Dynamic permeability of highly compressible porous layers under squeeze at constant velocity and under impact

Cristian S. Popescu[1)]

[1)]Department of Machine Elements and Tribology, University POLITEHNICA of Bucharest, Spl. Independentei 313, Bucharest 060042, Romania
cpopescu@omtr.pub.ro

Abstract

The ability of a highly compressible porous layer (HCPL), imbibed with a Newtonian liquid, to dissipate energy is underlined in recent papers related to ex-poro-hydrodynamic (XPHD) lubrication. The total absorption of energy of a squeeze/impact is due to the hydrodynamic forces generated within the HCPL. Mostly all XPHD processes take place in dynamic conditions, therefore it is essential to know if the permeability determined at constant thickness is adequate for such processes. For this reason, squeeze at constant velocity and impact tests were performed on HCPLs completely saturated with Newtonian liquids, thus the variation of dynamic permeability was determined.

Keywords: hydrodynamic lubrication; porous medium; squeeze and impact loading; dynamic permeability

1. Introduction

Recent papers related to ex-poro-hydrodynamic (XPHD) lubrication [1-6] describe the theoretical aspects of the ability to dissipate energy of a highly compressible porous layer (HCPL) imbibed with a Newtonian liquid. The dislocation of a liquid from a saturated porous and deformable layer resulting in pressure building-up was called EX-PORO-HYDRODYNAMIC [2].

The most common case-study is that of a HCPL saturated with Newtonian liquid placed on a rigid support and a carried load provided by a rigid body moving either on a tangential direction or on the normal direction.

Analytical models developed in XPHD lubrication for a tangential motion include slider bearings, such as step slider [1,2 and 3], fixed inclined slider [3] and the motion of red cells in narrow capillaries [4]. The normal motion implies the squeeze of the liquid from the HCPL, hence the analytical models study two types of configurations (constant velocity/under impact), such as the squeeze of a HCPL between two discs [5], the impact of a rectangular plate [6] and the impact of a rigid sphere [7]. The term compacticity was introduced as the instantaneous solid fraction of HCPL and it is the complement of porosity [5]. For the configurations involving a squeeze motion, the hydrodynamic forces generated in the internal structure of the HCPL allow, within certain limits, the total absorption of the energy of an impact.

The validation of the theoretical models with experimental results is possible only if the material properties of the HCPL (such as the fibre diameter, the porosity/compacticity and the permeability) are known. The experimental work performed in the field of XPHD lubrication includes the use of a thrust bearing with three shrouded-step pads [1,2], the permeability measurement in longitudinal direction of HCPLs when the flow takes place at constant thickness [8], and the impact of a rigid sphere on a HCPL imbibed with water [7]. The Darcy permeability is considered as function of porosity/compacticity [9], given by Kozeny-Carman equation [9 and 10], widely accepted in the modelling of the flow through porous media. The local thickness of the HCPL is modified throughout a dynamic process, remarked by the change in the compacticity of the solid fraction, i.e. also in permeability. Unfortunately, these experiments do not provide accurate results in the case of a dynamic process such as squeeze at constant velocity/under impact of a HCPL saturated with Newtonian liquid.

Ongoing research in the field includes the study of random soft porous media that generate lift forces to self sustained carried loads, under a sliding motion [11-16], such as an airborne jet train [13 and 15]. Although the same principles are applied, the soft porous material is used in conjunction with air, at extremely high porosities. In these cases there is a significant component of the elastic force developed by the solid fraction, which becomes negligible when the porous layer is saturated with liquid [11] and only qualitative comparison can be performed with the present study.

Porous materials that can be included in the HCPL category are: woven and unwoven textile materials, such as felt or wash-cloth [1,7 and 8], the endothelial surface glycocalyx that uniformly coats the mammals' microvessels [4, 11, 12 and 14], the fresh powder snow [11 and 12] or the goose down [15 and 16]. HCPLs can be used in a multitude of possible applications working either at atmospheric pressure as open systems (porous coating, viscosity pump, safety flooring) or under pressure as closed systems (shock absorber, squeeze film damper, airborne jet train). Applications using the properties of HCPLs would be less expensive than the existing applications, such as colloidal or electro-rheological dampers.

