# COMPLIANT POROUS LAYERS IMBIBED WITH LIQUIDS SQUEEZED AT CONSTANT VELOCITY BY A RIGID SPHERE

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*Lubrificatia ex-poro-hidrodinamica (XPHD), mecanism care genereaza film fluid autoportant prin expulzarea lubrifiantului imbibat intr-un strat poros foarte compresibil (HCPL), este puternic dependenta de variatia permeabilitatii structurii poroase. Aceasta lucrare studiaza variatia permeabilitatii cu deformatia HCPL. Experimentele au fost realizate pe doua materiale poroase imbibate cu glicerina, comprimate cu viteza constanta cu un indentor sferic. S-a analizat atat faza de comprimare, cat si cea de decomprimare. Rezultatele din faza de comprimare au fost utilizate pentru evaluarea permeabilitatii pe baza unui model teoretic publicat anterior. Se arata ca permeabilitatea variaza cu viteza de deformare a HCPL si deci ca notiunea de permeabilitate dinamica trebuie luata in considerare.*

*Ex-poro-hydrodynamic (XPHD) lubrication, a mechanism that generates self-sustained films when highly compressible porous layers (HCPL) imbibed with liquids are squeezed, is strongly dependent on permeability variation of the porous structure. The present paper analyzes the variation of the permeability with layer compression. The experiments were performed on two HCPLs imbibed with glycerine, squeezed at constant velocity by a spherical indenter. Both compression and decompression phases were analysed. Based on a previously published theoretical model the material permeability is evaluated from recorded data during compression. Permeability variation with squeeze velocity is evident, therefore, the concept of **dynamic permeability** must be considered.*

**Keywords:** hydrodynamic lubrication; porous structure; squeeze; spherical contact; permeability

## 1. Introduction

During recent years a new lubrication mechanism applicable to highly compressible porous layers (HCPL) acting as self-sustained films has been

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developed [1-4]. This new type of lubrication known as ex-poro-hydrodynamic (XPHD) lubrication [1] requires that the elastic compression forces of the HCPL solid phase are negligible compared to the hydrodynamic pressure forces generated within the porous layer [2].

Porous materials that can be considered as HCPL are: woven and unwoven textile materials, such as felt or wash-cloth [5], endothelial surface glycocalyx that uniformly coats the microvessels [6, 7], articular cartilage [2, 8] and fresh powder snow [9]. HCPLs imbibed with liquids may have a wide applicability from squeeze dampers and shock absorbers to protective equipment components in extreme sports and even as adequate flooring in gymnastics. The XPHD phenomenon has also an important biomimetic component, and therefore is very promising for future practice applications. Studies in this area are pursued by another research team from City University of New York who analyzes this phenomenon for random soft porous media that generate lift forces to self sustain carried loads under a sliding motion [6, 9-11].

Theoretical and experimental studies related to XPHD lubrication have increased in number in recent years due to the variety of configurations and possible applications [1-4, 7, 12]. These studies have emphasized the main dependencies between the functional and dimensional parameters and the HCPL properties. XPHD lubrication is strongly dependent on porosity/compacticity variation [13] and, consequently, on permeability variation of the porous structure. The compacticity of the porous structure is defined as the instantaneous solid fraction being complementary to porosity. The fluid flow within the HCPL considering a low permeability is a Darcy flow [13] and the HCPL permeability is correlated to compacticity/porosity according to Kozeny-Carman law [13, 14].

Several previous papers analyzed the XPHD lubrication for different pairs with sliding motion (wedge effect) or normal motion (squeeze effect). Most studies on XPHD are focused on squeeze effect considering different configurations as: circular disc on HCPL [2, 3], sphere on HCPL [4] or HCPL circular damper [12].

Recently, experiments concerning the squeeze process of HCPL saturated with liquids were performed at constant velocity for unwoven porous materials imbibed with water or oil [15]. These tests have analysed only the compression phase of the imbibed HCPL and concluded that the permeability must be considered in its dynamic form. Consequently a complex formula correlating the permeability with the thickness variation was proposed based on a modified form of Kozeny-Carman law. However, the proposed formulation has not been founded on a phenomenological basis, being only a result of a regression analysis.

