THE SQUEEZE OF AN IMBIBED SOFT POROUS MEDIA IN CONTACT WITH A PLASTIC BODY AT IMPACT LOADING. A HEURISTIC MODEL

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Many published studies on the behaviour of imbibed porous materials reveal a good potential in shock absorption. This phenomenom studied until now only in contact with rigid surfaces is based on a complex process that involves the squeeze of fluid from the porous layer at different levels of permeability. This innovative process which is strongly dependent on porosity variation, was studied under the name of ex-poro-hydrodynamic lubrication, and it describes the lift effects produced when highly compressible porous layers imbibed with liquids are squeezed.

The present work proposes a model for the squeeze process of a highly compressible porous layer imbibed with liquid interposed between a rigid sphere and a plastic body.

Analytical solutions are analyzed for two loading conditions: constant velocity and impact loading. For the first time it was used the "equivalent radius" concept. These results can be useful for the shock absorption systems.

Keywords: squeeze, porous structure, XPHD lubrication, spherical contact, "equivalent radius", plastic body

1. Introduction

Hydrodynamic squeeze process (HD) for different configurations has been continuously studied since 1950's and now is the subject of the Tribology textbooks [1].

Also, the squeeze process under elasto–hydrodynamic (EHD) conditions, in the case of impact loading was analyzed since 1970's. The papers [2-4] contain theoretical and experimental aspects of the EHD impact process.

During recent years a new lubrication mechanism has been developed. This new type of lubrication known as ex–poro–hydrodynamic (XPHD) lubrication [5] was studied theoretically and experimentally under impact squeeze conditions. The process takes place between a rigid impacting body (cylindrical or spherical) and a rigid surface covered with a highly compressible porous layer (HCPL) imbibed with liquid [6-11]. The XPHD lubrication process was especially

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studied at University Politehnica of Bucharest (UPB), but also at M.I.T. [12] and City University of New York [13].

The problem studied in this paper is when the rigid sphere impacting a plastic body (ballistic gelatin or plasticine) covered with a HCPL imbibed with liquid (Fig.1).

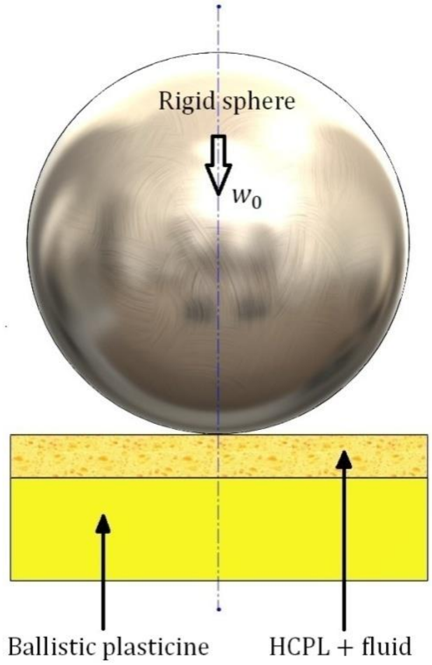


Fig.1 Definitions for the impacting ball problem (XPHD regime)

Same configuration is used for live shooting in order to evaluate a ballistic protection system such as bullet-resistant vest that protects a human body. The protective effect of the HCPL presence has been experimentally investigated in several studies. Fig.2a and Fig.2b show the results of some impact tests made by Popescu [6] using a steel ball of radius $R = 20\ mm$ with a mass $m = 264\ g$ by free fall from a height $H = 1\ m$ ($w_0 = 4.4\ m/s$) onto a plastic surface (modeling plasticine) covered with an unwoven textile material (Vileda) imbibed with water and protected by a thin layer of polyethylene. The presence of HCPL imbibed with water reduces the impact force, and thus the penetration depth.

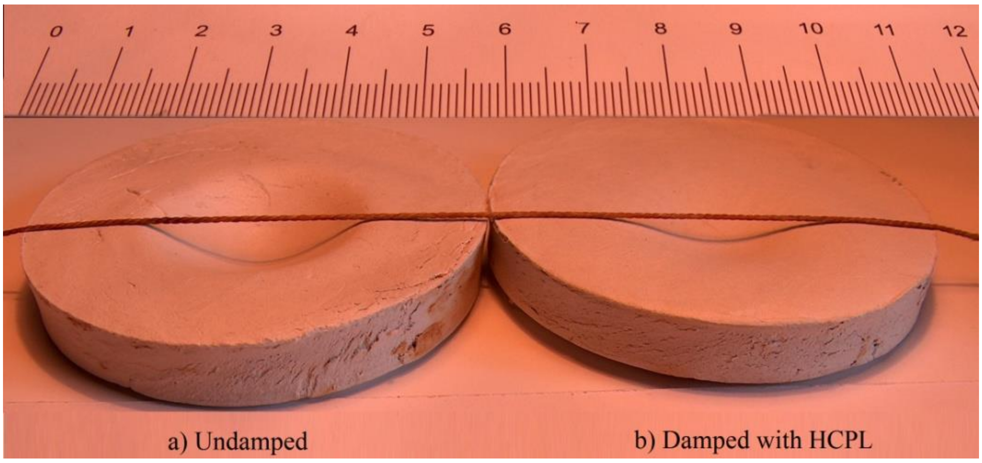


Fig.2a The evaluation of damping capacity using footprint left by the sphere [6]