Due to the fact that mostly all XPHD processes take place in dynamic conditions, it is essential to know if the permeability determined in stationary conditions [8] is adequate for such processes. For this reason, squeeze at constant velocity and impact tests were performed on HCPLs completely saturated with water or oil. Acquisitioned data provide force vs. thickness for the squeeze test and thickness vs. time for the impact test. Processing the data thus obtained, the variation of permeability in dynamic conditions was determined. The present paper proposes the first approach to determine the dynamic permeability of HCPLs completely saturated with Newtonian liquid.

2. Experimental studies performed in dynamic conditions on HCPLs saturated with Newtonian liquid

When a HCPL saturated with liquid is squeezed, the liquid flow is usually developed in longitudinal direction. The experimental study can be performed on axisymmetric configurations if the HCPL is isotropic on longitudinal direction. For a proper experimental analysis of a HCPL, four material properties have to be determined:

- fibre diameter $d\ [\mu m]$,
- initial compacticity σ_0 ($\sigma_0 = 1 - \varepsilon_0$ [5], where ε_0 is the initial porosity),
- initial thickness $h_0\ [mm]$,
- permeability $\phi\ [m^2]$.

When performing experimental studies, the pair HCPL - liquid to be used is chosen considering that besides the pores that are filled with liquid due to capillary effects, the fibres of the HCPL can absorb liquid too, thus making it more difficult to determine the permeability of the HCPL. Depending on the fibre's ability to absorb liquid, the initial thickness and initial compacticity of the HCPL are directly influenced by the liquid's viscosity. Some HCPLs are lyophobic, in this case the liquid cannot properly saturate the pores and the HCPL has a poor response when squeezed.

In order to determine the permeability of the HCPLs in dynamic conditions, two types of experiments were performed: squeeze at constant velocity between parallel discs and squeeze under impact with free falling balls. These configurations were chosen according to the XPHD theoretical models developed for the two cases [3 and 16]. The configuration of the parallel discs ensures an uniform thickness (constant thickness at a certain moment) and also provides an axisymmetric flow of liquid through the HCPL during the squeeze. In the case of impact the configuration of the spherical contact was chosen because the geometry is not influenced by the tangential positioning of the rigid bodies.

The HCPLs used in the experiments were unwoven textile materials made from fibres, the internal structure of these materials, named M1 and M2, is presented in Fig.1 [15].

Fig.1 Internal structure of HCPLs

The two materials were chosen after trying several HCPLs in combination with both water and oil, M1 being the material having the greatest fibre's ability to absorb liquid when water was used, M2 being the material having zero fibre absorption both for water and for oil. For the choice of the liquids to be used, in the case of M1 oil was excluded because its fibres did not absorb it, in the case of M2 both water and oil properly saturated the material, so the tests were performed using both combinations, but the behaviour of M2 was better observed when using oil, therefore one of the studies was performed on M1 saturated with water and the other one on M2 saturated with oil.

2.1. Squeeze at constant velocity of a HCPL saturated with Newtonian liquid

The experiment of squeeze at constant velocity was performed on the HCPL named M2, which has an estimated average fibre diameter of $12\ \mu m$ [8]. M2 has almost the same thickness when saturated with water as when saturated with oil because it has only synthetic fibres (which do not absorb the liquid) in its composition.

The liquid used is SAE20W50 oil, which has the viscosity $\eta_{26^\circ} = 0.301\ Pa \cdot s$. The squeeze at constant velocity experiment was performed on CETR UMT-2 (Center for Tribology Inc., Universal Nano+Micro+Macro Materials Tester). The squeeze configuration of disc+HCPL+liquid is presented in Fig.2. The rigid disc is parallel with the rigid support of the HCPL, thus ensuring an uniform thickness.

