (33)$$

where, σ_{mh} (1) and t_p (1) is a long-term ultimate strength and time to failure of the material for the first sample; σ_{mh} (2) and t_p (2) are the long-term strength limit and time to failure for the second sample. The dependence is given in Figures 4 to 7.

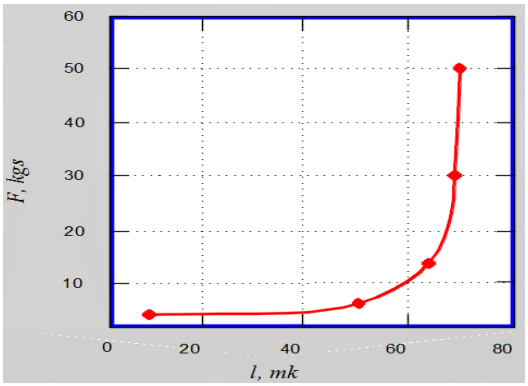

Figure 4. Deformation dependence of traction force, t = 20 °C

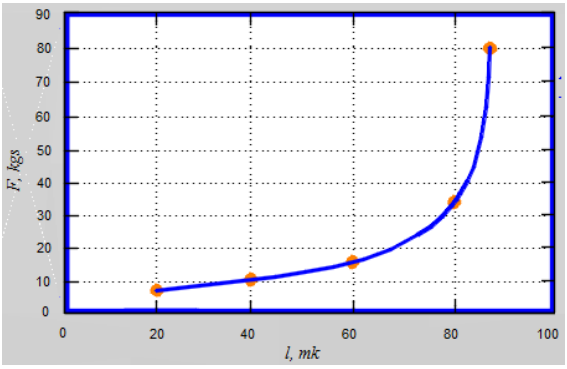

Figure 5. Deformation dependence of traction force, t = 500 °C

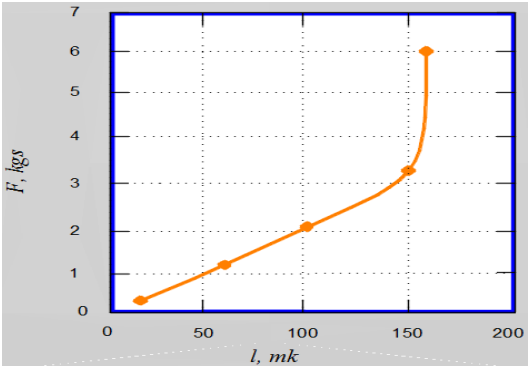

Figure 6. Deformation dependence of traction force

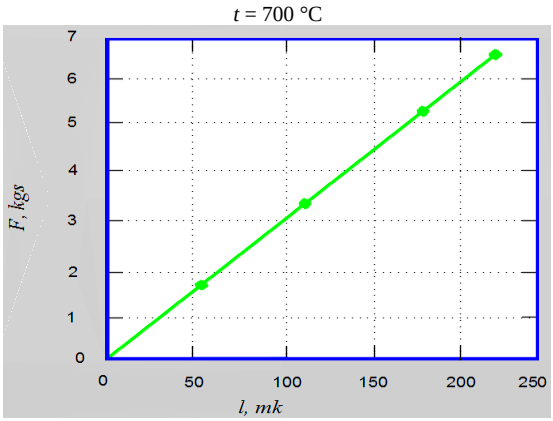

Figure 7. Deformation dependence of traction force, t = 900 °C

4. CONCLUSIONS

1. Expressions for mechanical characteristics of the material of construction with liquid filled pores were obtained.
2. Increasing the mass of the liquid in pores, the shear modulus decreases.
3. Theoretically it was proved that when the young modulus of the liquid in pores is greater than of the skeleton, increasing the mass of the liquid, the reduced young modulus increases, and vice versa when the young modulus of the liquid is less than of the skeleton, increasing the mass of the liquid, it decreases.
4. When pores are filled with incompressible liquid, increasing the mass of the liquid the Poisson ratio always increases, i.e., reduction is not possible.
5. Since during deformation the volume of the skeleton changes very little than the volume of the liquid, for the skeleton it is necessary to adopt a special heat capacity in constant volume. Since for the liquids in pores both volume and pressure change, it is necessary to adopt a special heat capacity in constant pressure.

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BIOGRAPHIES

Yusif Ashraf Orujov was born in Baku, Azerbaijan on October 7, 1954. He received the M.Sc. degree in Mathematics-Mechanics from Azerbaijan State University, Baku, Azerbaijan, in 1977. He received the Ph.D. degree in the field of technique from Azerbaijan State of Oil and Industry University, Baku, Azerbaijan, in 2015. Currently, he is an Assistant Professor at Department of Mechanics, Azerbaijan State of Oil and Industry University since 2008. He published 30 articles and a book. His scientific interests are theoretical mechanics, solid state mechanics and mechanics of composite materials.

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