This paper introduces a similar experimental study analysing the behaviour of the HCPLs imbibed with a Newtonian liquid squeezed at constant velocity by a spherical shaped indenter. The present work enriches the previous work by taking into account the decompression phase of the squeezed porous material (the refilling of the HCPL with lubricant). Various HCPLs saturated with glycerine were squeezed at different constant velocities considering a certain minimum compression thickness in order to avoid the damage of the material's structure.

The squeeze at constant velocity performed on compliant porous materials imbibed with Newtonian fluids is part of a series of tests in dynamic conditions which seek to estimate the damping capacity of these types of materials. These tests provide important information about the load generated in XPHD regime. Even though the process of squeeze at constant velocity is barely found in applications, the constant velocity model could be a basis of the theoretical approaches for impact conditions. These tests were used to determine important HCPL properties based on previously published analytical model [4].

## 2. Experimental setup

The experiments of squeeze at constant velocity were performed on CETR-UMT 2 (Universal Materials Tester) including data acquisition software.

The testing configuration is sketched in Fig. 1. The tested material, saturated with the liquid (after 24 hours of immersion in the lubricant), is placed in a rigid container and squeezed by a spherical shaped indenter rigidly mounted on a vertical carriage. The carriage is driven by a step-by-step electric motor allowing for a very accurate control of its position (accuracy within 1 micron). A load cell placed on top of the carriage is used to measure the normal force generated in a range of 0- 200 N with a resolution of 0.1 N

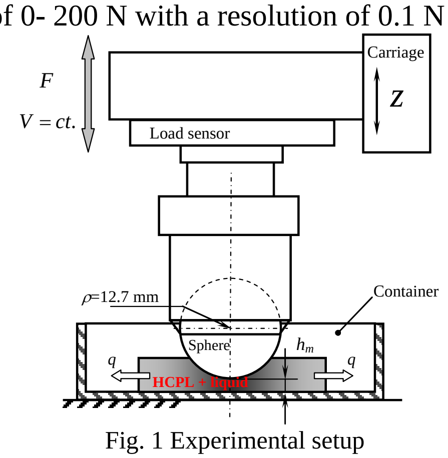



Fig. 1 Experimental setup

Three parameters were recorded during the tests: the force on vertical direction, the position of the carriage and the time. The initial position of the carriage was set before each squeeze test with respect to the fixed rigid support (container) in order to precisely evaluate the position of the carriage during the test. This initial position of the carriage was set a few millimetres over the upper side of the saturated material in order to compensate for velocity variation during carriage start-up. Unfortunately, the constant velocity condition is not valid for the beginning of the decompression phase when the acceleration of the carriage takes up to about 0.5 s depending on the velocity magnitude, Fig. 2.

The HCPLs were compressed until a minimum thickness of $h_m = 0.3mm$ was obtained, in order to prevent the damage of the material structure. Also, this limiting thickness guarantee a complete XPHD process that corresponds roughly to a range of compacticity of $\sigma = 0.1 \div 0.9$.

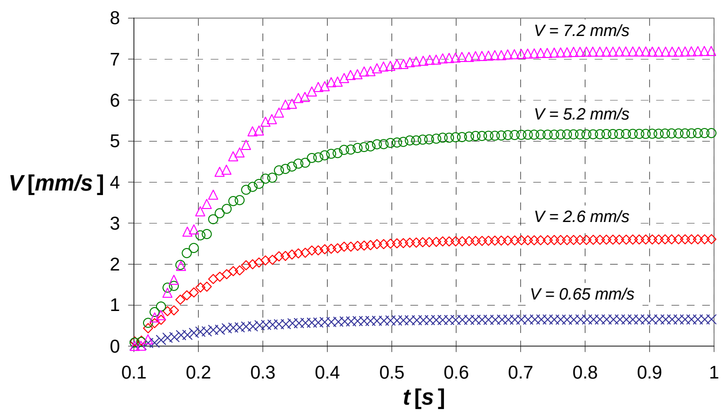


Fig. 2 Velocity profile for decompression of HCPL

After a short period of rest (the so-called relaxation time) necessary for porous material refill, the decompression phase was performed and corresponding data recorded. It must be noted that no addition lubricant was provided in the container during the tests.