Fig.2 Experimental setup for the squeeze at constant velocity, configuration disc+HCPL+liquid

The HCPL was squeezed at four constant velocities $0.5; 1; 5; 10\ mm/s$. An initial start position was set for the carriage, such as to allow the reach of a constant velocity before the contact of the disc with the HCPL. The parameters recorded during the test were: the force on the vertical direction, the position of the carriage and the time. The test was interrupted when the force reached 200N, avoiding an overloading of the DFH-20 sensor. The position of the carriage was recorded with respect to the fixed rigid support, chosen as reference, allowing the measurement of the thickness of

HCPL during the squeeze. Two probes of the same HCPL were kept sunken in oil 24 hours before testing. The experiment was performed starting from smaller to greater velocities. The probes were immersed in oil after each test for approximately 30 minutes in order to allow the re-absorption of the liquid into the pores. Two tests were performed at each of the mentioned velocities, using each time a separate probe, and a good repeatability of the test was observed. The initial contact of the disc with the HCPL results in the recording of a force that is no longer null, thus allowing an accurate measurement of the initial thickness using the position of the carriage, i.e. $h_0 = 4\ mm$, giving an initial compacticity $\sigma_0 = 0.1$. Experimental results for squeeze at constant velocity performed on M2 saturated with SAE20W50 oil are presented in Fig.3.

Fig.3 Experimental results for squeeze at constant velocity, configuration disc+HCPL+liquid

From right to left, the chart presents the increase of the force with the decrease of the thickness. At a given value of the force it can be noticed that the thickness of the HCPL is greater for higher velocities. This is due to the hydrodynamic pressure generated by the liquid squeezed through the pores. As the velocity of the upper plate is greater, the channels created by the dislocated liquid are more quickly constricted, thus increasing the pressure of the liquid. When a critical value that allows the liquid to overcome the entrapment regions is reached, all the liquid is squeezed from the HCPL. Finally, as the volume of the pores becomes smaller and the compacticity reaches values closer to 1, the hydrodynamic forces have no longer an important role.

2.2. Squeeze under impact of a HCPL saturated with Newtonian liquid

The experiment of squeeze under impact was performed on the HCPL named M1, which has an estimated average fibre diameter of $18\ \mu m$ [8]. M1 was saturated with water, with the viscosity of $\eta_{20^\circ} = 0.001\ Pa \cdot s$. This material has cellulose and cotton in its composition and allows the absorption of water both inside the pores and into the fibres, thus making the permeability measurement more difficult. In Fig.4 is presented the response of M1 when saturated with water. It is easily noticed that the increase in thickness of M1 when saturated with water is of 3-4 times than the thickness in a dry state.

Fig.4 Thickness response of HCPL M1 when saturated with water

The experiment performed is that of a sphere free falling on M1 saturated with water, placed on a fixed rigid support. During an impact, although the thickness is not uniform, the geometry is not influenced by the tangential positioning of the rigid bodies. The experimental setup is presented in Fig.5 [7].

Fig.5 Experimental setup for the impact, free falling test

The impact was recorded with a high speed camera at 6000 frames per second and the position of the ball was determined from the image post-processing, allowing for the minimum thickness h_m to be determined with respect to the rigid support. The impact test was performed with an elastomeric ball that has a much higher elastic modulus than the HCPL saturated with water, therefore considered rigid with respect to M1. The ball with the mass $M = 13.535\ g$ and the radius $\rho = 15.25\ mm$ was free launched from two different heights $\hat{H} = 122\ mm$ and $\hat{H} = 282\ mm$. For M1 saturated with water the initial thickness measured was $h_0 = 3.5\ mm$ at an initial compacticity of $\sigma_0 = 0.038$. The parameters recorded during the test were the position of the ball and the time. The thickness of M1 during the impact was determined using the position of the ball with respect to the position of the rigid support. Several tests were performed for each height and a good repeatability was observed. The experimental results show the position of the ball free falling from $\hat{H} = 122\ mm$ and $\hat{H} = 282\ mm$, also the thickness variation during the impact with M1 saturated with water, Fig.6. For $\hat{H} = 122\ mm$ the impact of the sphere free falling directly on the rigid support (without HCPL) was included, but solely to better show the effect of using the HCPL saturated with water.

Fig.6 Experimental results showing the position of the ball and an enlarged view of the thickness variation during the impact, configuration sphere+M1+water

In both cases, all of the kinetic energy of the ball is absorbed by the HCPL saturated with water. It can be noticed that an increase in the initial kinetic energy determines a smaller final thickness h_{mf}. Therefore, over a certain launching height the HCPL is no longer able to absorb all the energy and the ball rebounds with a rest of the initial energy.

The experimental configuration, the HCPL and the liquid used are summarized in Table.1.