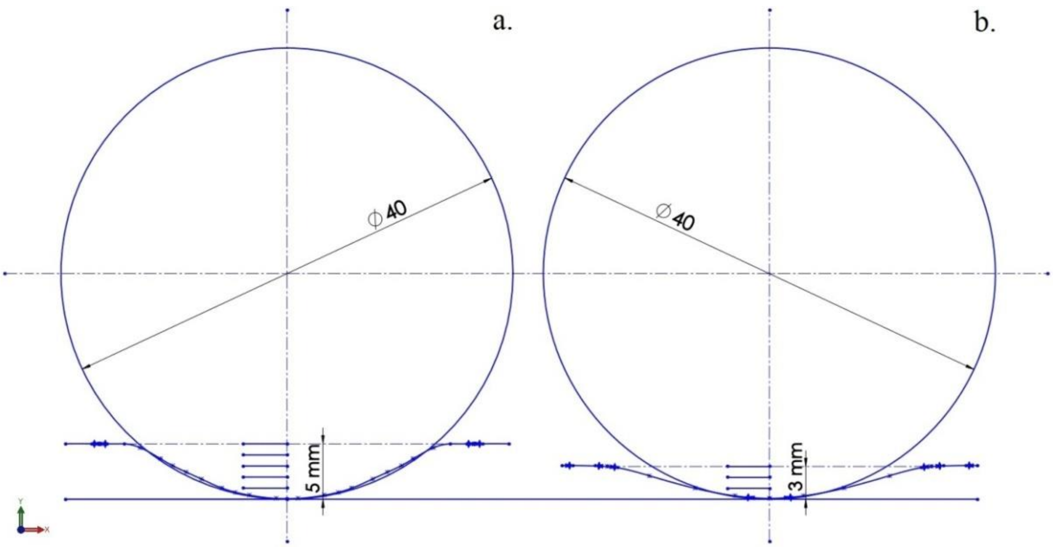


Fig.2b The penetration depth in the plasticine for unimpregnated (a) and impregnated HCPL (b) [6]

The same behaviour happens at ballistic velocities in a similar context. In paper [14] are presented the results of ballistic tests performed using a smooth bore helium gas gun (Taylor impact test rig), based on a projectile impact velocity of $w_0 = 244\ m/s$ and a projectile diameter of 5.6 mm. The test results for the ballistic performance of 4 layers of Kevlar and 4 layers of Kevlar impregnated with a colloidal shear thickening fluid (STF) are presented in Fig.3.

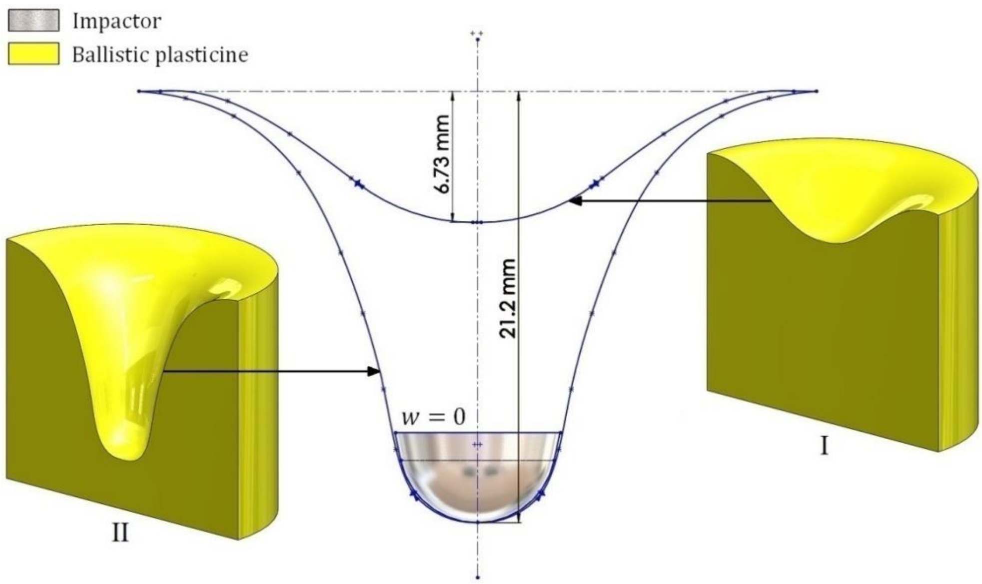


Fig.3 The profile of penetration depth in the ballistic clay witness for the samples with 4 layers of Kevlar impregnated with 8 ml of shear thickening fluid and separated by aluminum foils (50 μm thickness) – (I), respectively 4-layer dry Kevlar samples – (II) [14]

The main conclusion that can be drawn from the experiments presented by Lee [14] is that the impregnated Kevlar fabric with shear thickening fluid (STF) decreases drastically the value of the maximum (peak) force.

In technical literature the majority of theoretical studies consider that the porous material is compressed on a hard backing material. Very few studies can be found for deformable backing materials. This paper proposes a heuristic model to describe the behaviour of a damping structure based on an imbibed porous layer in contact with a support plastic body.

According Kozeny–Carman law for porosity–permeability correlation [15-16] and using *"equivalent radius"* concept, it is possible to find closed form solutions for squeeze at constant speed and squeeze with impacting load of a soft porous media imbibed with liquid in contact with a plastic body.

2. The heuristic model

To present the heuristic model, Fig. 4 shows the comparative analysis of the impact process between a rigid ball of radius, ρ_i and a porous material of thickness, h_0 and porosity, ε_0 imbibed with a Newtonian fluid of viscosity, η, placed either on a rigid body (Fig.4a) or on a plastic body (Fig.4b).