The tested materials were immersed in lubricant for 24 hours before testing. After each test, the specimen was sunk in the lubricant in order to refill it completely. Two tests were performed for the same specimen at each velocity and a very good repeatability of the tests was observed.

### 3. Tested materials and lubricant

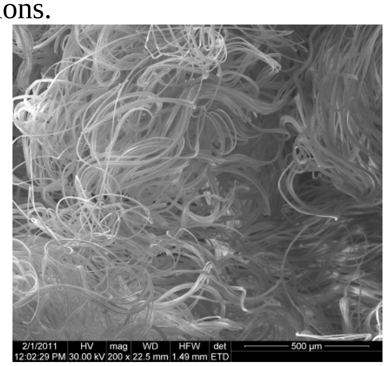
The imbibing liquid is glycerine of 100% concentration with a viscosity at room temperature of $\eta_{24^0} = 0.903 Pa \cdot s$. Two types of porous materials were selected for these reported tests. Material S1 is a woven textile having micro-fibres in its structure and material S2 is an unwoven textile that is characterised by both fibres and pores. Both show a small thickness modification when imbibed with glycerine. Due to glycerine high viscosity and material structure, sample S2 is slightly swollen, while sample S1 is a bit flattened. The initial thickness of the saturated HCPLs can be easily obtained from the experimental results: one can read the value of the carriage position, which indicates also the thickness variation, when the force differs from zero. Table 1 presents some important characteristics of the tested HCPLs.

*Table 1*

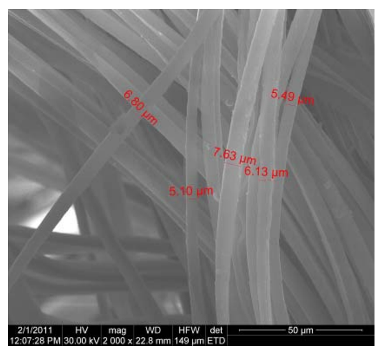
**The characteristics of the tested materials**

| | Type | Composition | Average fibre dimension | $h_0$-dry | $h_0$-imbibed | $\sigma_0$-imbibed |
|---|---|---|---|---|---|---|
| **S1** | Woven | 85% polyester<br>15% polyamide | $d_f$ = 6.5 μm | 3.5 mm | 3.4 mm | 0.076 |
| **S2** | Unwoven | 70% cellulose<br>30% cotton | $d_f$ = 12 μm | 5 mm | 5.5 mm | 0.172 |

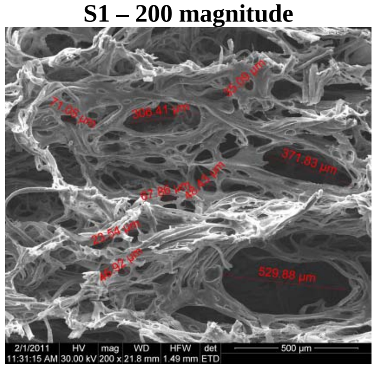
In order to have a clearer view of the structure of these porous materials some SEM images are presented in Fig. 3. The sample analysis was performed using a Quanta Inspect F FEG (field emission gun) scanning electron microscope with 1.2 nm resolution and energy-dispersive X-ray spectroscopy (EDS) having 133 eV MnK resolution. For SEM investigation the samples have been visualized at different orders of magnitude and provided important data for fibre and pore dimensions.