3. Dynamic permeability

One of the hypotheses used in the theoretical models in XPHD lubrication states that the impact in squeeze conditions can be described using the component properties measured in static conditions [6]. The objective of the current paper is to verify the validity of this hypothesis by dynamic experiments, introducing the dynamic permeability of a HCPL.

Permeability for a steady flow is related to the constant thickness of a HCPL, therefore permeability variation in static conditions can be approximated by functions such as Kozeny-Carman [9 and 10] or Pseudo-Kozeny-Carman [8], with respect to a certain compacticity/thickness and a constant complex parameter D:

Kozeny-Carman (K-C) $\phi = \frac{D(1-\sigma)^3}{\sigma^2}$ (1)

Pseudo-Kozeny-Carman (P-K-C) $\phi = \frac{D(1-\sigma)^2}{\sigma}$ (2)

where the compacticity at a certain thickness is derived from the assumption that the solid fraction of the HCPL is invariable during the squeeze process: $\sigma = \sigma_0 h_0 / h$ [2].

Squeeze at constant velocity and under impact of a HCPL involve a continuous change of the hydrodynamic forces that determine a variation in the average velocity of the liquid, altogether with the thickness variation of the HCPL, therefore the complex parameter determined for a constant thickness in a steady flow, becomes no longer valid for an unsteady flow. Considering both the variation of the thickness and the variation of the complex parameter D, one obtains the dynamic permeability for a HCPL. In Fig.7 is represented the type of the permeability in function of the varying parameters. In a steady flow the static permeability is only influenced by a possible variation of thickness. In an unsteady flow the thickness is changed at each time step. The permeability is considered cvasi-static if the complex parameter D is constant. If the complex parameter D is variable then the permeability is considered dynamic.

Fig.7 Diagram showing the types of flow and the types of permeability in function of the varying parameters

When all the experimental data is used, respectively velocity and thickness for impact and force and thickness for constant velocity, a variation of the complex parameter is obtained. Studying the behaviour of the complex parameter during the squeeze process, a parabolic variation with respect to thickness was observed, therefore the Least Squares Parabola Method was used to determine the coefficients of an averaged function that approximates the experimental data.

The unknown coefficients of a parabolic function y(x)=a+bx+cx^2 that best fit the set of experimental data (x_i,y_i), where i=1÷n and n is the number of experimental points, are obtained from the following system of equations:

$$\begin{cases} \sum_{i=1}^{n} y_i = a\sum_{i=1}^{n} 1 + b\sum_{i=1}^{n} x_i + c\sum_{i=1}^{n} x_i^2 \\ \sum_{i=1}^{n} x_i\, y_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i^3 \\ \sum_{i=1}^{n} x_i^2\, y_i = a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^4 \end{cases}$$

3.1. Dynamic permeability in case of squeeze at constant velocity of a HCPL saturated with Newtonian liquid

The permeability for a squeeze at constant velocity of the configuration disc+HCPL+liquid [5] is:

$\phi = \frac{\pi \eta R^4 V (1-\sigma)}{8 F h}$ (3)

Using the previous equations one obtains the complex parameters of the HCPL squeezed at constant velocity, with respect to force as function of thickness:

$D_{K-C} = \frac{\pi \eta R^4 V}{8F} \cdot \frac{\sigma_0^2 h_0^2}{h(h-\sigma_0 h_0)^2}$ (4)

$D_{P-K-C} = \frac{\pi \eta R^4 V}{8F} \cdot \frac{\sigma_0 h_0}{h(h-\sigma_0 h_0)}$ (5)

The first step was to obtain values for the complex parameters at a certain thickness and an experimentally determined force. Therefore, from the squeeze test at $v = 5\ mm/s$ and the configuration disc+M2+oil, at the thickness $h = 2\ mm$ and the force $F = 25.5\ N$ the constant complex parameters are obtained: $D_{K-C} = 4.83 \cdot 10^{-11}\ m^2$ and $D_{P-K-C} = 1.93 \cdot 10^{-10}\ m^2$.

Therefore, considering only K-C (4), an average function was approximated to best fit the experimental points:

$D_{K-C}^{approx} = \frac{d^2}{16k}(2.21 - 8.68H + 10.251H^2)$ (6)

where d is the average fibre diameter of M2 and $k = 0.18 \ldots 0.2$ is the determined material constant.