The impact process in the case of placing HCPL on a rigid surface has been previously studied, modelled and validated by convincing experimental impact tests [6-7].

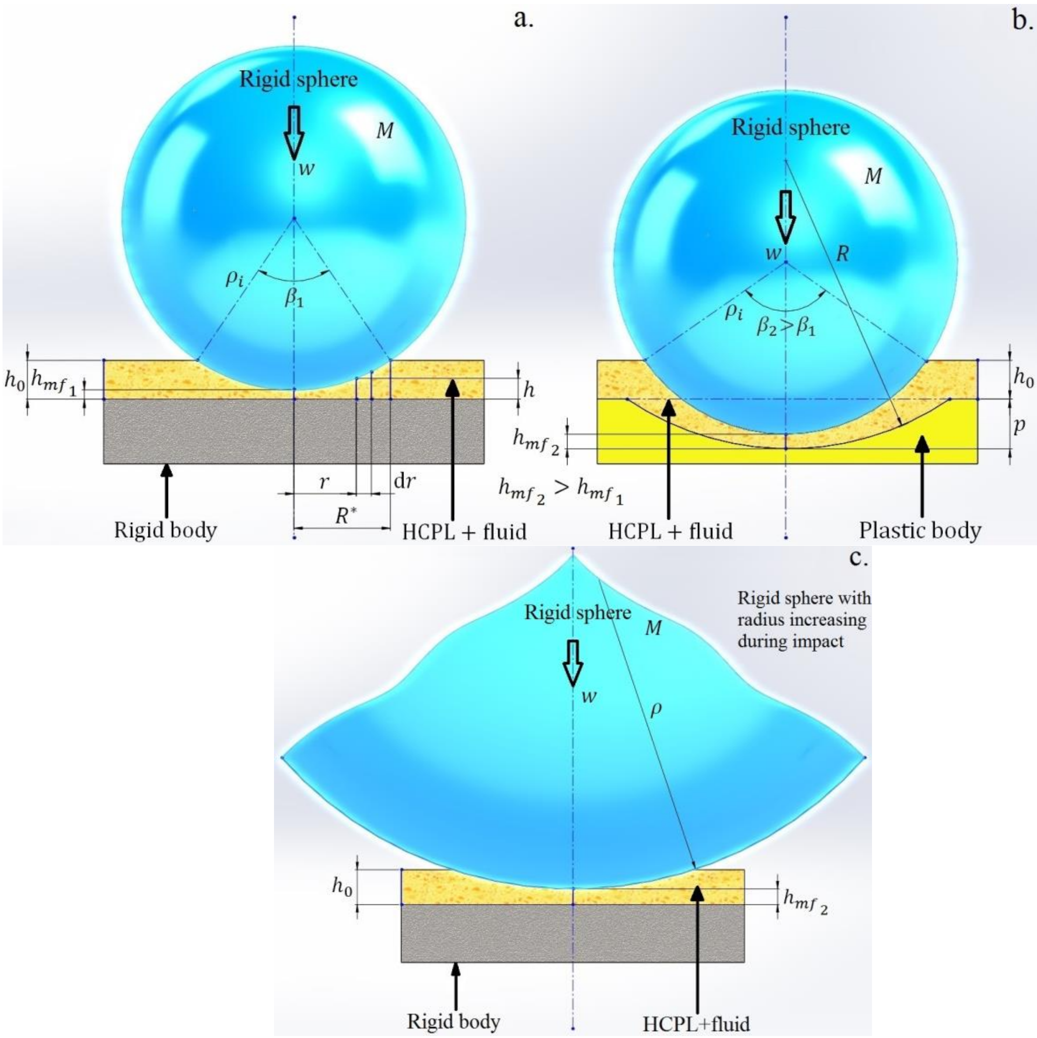


Fig.4 The sphere–on–rigid plane configuration (a) vs. the sphere–on–deformable plane configuration (b) simulated by the equivalent sphere method (c)

In the second case when the porous material is placed in contact with a plastic body (Fig.4b), the impact process is more complex due to the simultaneous deformation of both the porous layer and the plastic body. In this case, the new geometric parameters of the footprint in the plastic body are contact radius, R, and penetration depth, p. From the experimental tests performed in the Department of Machine Elements and Tribology in University POLITEHNICA of Bucharest and other places [14] can be found that final HCPL thickness, h_{mf} is higher than in the rigid case ($h_{mf\,2} > h_{mf\,1}$).

The modelling of the simultaneous deformation process of the porous material and the plastic body was not performed. In the proposed heuristic model the plastic body is replaced by a rigid one, and the real impacting ball of mass, M with constant radius, ρ_i is equivalent to an imaginary sphere (also rigid) of mass, M and with variable radius, ρ which is increasing during impact (Fig.4c). This substitution leads to the same effects of reducing the impact force and increasing the final HCPL thickness, h_{mf} .

For the quantitative analysis using this heuristic model, a relationship between the equivalent radius, ρ, and the minimum thickness of HCPL, h_m was proposed as:

$$\rho = \rho_i + \alpha \frac{h_0 - h_m}{h_m} \quad (1)$$

where ρ_i – the impacting sphere radius, α – the complex parameter of the equivalent radius and h_0 – the initial thickness of the porous layer.