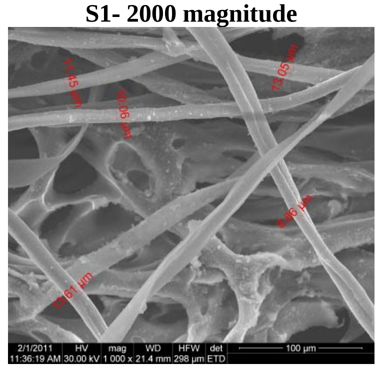

**S1 – 200 magnitude**




**S1- 2000 magnitude**




**S2 – 200 magnitude**




**S2- 1000 magnitude**

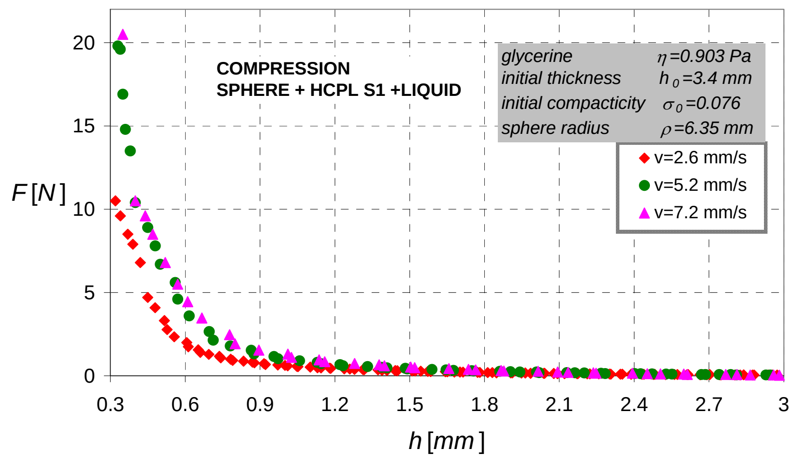
Fig. 3 SEM images of the tested materials S1 and S2

## 4. Results and discussion

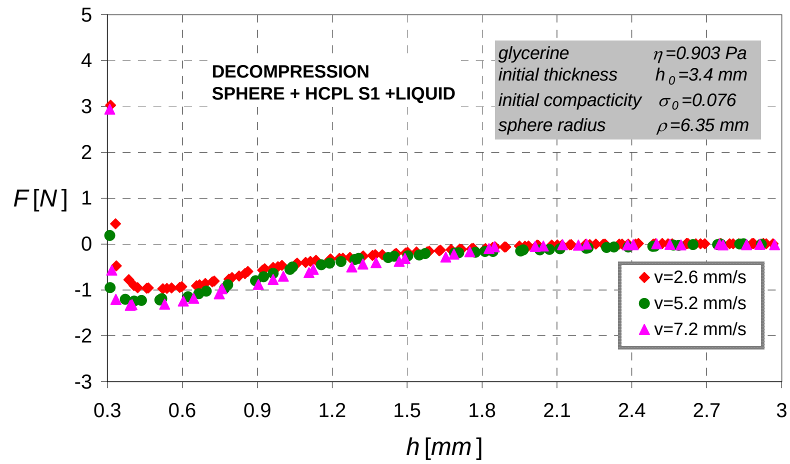
A large number of tests have been carried out for different squeeze velocities. For the present work four values were selected: 0.65; 2.6; 5.2; 7.2 *mm/s*.

### 4.1 Experimental results

The vertical force, *F*, and the thickness of the HCPL, *h*, have been selected for graphic representation. Experimental results for squeeze at constant velocity performed on HCPL S1 saturated with glycerine for both compression and decompression phases are presented in Fig. 4.