Fig.8 shows a comparison between the averaged approximated function and the experimental complex parameter as function of thickness, obtained with (4), at constant squeeze velocities of $v = 0.5;\, 1;\, 5;\, 10\ mm/s$, for the configuration disc+M2+oil. One can notice an increase of the parabolic behaviour with squeeze velocity and a minimum of the complex parameter in all the variations.

Fig.8 Approximated function of the variable complex parameter for squeeze at constant velocity vs. experimentally determined complex parameters for $v = 0.5;\, 1;\, 5;\, 10\ mm/s$

The second step was to compare the force variation as function of thickness determined from the experiment and the one obtained using a parabolic variation of the complex parameter, for the discussed configuration, Fig.9. One can notice the response of the HCPL by following a given value of the force that is reached at a greater thickness as the velocity is increased, such that a velocity ten times higher will double the thickness of the HCPL. Considering that only one approximated function is used for all the variations, a very good agreement with the experimental results is observed, especially at higher velocities.

Fig.9 Force variations determined experimentally vs. the theoretical ones obtained with a variable complex parameter, for squeeze at constant velocity

Furthermore, a comparison at $v = 10\ mm/s$ of the force variations, the ones determined from the experiment and the theoretical ones, obtained with constant ($D_{K-C} = 4.83 \cdot 10^{-11}\ m^2$) and variable (4) complex parameters, is presented in Fig.10. The difference between the constant and the variable complex parameters is better underlined at small compacticities, the force computed with a constant parameter being 4-5 times higher than the one experimentally obtained. A very good correspondence is observed between the force computed with a variable complex parameter and the experimental data.

Fig.10 Force variation determined experimentally vs. the theoretical ones obtained with constant and variable complex parameter, for squeeze at $v = 10\ mm/s$

The variation of the dynamic permeability for squeeze vs. the experimentally obtained one and the variation of the permeability with a constant complex parameter, at $v = 10\ mm/s$, are plotted in Fig.11. A very good correspondence between the dynamic permeability variation (variable complex parameter) and the experimental data is observed. One can notice a great difference between the cvasi-static permeability (constant complex parameter) and the dynamic permeability, such that at a compacticity of 0.13 the cvasi-static permeability is about four times smaller than the dynamic and experimental ones.

Fig.11 Permeability variation determined experimentally vs. the theoretical ones obtained with constant and variable complex parameter, for squeeze at constant velocity

3.2. Dynamic permeability in case of squeeze under impact of a HCPL saturated with Newtonian liquid

The theoretical model of the impact of a rigid sphere on a HCPL imbibed with a Newtonian liquid provides the maximal value of the complex parameter [7]:

$$D_{K-C}^{\max} = \frac{3\pi}{4}\frac{\rho^2}{M\sqrt{\hat{H}}}\frac{\eta h_0^2}{\sqrt{2g}}\frac{\sigma_0^2}{(1-\sigma_0)^2}(2\sigma_0 - 0.5\sigma_0^2 - 1.5 - \ln\sigma_0) \quad (7)$$

The complex parameter of the HCPL can be computed with respect to the velocity of the sphere and the minimum thickness of the HCPL:

$$D_{K-C} = \frac{\pi}{8}\frac{\mathrm{h}_0^2}{V - V_0}\frac{\eta\rho^2}{M} f(\sigma_0, H_m) \quad (8)$$

In the case of the impact of a rigid sphere on M1 saturated with water the Least Squares Parabola Method was applied to approximate an average function of the complex parameter only for K-C (8). The experimental data provides the velocity of the sphere up to the point when it becomes zero due to energy dissipation and also at the beginning of the "rebound" of the sphere, therefore allowing the study of the two stages of the impact: compression and decompression of the HCPL. The approximated functions of the complex parameter for the two stages are:

$$\begin{aligned} D_{compr}^{approx} &= \frac{d^2}{16k}(0.145 - 0.343H + 0.282H^2) \\ D_{decompr}^{approx} &= \frac{d^2}{16k}(0.077 - 0.315H + 0.355H^2) \end{aligned} \quad (13)$$

where d is the average fibre diameter of M1 and $k = 5$ is the determined material constant.