In dimensionless form, the virtual variable radius, $\bar{\rho}$ can be written under this form:

$$\bar{\rho} = 1 + \bar{\alpha} \frac{1 - H_m}{H_m} \quad (2)$$

where $\bar{\rho}$ – the dimensionless equivalent radius ($\bar{\rho} = \rho/\rho_i$), $\bar{\alpha}$ – the dimensionless complex parameter ($\bar{\alpha} = \alpha/\rho_i$) and H_m – the dimensionless minimum thickness of the porous layer, $H_m = h_m / h_0$.

This equation along with those related to XPHD modelling will lead to the analytical heuristic model proposed in this article.

The value of the dimensionless complex parameter, $\bar{\alpha}$ depends both on the structure of HCPL and the fluid involved, as well as the plastic body characteristics. The minimum value of the complex parameter ($\bar{\alpha} = 0$) corresponds to the rigid surface case.

Fig. 5 presents the variation of the dimensionless equivalent radius in function of the dimensionless minimum HCPL thickness, H_m for different values of complex parameter, $\bar{\alpha}$. As shown in the graph, equivalent radius increases with increasing complex parameter, $\bar{\alpha}$ for a given H_m.

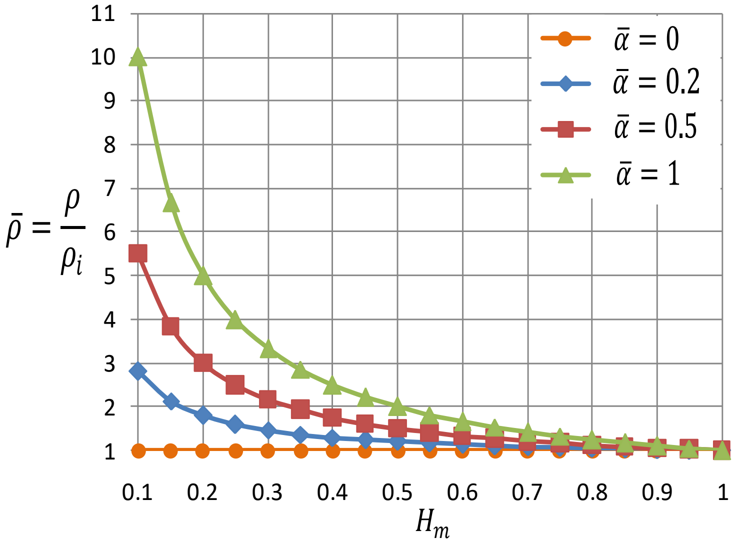


Fig.5 Variation of the dimensionless equivalent radius, $\bar{\rho}$ function of the dimensionless HCPL thickness, H_m

3. XPHD hypotheses

Ex–poro–hydrodynamic (XPHD) lubrication describes the lifting effect produced by the flow of fluid through an extremely compressible porous material subjected to compression.

The flow in the porous layer follows the law of Darcy [17]. Accordingly, the pressure gradient in radial direction is proportional to the mean velocity of the Newtonian fluid in porous media, u_m:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{\eta}{\phi} u_m \tag{3}$$

For the sake of simplicity, we define the porous media using compactness which is the complement of porosity:

$$\sigma = 1 - \varepsilon \tag{4}$$

Assuming that the solid fraction of the porous layer is preserved during compaction due to the HCPL thinness, the solid matrix conservation yields to the following equation:

$$\sigma h = \sigma_0 h_0 \tag{5}$$

The variation of permeability with deformation/porosity is the most important characteristic of porous materials in XPHD lubrication. In this paper as well in the previously published studies ([5]-[11], [18]), the local permeability is expressed with Kozeny–Carman law [15]:

$$\phi = \frac{D(H-\sigma_0)^3}{H{\sigma_0}^2} \tag{6}$$

where $D = {d_f}^2/16k$ is a complex parameter, $k = 5 \div 10$ (correction factor determined experimentally), d_f is fibbers diameter and σ_0 is the initial compactness.

uring impact process, the thickness of the porous material under compression can be expressed with classical parabolic approximation:

$$h = h_m + \frac{r^2}{2\rho} \tag{7}$$

Changing to dimensionless form, equation (7) take the form:

$$H = H_m + \frac{x^2}{\bar{\rho}} \tag{8}$$

where $x = r/\sqrt{2\rho_i h_0}$ is dimensionless radial coordinate.

The particular form of equation (8) on the contact surface limit ($r = R^*$ and $x = X$) is:

$$X^2 = (1 - H_m)\bar{\rho} \tag{9}$$

where X is the dimensionless contact radius.

All these hypotheses defining XPHD lubrication were accepted and validated experimentally in the previous studies performed in the Department of Machine Elements and Tribology in University Politehnica of Bucharest ([5]-[11]).

4. Analytical solutions

The squeeze process of a soft porous media imbibed with liquid in contact with a plastic surface is studied under two loading condition: *constant velocity* and *impact loading*. Each of them will be presented separately in the following sections of the paper. During compression, the axis of the sphere remains parallel with the reference plane considered. In the theoretical analysis, dimensionless forms have been also used, which makes it easier.