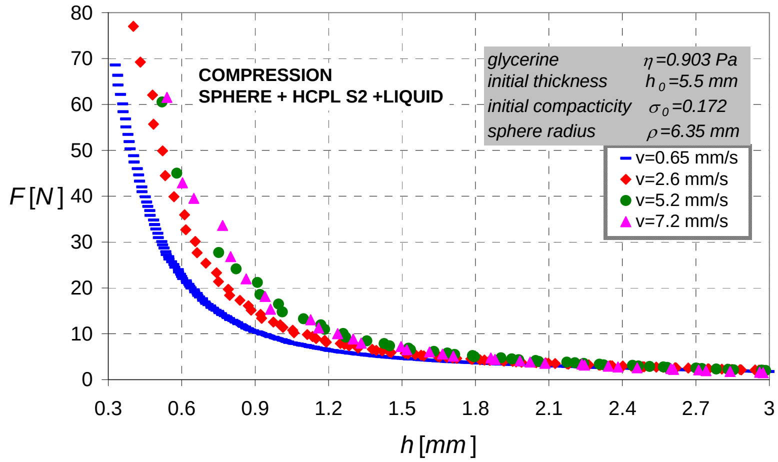

a. Compression



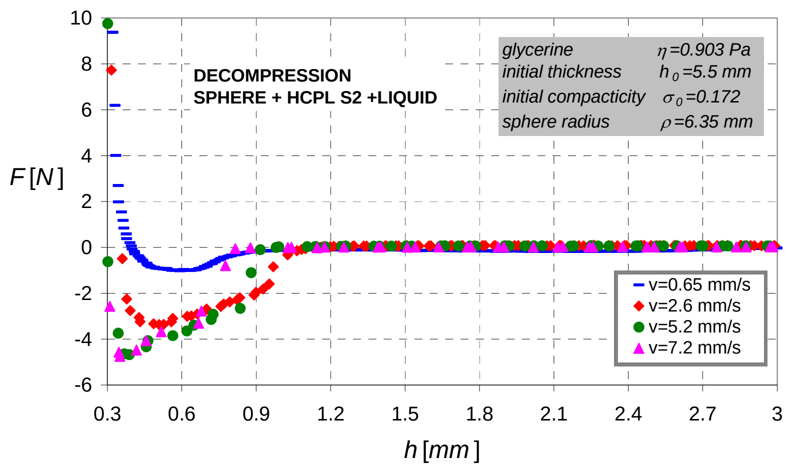

b. Decompression

Fig. 4 Compression and decompression phases for squeeze of HCPL S1

Fig. 5 presents, in the same manner, the force generated for the squeeze of material S2 for both compression and decompression phases. In order to have a clearer overview of the process the same scale for variation of thickness was used for both Figs. 4 and 5 even thought the initial thicknesses of the HCPLs are different.




a. Compression




b. Decompression

Fig. 5 Compression and decompression phases for squeeze of HCPL S2

One can observe a higher generated force for a greater velocity. As the velocity increases, the pressure of the liquid that flows inside the pores increases due to a faster constriction of the flowing pass generated by the dislocated fluid.

A similar process occurs for decompression phase, but in reversed conditions. The decompression phase is an equivalent of the refilling of the porous material with the dislocated liquid. The force is suddenly decreasing and a small depression occurs until the layer recovers 1 mm thickness. However, this phase can be hardily analysed because its extension in time is almost equal as the period of upward acceleration, see Fig. 2. Hence, constant velocity assumption is no longer valid.

### 4.2 Permeability analysis

The squeeze at constant velocity of saturated HCPLs can be used to determine an experimental permeability variation of the HCPLs. A closed form analytical solution for the squeeze of HCPL using a spherical shaped indenter was previously presented in [4]. This model has been developed only for the compression phase, no analysis being proposed for the refilling corresponding to decompression phase. This theory is based on Darcy flow model, widely used in the theory of porous media, and on the permeability law according to Kozeny-Carman:

$$\phi = \frac{D(1-\sigma)^3}{\sigma^2} \tag{1}$$

where $D = d_f^2/16k$ is a complex parameter of HCPL, $k$ is a correction constant and $\sigma = \sigma_0 h_0 / h$ is the local compacticity function of HCPL thickness.