The comparison of the complex parameter variations obtained from the experiment and from the parabolic approximation (13) is shown in Fig.12. A very good agreement with the experimental results is observed from the beginning of the impact until the thickness decreases around 0.4 mm.

Fig.12 Approximated functions of the variable complex parameters for compression and decompression stages of the impact vs. experimentally determined ones

Prior to the analysis of the permeability variation, a study of the velocity during the impact was performed, allowing the comparison of the adimensional velocities determined from the experiment with the theoretical ones computed with the constant complex parameter obtained from the maximum dimensionless impulse (7) ($D = 7.674 \cdot 10^{-13}\ m^2$) [7], the average constant complex parameter obtained from the steady flow experiment ($D = 2.42 \cdot 10^{-12}\ m^2$) [8] and the variable complex parameter from (13), Fig.13. One can observe a very good agreement between the velocity variation computed with the variable complex parameter (13) and the experimental velocity, also the velocity given by the maximum allowable impulse is giving acceptable results. The variation of velocity computed with the constant complex parameter determined from a steady flow experiment does not provide a good behaviour over a dynamic process, thus raising some questions about the validity of the hypothesis that the static permeability determined from a steady flow experiment can be used for a dynamic process.

Fig.13 Comparison of the dimensionless velocity in the compression stage of the impact obtained with complex parameter determined from: steady flow, maximum impulse and dynamic method

The variation of the permeability obtained from the experiment is plotted vs. the computed dynamic permeability for impact in Fig.14. One can observe a very good correspondence between the computed dynamic permeability and the experimental one for both of the stages studied: compression and decompression.

Fig.14 Permeability variation determined experimentally vs. the theoretical one obtained with dynamic method, for the two stages of the impact

Nevertheless, a complete view over the variation of the permeability is given by the comparison between the dynamic permeability and the static one computed with the constant complex parameter given by the maximum allowable impulse. An enlarged view of this comparison, that also contains the permeability determined from the experiment, is presented in Fig.15. The previous agreement between experimental results and dynamic permeability is confirmed in this enlarged view. The difference between the static permeability offered by the maximum impulse and the dynamic one reaches acceptable values near the end of the impact when the compacticity is greater than 0.6.

Fig.15 Permeability variation determined experimentally vs. the one obtained with the constant variable complex parameter given by maximum impulse and the variable one given by the dynamic permeability method

4. Discussion

One of the hypotheses of the theoretical models for a HCPL squeezed under impact that is saturated with Newtonian liquid and placed on a rigid support, recently introduced, states that the squeeze under impact can be described using the component properties measured in static conditions [6]. The objective of the current paper is to verify the validity of this hypothesis by dynamic experiments, introducing a method to determine the dynamic permeability variation of a HCPL.

If the permeability variation in a steady flow is computed by a function such as K-C or similar, extending it for a dynamic regime should allow the variation of dynamic parameters by keeping the same form, thus the analysis of a dynamic regime should begin with the evaluation of the complex parameter D. An increase of the parabolic behaviour with squeeze velocity is noticed. This has a direct influence on the force sustained by the HCPL, respectively, a velocity ten times higher will double the thickness of the HCPL. Furthermore, the difference between the constant and the variable complex parameters is better underlined at small compacticities, the force computed with a constant parameter is 4-5 times higher than the one experimentally obtained. From the comparison of the permeability variation from the squeeze at constant velocity of the HCPL saturated with Newtonian liquid, a very good correspondence between the dynamic permeability and the permeability obtained from the experiment, throughout the process, is noticed.

The same method was applied for the impact case study, adding the decompression stage. Although the comparison between the velocity determined from the experiment and the one obtained from the theoretical models shows promising results, the validation of these models should be performed with respect to permeability variation. Also, a great difference between the experimentally determined velocity and the one resulting from the use of average constant complex parameter determined from a steady flow is noticed. A very good agreement between the experimental permeability and the dynamically obtained one is remarked. A comparison of the dynamic permeability vs. the permeability determined from the experiment and the permeability obtained with a maximal value of the complex parameter is presented. The compression stage of the impact takes place in the compacticity range of $0.038 \div 0.77$ and the permeability variation obtained with a constant complex parameter has acceptable errors near the end of the impact, when the compacticity reaches values over 0.6. Although the XPHD lubrication is restricted to a relative interval of compacticity, roughly between $0.2 \div 0.8$, the present method allows the extension of these limits.