4.1 Constant velocity squeeze

The flow conservation equation for a given normal velocity, w, can be expressed function of HCPL properties as:

$$\pi r^2 w = -2\pi r \frac{\phi h}{\eta} \frac{\mathrm{d}p}{\mathrm{d}r} \tag{10}$$

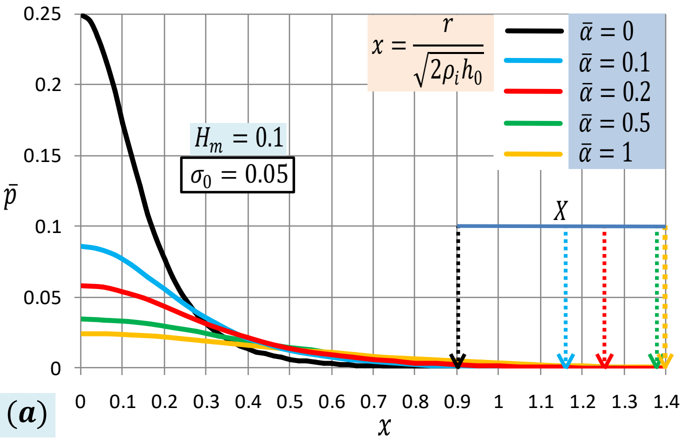
Re-arranging the terms, combining equations (5), (6) and (8), and using dimensionless pressure, $\bar{p} = pD/\eta\rho_i w$, we obtain the following pressure gradient, which, in dimensionless form, can be expressed as:

$$\frac{\mathrm{d}\bar{p}}{\mathrm{d}x} = -\frac{{\sigma_0}^2 \bar{\rho}^3 x}{[\bar{\rho}(H_m - \sigma_0) + x^2]^3} \tag{11}$$

Assuming zero pressure on the outer edge of the porous layer ($p = 0$ for $x = X$), after integration and some algebra, the dimensionless pressure distribution yields:

$$\bar{p} = \frac{{\sigma_0}^2 \bar{\rho}}{4} \left\{ \frac{\bar{\rho}^2}{[\bar{\rho}(H_m - \sigma_0) + x^2]^2} - \frac{1}{(1 - \sigma_0)^2} \right\} \tag{12}$$

Figure 6 presents the pressure distributions during compression for different values of complex parameter, $\bar{\alpha}$. Increasing the complex parameter, $\bar{\alpha}$, the maximum pressure decreases strongly and the footprint area extends.



$(\boldsymbol{a})$

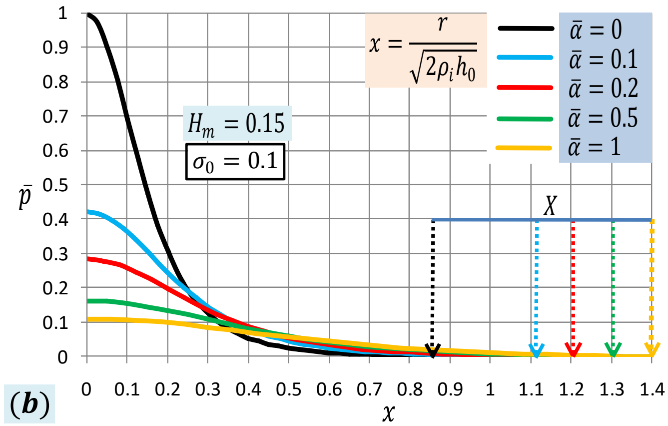


Fig.6 Pressure distributions at the contact center for initial compactness, $\sigma_0 = 0.05$ (a), respectively $\sigma_0 = 0.1$ (b)

Integrating the pressure distribution on the surface of contact, we can obtain the dimension lift force for constant velocity at a given deformation:

$$F = \frac{4\pi\eta{\rho_i}^2 h_0 w}{D}\int_0^X \bar{p}x\mathrm{d}x = \frac{\pi\eta{\rho_i}^2 h_0 w{\sigma_0}^2\bar{\rho}^2}{2D(1-\sigma_0)^2}\frac{(1-H_m)^2}{(H_m-\sigma_0)} \tag{13}$$

Using the "equivalent radius" concept and dimensionless form of the lift force, $\bar{F} = FD/\eta{\rho_i}^2 h_0 w$, we get:

$$\bar{F} = \frac{\pi{\sigma_0}^2}{2(1-\sigma_0)^2}\left(1+\bar{\alpha}\frac{1-H_m}{H_m}\right)^2\frac{(1-H_m)^2}{(H_m-\sigma_0)} \tag{14}$$

From equation (14) one can observe that the lift force generated during squeezing at any moment defined by compressed layer thickness, H_m, depends on the two parameters: the initial compactness, σ_0 and the complex parameter, $\bar{\alpha}$.

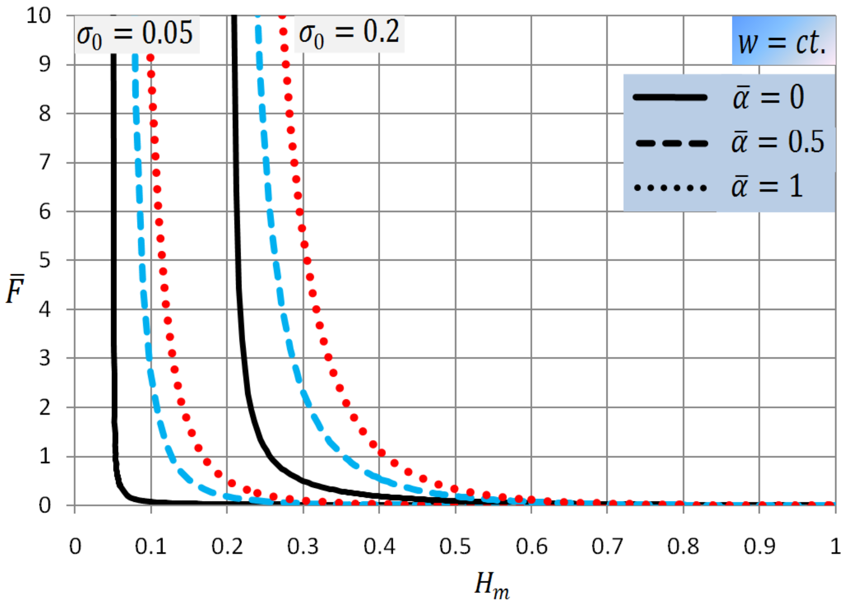


Fig.7 Variation of the dimensionless lift force, $\bar{F}$ for different complex parameters, $\bar{\alpha}$