Therefore, the generated force according to this theoretical model is:

$$F = -\frac{\pi\eta\rho^2 h_0 V_0}{8D} f_1(\sigma_0, H_m) \tag{2}$$

where

$$f_1(\sigma_0, H_m) = \frac{\sigma_0^2(1-H_m)^2(4H_m-\sigma_0)}{H_m^2(1-\sigma_0)^2} - \frac{2\sigma_0^3}{(1-\sigma_0)}\frac{(1-H_m)}{H_m^2} - \frac{2\sigma_0^3}{H_m^2}\ln\left(\frac{H_m-\sigma_0}{1-\sigma_0}\right) \tag{3}$$

Assuming valid the above model one can derive the values for the material constant $D$ using the experimental data:

$$D_{\exp} = -\frac{\pi\eta\rho^2 h_0 V}{8F_{\exp}} f_1(\sigma_0, H_m) \tag{4}$$

Fig. 6 presents experimental values for the complex parameter $D$ for all constant velocities in the case of compression phase of material S2. For each squeeze velocity one can remark quasi-constant values of $D$ for a large range of HCPL thickness. The greater values are recorded at the beginning of sphere-to-plane contact can be explained by the uncertainty of the first contact position. On the other hand for high compression rates a slight increase of $D$ can be seen at any squeeze velocity. This can be explained by the influence of the elasticity of the solid fraction. However, the complex parameter $D$ varies sensibly with velocity which yields to the necessity of analysing the permeability in dynamic conditions. Similar results were obtained experimentally by Popescu and, consequently, a model of dynamic permeability was proposed in [15].

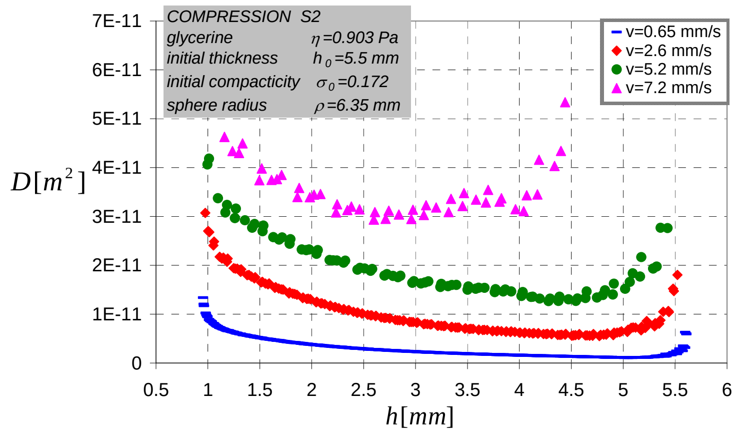



Fig. 6 The variation of complex parameter $D$ for compression of S2

Also the permeability variation can be derived from the contact force expression or, in an equivalent manner, using $D_{exp}$ from (4) in the permeability expression according to Kozeny-Carman law given by Eq. (1).

The variation of permeability using the experimental data is presented in Figs. 7 and 8 as a function of the compacticity $\sigma$ for both squeeze processes of materials S1 and S2.