A qualitative comparison of the results from the present paper can be done with the results obtained by Al-Chidiac et al. [16]. Although the same principles are applied in both cases, the soft porous material saturated with air at extremely high porosities allows a significant component of the elastic force to be developed, but when liquid is used to saturate a porous layer subjected to a dynamic loading the hydrodynamic forces are predominant. Nevertheless, the results obtained from the cvasi-static compaction of the soft porous material show the same behaviour of the force as the results obtained from the dynamic experiment performed for the squeeze at constant velocity of a HCPL saturated with oil. Also, a comparison can be made in the case of the impact of a porous material. The same kind of variation is observed in case of the thickness variation of the soft porous material when impacted by a rigid disc and the minimal thickness variation when a highly porous layer saturated with water is squeezed under impact by a sphere.

5. Conclusions

One of the hypotheses used in the theoretical models in XPHD lubrication states that the impact in squeeze conditions can be described using the component properties measured in static conditions [6]. The objective of the current paper is to verify the validity of this hypothesis by two dynamic experiments that were performed on highly compressible porous layers saturated with Newtonian liquids: squeeze at constant velocity and under impact..

In order to compute the permeability variation, another parameter has to be determined, such as force (constant velocity) or velocity (impact). Although the comparison between these parameters determined from the experiment and the ones obtained from the theoretical models shows promising results, the validation of these models should be performed also with respect to permeability variation.

For a clear view of the types of permeability used in this paper, a classification is introduced, function of the type of flow, thickness and other parameters. The difference between the static permeability (determined for a steady flow), the cvasi-static permeability (determined for a critical/maximal value) and the dynamic permeability (determined for an unsteady flow) is underlined.

It is shown that the static permeability of a HCPL, determined from an experiment at constant thickness, is hardly acceptable as valid for an unsteady flow (variable thickness), therefore when analyzing a dynamic process, such as squeeze under impact, the permeability of a HCPL should be considered throughout the entire process, thus a dynamic permeability method was stated for highly compressible porous layers under squeeze at constant velocity and under impact.

6. Acknowledgments

Financial support for the work described in this paper was provided by National University Research Council (CNCSIS) under Grant IDEI 912.

I would like to express my gratitude to Professor Mircea Pascovici for teachings and advices regarding XPHD lubrication.

Thanks to Professors Valéry Valle and Patrick Lacouture, from University of Poitiers-LMS, who offered invaluable technical support for the impact test. Also thanks to Professors Corneliu Bălan, Traian Cicone and Associated Professor Adrian Predescu, from University Politehnica of Bucharest, for providing the necessary equipment for the squeeze at constant velocity test.

7. Nomenclature

d – fibre diameter of HCPL
D – complex parameter of HCPL, $D = d^2/16k$
F – force
h – HCPL thickness in the contact area
H – dimensionless layer thickness, h/h_0
$\hat{H}$ – launch height in free falling ball test
k – correction constant
M – mass of impact
$\overline{M}$ – dimensionless impulse
p – pressure
Po –dimensionless property of HCPL, $\mathrm{Po} = \mathrm{h}_0^2/D$
q – flow rate
r – radial coordinate
R – maximal radius of the apparent area of contact between sphere and HCPL
t – time
u_m – mean velocity trough HCPL
v – constant velocity in squeeze experiment

V – velocity
$\overline{V}$ – dimensionless impact velocity, V/V_0
Greek letters
η – liquid viscosity
ρ – sphere radius
σ – HCPL compacticity
ϕ – HCPL permeability
Subscripts/ Superscripts/ Abbreviations/ Acronyms
0 – initial
$approx$ – approximated
$calc$ – calculated
$compr$ – compression
ct – constant
$decompr$ – compression
$\exp$ – experimental
m – minimal
max – maximum/maximal
var – variable
$HCPL$ – highly compressible porous layer
$K-C$ – Kozeny-Carman
$P-K-C$ – Pseudo-Kozeny-Carman
$XPHD$ – ex-poro-hydrodynamic lubrication

8. APPENDIX

Liquid flow rate through a porous media, considering low permeability, can be modeled by Darcy's law [9]:

$$q_p = -\frac{\phi h}{\eta}\nabla p \quad \text{(A1)}$$

where the flow rate is $q_p = u_m h$ and u_m is the average velocity through porous media.