As seen from Fig. 7, the lift force increases with the compression of the material, due to the flow resistance that increases and generates high pressures. The variation of the lift force is plotted in comparison with the rigid model case ($\bar{\alpha} = 0$). It is visible on figure that force generated increases with increasing complex parameter.

At the beginning of the compression, the lift force is low, and sharply increases after more than half of the compression.

4.2 Squeeze under impact loading

In the case of *impact loading*, assume that the ball with mass M is dropped from an initial height onto a porous layer imbibed with liquid. At the initial moment of impact the sphere has reached the porous material and begins to squeeze the liquid away.

To obtain the force under impact, one must suppose an infinitesimal time step dt, when the velocity can be supposed as constant. For the analysis of the squeeze process under shock conditions the method proposed by Bowden and Tabor [19] will be used. It consists of the impulse conservation application:

$$M\mathrm{d}w = -F\mathrm{d}t \tag{15}$$

Using the lift force that was calculated previously $-$ Eq.(13) and re-arranging the terms, equation (15) can be expressed as:

$$\mathrm{d}w = -\frac{\pi\eta{\rho_i}^2 h_0 w {\sigma_0}^2 \bar{\rho}^2}{2MD(1-\sigma_0)^2}\frac{(1-H_m)^2}{(H_m-\sigma_0)}\mathrm{d}t \tag{16}$$

Noting that $w/h_0 = -\mathrm{d}H_m/\mathrm{d}t$ and $w = w_0$ for $H_m = 1$, the normal velocity variation, w of the rigid ball with the dropping mass M, is obtained by integration:

$$w = w_0 + \frac{\pi\eta{\rho_i}^2{h_0}^2{\sigma_0}^2}{2MD(1-\sigma_0)^2}f(\alpha) \tag{17}$$

where w_0 is the speed of the impacting body at contact, and the parametric function, $f(\alpha)$ can be calculated using the expression:

$$f(\alpha) = \left\{(1-\sigma_0)^2\left[1+\frac{\alpha(1-\sigma_0)}{\rho_i\sigma_0}\right]^2 \ln\frac{H_m-\sigma_0}{1-\sigma_0} - \frac{\alpha}{\rho_i{\sigma_0}^2}\left[2\sigma_0+\frac{\alpha}{\rho_i}(1-4\sigma_0)\right]\ln H_m + \right.$$
$$+(1-H_m)\left[2\left(1-\frac{\alpha}{\rho_i}\right)\left(1-\frac{2\alpha}{\rho_i}\right)-\sigma_0\left(1-\frac{\alpha}{\rho_i}\right)^2-\frac{1}{2}(1+H_m)\left(1-\frac{\alpha}{\rho_i}\right)^2\right.$$
$$\left.\left. + \frac{\alpha^2}{{\rho_i}^2 H_m\sigma_0}\right]\right\} \tag{17a}$$

Introducing equation (17) into equation (13) and changing to dimensionless form, results the variation of the dimensionless impact force, $\bar{F}_S$, function of the thickness of deformed porous layer, H_m for a given dimensionless mass, $\bar{M} = MDw_0/\eta{\rho_i}^2{h_0}^2$:

$$\bar{F}_S = \frac{\pi{\sigma_0}^2}{2(1-\sigma_0)^2}\left(1+\bar{\alpha}\frac{1-H_m}{H_m}\right)^2\frac{(1-H_m)^2}{(H_m-\sigma_0)}\left[1\right.$$
$$\left.+\frac{\pi{\sigma_0}^2}{2\bar{M}(1-\sigma_0)^2}f(\bar{\alpha})\right] \tag{18}$$

where $\bar{F}_S = F_S D/\eta{\rho_i}^2 h_0 w_0$ is the dimensionless impact load, and the parametric function in dimensionless form is expressed as follows:

$$f(\bar{\alpha}) = \left\{(1-\sigma_0)^2\left[1+\frac{\bar{\alpha}(1-\sigma_0)}{\sigma_0}\right]^2\ln\frac{H_m-\sigma_0}{1-\sigma_0}\right.$$
$$-\frac{\bar{\alpha}}{{\sigma_0}^2}[2\sigma_0+\bar{\alpha}(1-4\sigma_0)]\ln H_m +$$

$$+(1-H_m)\left[2(1-\bar{\alpha})(1-2\bar{\alpha})-\ \sigma_0(1-\bar{\alpha})^2-\frac{1}{2}(1+H_m)(1-\bar{\alpha})^2\right.$$
$$\left.\left.+\frac{\bar{\alpha}^2}{H_m\sigma_0}\right]\right\} \quad (18a)$$