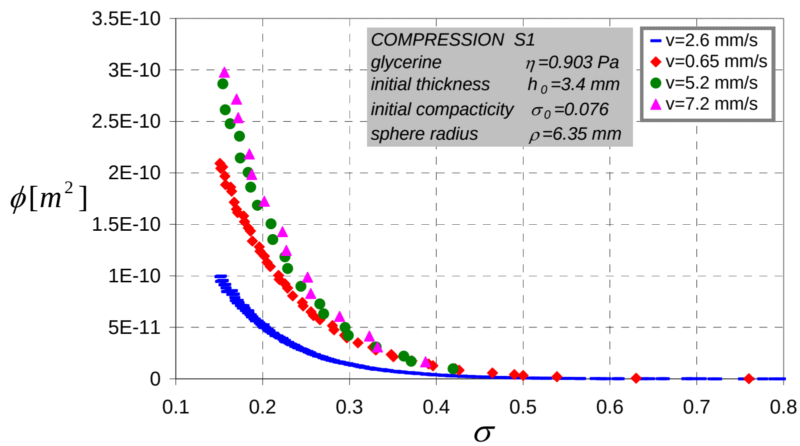



Fig. 7 The variation of permeability $\phi$ for compression of S1

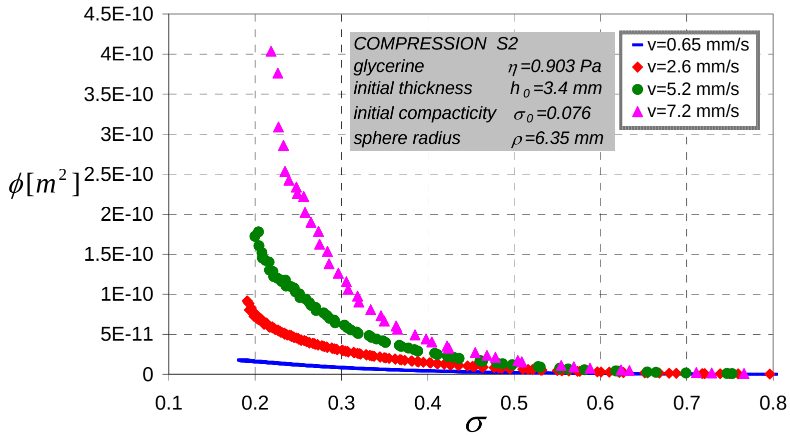



Fig. 8 The variation of permeability $\phi$ for compression of S2

It is important to be mentioned that when the thickness decreases the compacticity increases. Therefore, the variation of permeability is decreasing as the compacticity $\sigma$ increases or as the thickness $h$ decreases. One can also observe higher values of permeability for higher velocities, differences that is more emphasized for the squeeze of material S2. This observation can be explained by taking into consideration the dynamic conditions of the process. Thus, the permeability measured in static conditions is not quite appropriate in the analysis of processes developed in dynamic conditions. In this case permeability is not only a function of the HCPL fibre diameter, but also a function of velocity.

### 4.3 Validation of XPHD theoretical model

The experimental results play an important role in the validation of theoretical models already developed for XPHD squeeze process for sphere on HCPL contact [4].

For validation of the theoretical model two constant velocities were chosen: $V = 2.6$ and $7.2\, mm/s$. Figs. 9 and 10 present the variation of the contact force as a function of thickness for the squeeze process at constant velocity of materials S1 and S2. In the theoretical variation of the force the complex parameter $D$ was considered to be an average of the experimental values obtained according to Section 4.2. The average values of the complex parameter $D$ for all four velocities are presented in Table 2.

*Table 2*

**The complex parameter *D* for the tested HCPLs**

| | ***V* = 0.65 *mm/s*** | ***V* = 2.6 *mm/s*** | ***V* = 5.2 *mm/s*** | ***V* = 7.2 *mm/s*** |
|---|---|---|---|---|
| **S1** | $2.24 \cdot 10^{-12}$ | $5.74 \cdot 10^{-12}$ | $7.54 \cdot 10^{-12}$ | $9.28 \cdot 10^{-12}$ |
| **S2** | $2.86 \cdot 10^{-12}$ | $1.65 \cdot 10^{-11}$ | $2.23 \cdot 10^{-11}$ | $3.58 \cdot 10^{-11}$ |

