Experimental investigation of decreasing porosity and permeability of bead packing at suspension flow

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Abstract. This study presents the experimental results of decreasing bead packing porosity and permeability during the flow of a suspension through the bead packing. The retention of solid particles was investigated as a function of the ratio of the particle diameter \( d \) to the diameter of the balls of packing \( D \). The experiments were carried out for various ratios \( d/D \), which varied from 0.046 to 0.109. The solids content of the inlet suspension varied from 0.001 to 0.02.

1. Introduction
Particle transport in porous media is an important process in the hydrogeological environment as well as in engineered systems. Particle deposition in porous media has been a research topic for both petroleum industry and water treatment industry. It is a complex process due to the complex nature of porous media and the properties of injected particles and fluids. The process of retaining particles of the suspension depends on the size of particles, the channels of the porous medium; physicochemical properties of particles and surface of a porous medium [1, 2, 3]. Retention leads to an increase in hydrodynamic resistance to fluid flow in a porous sample. In [1] two main mechanisms of colmatation (particle retention in a porous medium) were distinguished: mechanical filtration for large particles (diameter \( d > 30 \mu m \)), and a physicochemical filtration for small particles (diameter of about 1 \( \mu m \)) for mean particles (3 \( \mu m \) < diameter < 30 \( \mu m \)), both mechanical and physicochemical phenomena intervene. Later [3, 4], a third retention mechanism of colloid deposition in saturated porous media has commonly been identified during the filtration of suspensions -straining (retention in narrow pore throat).

Bead packing and sandpack are simple models of porous medium, used by many researchers to investigate filtration of suspension, particle movement and deposition [2, 4, 6, 8-12]. Physicochemical filtration theory [1, 3-6] has been developed and is now often used to characterize colloid attachment in porous media. The influence of \( d/D \) for small (colloid) particle was investigated in [4-6]. Mechanisms of deposition for large particles have been determined in [8-10] in dependence of the ratio of suspension particle diameter on diameter of pack bead. They [10] found that for \( d/D > 0.1 \), the porous medium is irreversibly blocked and a filter cake is formed; for \( d/D < 0.05 \), the retention remains always low and for the intermediate values a partial blocking of the porous bed may occur (this depends on particle shape and bed porosity). Experimental studies of deposition of ~6 \( \mu m \) particles have been conducted in bead packing [11, 12] and in core samples [7, 13].
The aim of this work is to present the results of an experimental study on the change in porosity and permeability of monodisperse packing of balls, when a suspension of large particles ($d > 30 \, \mu m$) of approximately the same size flows in it.

2. Experimental Equipment.

The retention of solid particles in the bead packing during a suspension flow through it under the controlled conditions was studied experimentally on the setup described in [9]. The setup (see Fig. 1) included a working section packed with glass beads, measuring graduated cylinders, differential pressure sensors, a computer, ADC, tank constant level with a mixer, inlet and outlet tubes, and webcam.

To study particle deposition within a packed bed, a well defined granular material, i.e. spherical glass beads is packed in the column to form a porous bed with a fixed porosity. The porosity of bead packing was determined from the geometrical parameter of the working section (its length, diameter), mass of glass beads, and their density. Then the bead packing was filled under vacuum with water, followed by its displacement with a water-glycerin solution. During the flow of a water-glycerin solution, the permeability of the bead packing was determined. After preliminary measurements of permeability, the test suspension was injected into a bottom of vertical laboratory column packed with glass beads. The temperature of the suspension was monitored and kept constant during the injection process.

In the process of filtering the suspension through a porous medium, differential pressure was measured by differential strain gauges. This made it possible to determine the local change in permeability along the length of the porous medium. Preliminary calibration of the sensors showed a linear dependence of the output signal on the pressure drop across them.

Figure 1. Schematic diagram of the glass pack setup–a. Pictures b show glass beads-1; aluminosilicate spheres -2 (100-140 \, \mu m), -3 (50-80 \, \mu m).
The signal from the sensors passed through the ADC to the computer. The change in the volumetric flow rate of the suspension was recorded by a video camera to fill 250 ml measuring cylinders with liquid at the outlet of the working section.

The measured flow rate and pressure drops determined the average and local permeability of the bead pack. In the experiment, the number of microspheres passed through the packing in each half-liter portion of the filtrate was determined. This was accomplished by isolating the microspheres in each portion of the outlet suspension, using the density difference between the water-glycerin solution and the aluminosilicate microspheres. After thorough washing in hot water and separation of microspheres on a fine sieve (40 μm), they were dried and weighed. After the experiment, the working section with bead packing was disassembled so that the volumes of the porous medium located between the pressure sensors were distinguished. These volumes were washed in separate containers. When washing, particles of the suspension floated in water, and balls of packing fell to the bottom. The separated suspension particles were washed, separated on a sieve, dried, and weighed.

3. Experimental Results

Figure 2 represents the average permeability of bead packing during suspension flow of 80-100 μm aluminosilicate spheres in water-glycerin solution at two pressure drops and three initial solid content. Received data show that permeability is determined by the total volume of suspension particles $V_{\text{sus}} \cdot C_{\text{in}}$. This result was obtained in [9] for local permeabilities of bead packing. Here you can see insignificant influence of initial velocity on average permeability. The maximum filtration velocity of suspension in the experiments was 0.26 cm/s. Unlike filtration of colloidal suspensions [2], the initial velocity has little effect on the change in the permeability of the bead packing. Symbols 2, 4 on figure 2 corresponds 60% increased initial filtration velocity of suspension of 80-100 μm aluminosilicate spheres.

![Figure 2](image_url)

**Figure 2.** The normalized permeability of the bead packing depending on the volume of particles received with the suspension of 80-100 μm microspheres. Lines 1, 2 correspond to 0.3% solid content suspension, 3 -0.5%, 4 0.7%. Lines 1, 3 correspond to 14 kPa pressure drop, 2, 4 ones correspond to 22.5 kPa pressure drop.
Figure 3. The normalized solid phase concentration of outlet suspension for different ratios of diameter of particle suspension to diameter of glass bead versus pumped suspension volume. Inlet solid content is 0.3%.

Figure 4. A histogram of the distribution of retained particles along the bead packing after flow of 0.3% suspension of aluminosilicate particles with different sizes.

The value of retained particles can be determined from data on outlet solid phase content. Figure 3 represents the outlet solid phase content during the flow suspension of different sizes 77.3 ± 6, 92.7 ± 6, 123.0 ± 12 μm. These sizes correspond to 0.068, 0.082, 0.109 ratio diameter of suspension particle to diameter of bead pack respectively. An increase in particle sizes gives in result the lower outlet content of solid particles.

Figure 4 depicts deposition profiles after 0.3% solid content suspension flow of different size particles. The profile of maximal size particles corresponds to classical solution of deep bed filtration theory. The profiles of other retained particles do not correspond to the theory. It concerned with small quantity of deposition.

Figure 5 depicts normalized permeability of bead packing versus the value of retaining particles. The reduction of permeability is determined with the value of deposition. That parameter does not depend on the size of retained particle, as in [13], where experiments were conducted with the cores.
Figure 5. Normalized permeability of bead packing versus volume fraction of retained particles. Different symbols correspond to various sizes of suspension particles. Here is the volume of deposited particle per unit filter volume.

4. Summary
The suspension flow through bead packing was investigated experimentally for different ratios of the diameter of suspension particle to diameter of bead pack. It was found that the permeability reduction was uniquely correlated with the amount of particles retained within the specimen independent of the injected influent concentration, injected velocity, injected fluid volume, and particle deposition profile. Local permeability of bead pack was determined with the volume of retained particles.

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