By making $\bar{\alpha}\to 0$ and $\bar{\alpha}\to 1$ in equation (18), the particular forms of the impact load equation for considered model yield:

$$\bar{F}_S^{XPHD}\Big|_{\bar{\alpha}=0}=\frac{\pi{\sigma_0}^2}{2(1-\sigma_0)^2}\frac{(1-H_m)^2}{(H_m-\sigma_0)}\left[1+\frac{\pi{\sigma_0}^2}{2\bar{M}(1-\sigma_0)^2}f_0(\sigma_0,H_m)\right] \quad (19a)$$

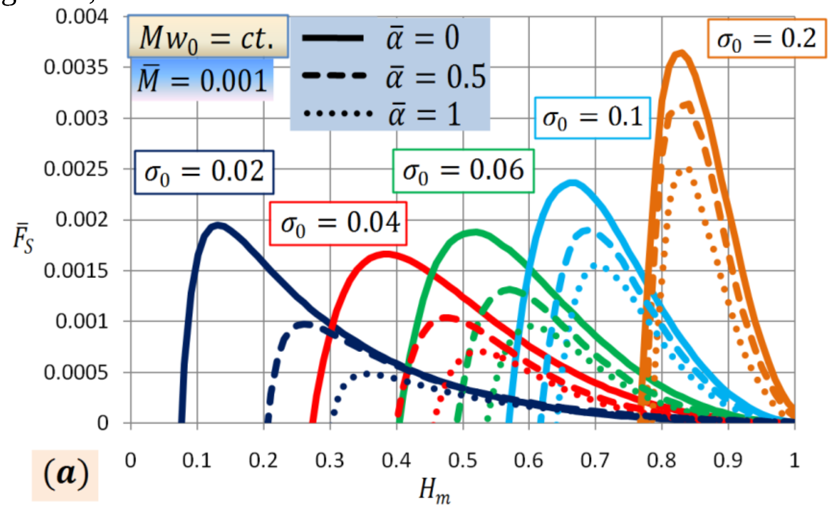
$$\bar{F}_S^{XPHD}\Big|_{\bar{\alpha}=1}=\frac{\pi{\sigma_0}^2}{2(1-\sigma_0)^2}\frac{(1-H_m)^2}{(H_m-\sigma_0){H_m}^2}\left[1+\frac{\pi{\sigma_0}^2}{2\bar{M}(1-\sigma_0)^2}f_1(\sigma_0,H_m)\right] \quad (19b)$$

where:

$$\left.\begin{aligned}f_0(\sigma_0,H_m)&=(1-\sigma_0)^2\ln\frac{H_m-\sigma_0}{1-\sigma_0}+(1-H_m)\left[2-\sigma_0-\frac{1}{2}(1+H_m)\right]\\ f_1(\sigma_0,H_m)&=\frac{1}{{\sigma_0}^2}\left[(1-\sigma_0)^2\ln\frac{H_m-\sigma_0}{1-\sigma_0}-(1-2\sigma_0)\ln H_m+\frac{(1-H_m)\sigma_0}{H_m}\right]\end{aligned}\right\} \quad (19c)$$

From equation (18) one can remark that the dimensionless impact force at each moment depends on three parameters: initial compactness, σ_0, dimensionless impulse, $\bar{M}$ and dimensionless complex parameter of the equivalent radius, $\bar{\alpha}$.

The variation of the dimensionless impact load, $\bar{F}_S$, function of dimensionless thickness, H_m is represented in Fig. 8 for different values of impacting mass, $\bar{M}$.



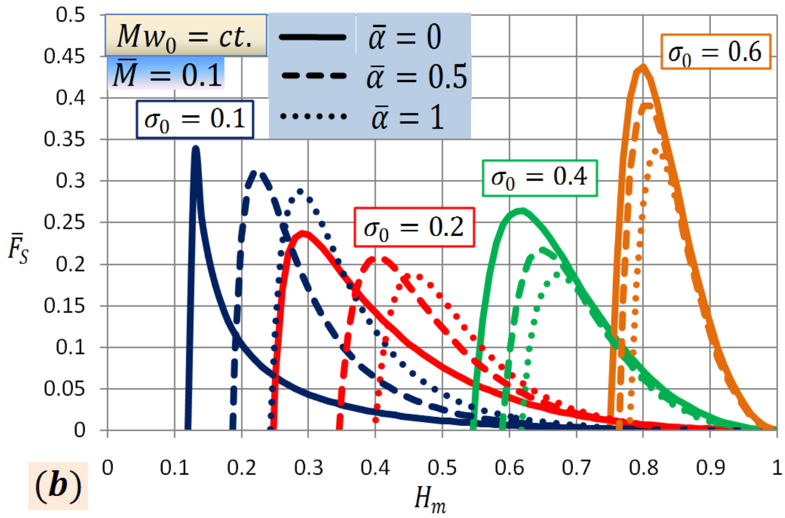


Fig.8 Variation of the dimensionless impact force, $\bar{F}_S$, versus dimensionless layer thickness, H_m for imposed impulse, $\bar{M} = 0.001$ (a) and $\bar{M} = 0.1$ (b)

The variation of impact load, $\bar{F}_S$, is plotted for different values of initial compactness, σ_0. A series of two values for dimensionless dropping mass, $\bar{M} = 0.001$, respectively $\bar{M} = 0.1$ covers some probable practical cases for the numerical applications.

A comparative study for different surfaces (rigid vs. plastic–deformable) was done in order to establish the best that has the lowest peak force. It can be seen that maximum force decreases with increasing of the complex parameter.