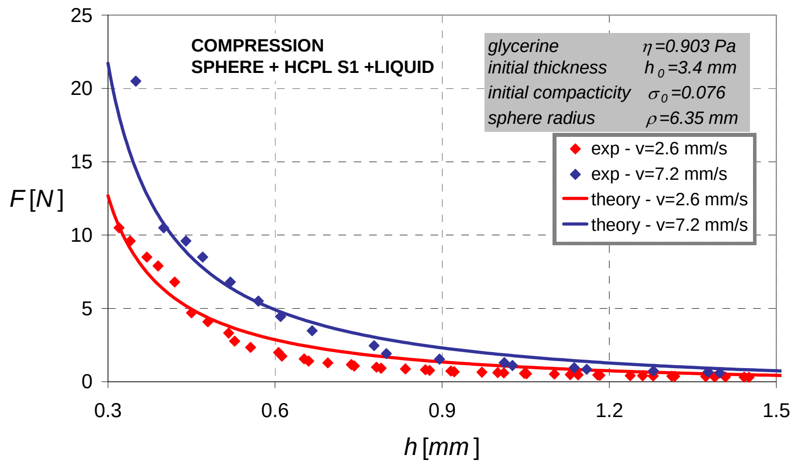



Fig. 9 Theoretical *vs.* experimental results of contact force for squeeze of S1

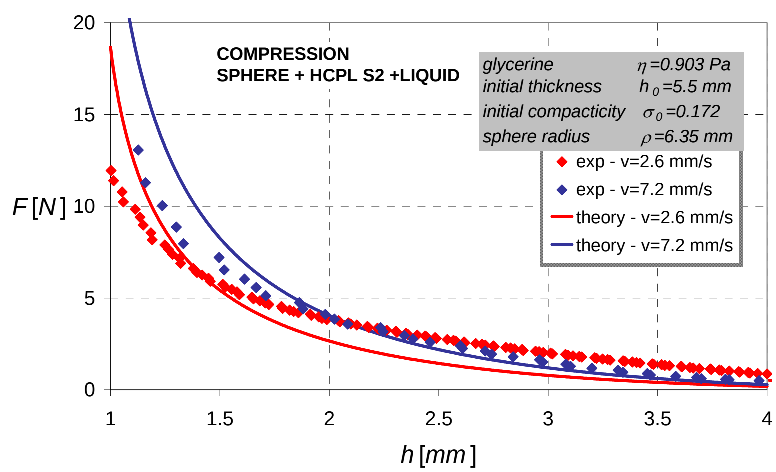



Fig. 10 Theoretical *vs.* experimental results of contact force for squeeze of S2

Even though in the theoretical variation of the force an average value of the complex parameter *D* was used the differences between the experimental and theoretical variations are not alarming. In both Figs. 9 and 10 one can remark a satisfactory correlation between the theoretical and experimental results for the generated force for the squeeze process.

## 5. Conclusions

The present experimental study analyses the behaviour of woven and unwoven highly compressible porous layers imbibed with glycerine squeezed at constant velocity by a rigid sphere. The experimental work considered also the decompression phase of the squeezed porous layers.

These tests provide important information about the generated load in XPHD regime and some important material characteristics like permeability variation, material parameter *D*, initial HCPL thickness. It was found that the permeability and, implicitly, the complex parameter *D*, is a function not only of the material fibre dimension, but also of velocity. This observation leads to the necessity of analysing the HCPL permeability considering dynamic conditions besides the HCPL structure in the case of dynamic processes.

The experimental results were used to verify the theoretical models already developed for XPHD squeeze at constant velocity for sphere on HCPL contact. A satisfactory correlation between the theoretical and experimental results was found.

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## Notations

$D$ – complex parameter of HCPL
$d_f$ – fibre diameter of HCPL
$F$ – force
$h$ – layer thickness
$H$ – dimensionless layer thickness, $h/h_0$
$k$ – correction constant in Kozeny-Carman law
$q$ – flow rate
$r$ – radial coordinate
$R$ – radius of an apparent/nominal area of a circle/disc
$t$ – time
$tr$ – relaxation time
$V$ – velocity
$z$ – carriage position

$\varepsilon$ – HCPL porosity
$\eta$ – liquid viscosity
$\rho$ – sphere radius
$\sigma$ – HCPL compacticity
$\phi$ – HCPL permeability according to Kozeny-Carman law, $D(1-\sigma)^3/\sigma^2$

**Subscripts**

0 – initial
exp – experimental values
$m$ – minimum, value corresponding to mid-plane

**Acronyms**

HCPL – highly compressible porous layer
XPHD – ex-poro-hydrodynamic

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