General assumptions considered in XPHD lubrication [2] are:

- the elastic forces of a HCPL are negligible compared to the liquid flow resistance;
- the liquid is Newtonian and the flow is considered in longitudinal direction, isothermal and isoviscous;
- HCPL is homogeneous and isotropic, with constant pressure across thickness;
- local deformation is considered only in normal direction and the solid fraction is conserved, $\sigma h = \sigma_0 h_0$.

The equation of flow rate conservation for a HCPL, saturated with Newtonian liquid, squeezed at normal velocity in polar coordinates [5], is:

$$-2\pi r\frac{\phi h}{\eta}\frac{\partial \mathrm{p}}{\partial \mathrm{r}} = \pi r^2(1-\sigma)V \quad \text{(A2)}$$

The permeability variation is computed using the following relations:

Kozeny-Carman(K-C) [9 and 10] $\phi = \dfrac{D(1-\sigma)^3}{\sigma^2}$ (A3)

Pseudo-Kozeny-Carman(P-K-C) [8] $\phi = \dfrac{D(1-\sigma)^2}{\sigma}$ (A4)

First theoretical model studied is the squeeze of a HCPL saturated with Newtonian liquid at constant velocity, which is presented in Fig.16a [5].

Fig.16 Boundary conditions for (a) squeeze at constant velocity and (b) squeeze under impact

After obtaining the force by applying the boundary conditions and pressure integration [5], the permeability is:

$$\phi = \frac{\pi\eta R^4 V(1-\sigma)}{8Fh} \quad \text{(A5)}$$

Furthermore, using (A3) and (A4), the complex parameters of the HCPL, with respect to force as function of thickness, are:

$$D_{K-C} = \frac{\pi\eta R^4 V}{8F}\cdot\frac{\sigma_0^2 h_0^2}{h(h-\sigma_0 h_0)^2} \quad \text{(A6)}$$

$$D_{P-K-C} = \frac{\pi\eta R^4 V}{8F}\cdot\frac{\sigma_0 h_0}{h(h-\sigma_0 h_0)} \quad \text{(A7)}$$

The second model analyzed is the impact of a rigid sphere on a HCPL placed on a rigid support, saturated with Newtonian liquid, presented in Fig.16b [3 and 7].

The maximum allowable impulse can be determined for a sphere that has an initial velocity $V_0 = \sqrt{2g\hat{H}}$ [7]:

$$\overline{M}_{max} = \frac{M\sqrt{\hat{H}}}{\rho^2}\frac{\sqrt{2g}}{\eta} \quad \text{(A8)}$$

Momentum conservation under impact, proposed by Bowden and Tabor [17], gives the adimensional velocity [7]:

$$\overline{V} = 1 + \frac{\pi}{8}\frac{\text{Po}}{\overline{\overline{M}}} f(\sigma_0, H_m) \quad \text{(A9)}$$

where $f(\sigma_0, H_m) = \frac{\sigma_0^2}{(1-\sigma_0)^2}\left\{\frac{2(H_m-\sigma_0)(1-\sigma_0)^2}{H_m}\ln\left[\frac{1-\sigma_0}{H_m-\sigma_0}\right] + 6\ln H_m + \right.$

$$\left. + (1-H_m)\left[\frac{\sigma_0(3-2\sigma_0)}{H_m} + \sigma_0 + 6 - 2H_m\right]\right\}$$

and the maximal value of the complex parameter [7]:

$$D_{K-C}^{max} = \frac{3\pi}{4}\frac{\rho^2}{M\sqrt{\hat{H}}}\frac{\eta h_0^2}{\sqrt{2g}}\frac{\sigma_0^2}{(1-\sigma_0)^2}(2\sigma_0 - 0.5\sigma_0^2 - 1.5 - \ln\sigma_0) \quad \text{(A10)}$$

The complex parameter of the HCPL can also be computed with respect to thickness and velocity during an impact:

$$D_{K-C} = \frac{\pi}{8}\frac{\text{h}_0^2}{V - V_0}\frac{\eta\rho^2}{M} f(\sigma_0, H_m) \quad \text{(A11)}$$

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