In other words, the more deformable is the contact surface (($\bar{\alpha}$ increases), the lower is the shock force. At the same time, one can observed that the peak force increases with increasing impact mass, $\bar{M}$.

Using this dimensionless analysis, interesting results such as limit–thickness, H_{mf} can be obtained within this investigation. The location of the limit thickness for each $\bar{\alpha}$ value can be found from the void shock force ($\bar{F}_S = 0$). This equation does not have an analytical solution because of the logarithmic term in the force variation. An overview of the numerical solution can be seen in Fig. 9 and the plot presents clearly that the higher is the complex parameter, the higher is the final HCPL thickness, and thus the attenuation effect increases. Thus, one can remark that for the dimensionless complex parameter, $\bar{\alpha} = 1$ will rise the final minimum thickness, H_{mf} with a factor of 3 according to those found experimentally by [20].

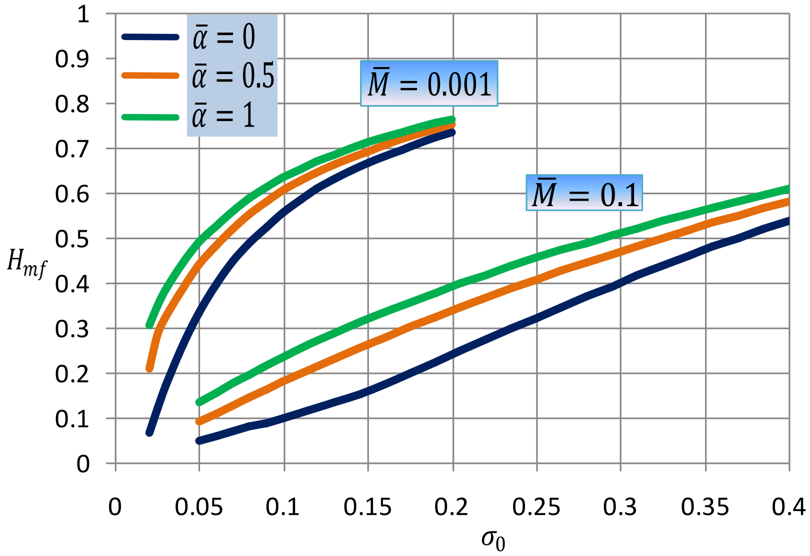


Fig.9 Variation of the final HCPL thickness function of the initial compactness

5. Conclusions

The squeeze process of a soft porous media imbibed with Newtonian liquid in contact with a plastic body was studied analytically under two loading conditions: *constant velocity* and *impact loading*.

In the proposed heuristic model the plastic body is replaced by a rigid one, and the real impacting ball of mass, M with constant radius, ρ_i is equivalent to an imaginary sphere (also rigid) of mass, M and with variable radius, ρ which is increasing during impact. This substitution allows an analytical approach in XPHD conditions and leads to the notable effects of minimizing the impact force and increasing the final HCPL thickness, according to the experimental results.

For the quantitative determination of the complex parameter, $\bar{\alpha}$ used to describe the equivalent radius variation for the various HCPL imbibed with liquids, as well for the possible plastic bodies, is required a thorough experimental research.

In the absence of the rigorous theoretical solutions, analytical or numerical, this approximate modelling can lead to a qualitative understanding of the complex processes investigated experimentally in the firing range.

Nomenclature

Latin letters

d_f	– fibber diameter of the HCPL [m]
D	– complex permeability parameter [m^2]
F	– lift force [N]
$\bar{F}$	– dimensionless lift force, $\bar{F} = FD/\eta\rho_i{}^2 h_0 w$ [–]
h_m	– minimum thickness of the porous material [m]
h_{mf}	– final minimum thickness of the HCPL when $w = 0$ [m]
H_m	– dimensionless minimum HCPL thickness, $H_m = h_m/h_0$ [–]
k	– dimensionless constant in Kozeny–Carman equation [–]
M	– mass of impact [kg]
$\bar{M}$	– dimesionless impact load, $\bar{M} = MDw_0/\eta\,\rho_i{}^2 h_0{}^2$ [–]
p	– pressure [Pa], penetration depth [m]
r	– radial coordinate [m]
R	– contact (footprint) radius [m]
R^*	– outer contact radius [m]
t	– time [s]
u_m	– mean fluid velocity [m/s]
w	– compression velocity [m/s]
x	– dimesionless radial coordinate, $x = r/\sqrt{2\rho_i h_0}$ [–]
X	– dimensionless contact radius, $X = \sqrt{\bar{\rho}(1 - H_m)}$ [–]

Greek letters

α	– complex parameter of the equivalent radius [m]
$\bar{\alpha}$	– dimensionless complex parameter, $\bar{\alpha} = \alpha/\rho_i$ [–]
ε	– porosity [–]
η	– viscosity of the fluid [Pa·s]
ρ_i	– sphere radius [m]
ρ	– "equivalent radius" [m]
$\bar{\rho}$	– dimensionless equivalent radius, $\bar{\rho} = \rho/\rho_i$ [–]
σ	– compactness [–]
ϕ	– permeability of the porous layer [m^2]

Subscripts

0	– initial, value corresponding to undeformed layer
f	– final value
m	– value corresponding to mid-plane
S	– shock/impact

Acronyms

EHD	– Elasto–Hydrodynamic
$HCPL$	– Highly Compressible Porous Layer
HD	– Hydrodynamic
STF	– Shear Thickening Fluid
$XPHD$	– Ex–Poro–Hydrodynamic

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