Experimental and theoretical compression studies on porcine skin

Citation for published version (APA):
Oomens, C. W. J., Campen, van, D. H., Grootenboer, H. J., & Boer, de, L. J. (1985). Experimental and theoretical compression studies on porcine skin. In S. M. Perren, & E. Schneider (Eds.), *Biomechanics : current interdisciplinary research : selected proceedings of the fourth meeting of the European Society of Biomechanics in collaboration with the European Society of Biomaterials, September 24-26, 1984, Davos, Switzerland* (pp. 227-232). Nijhoff.

Document status and date:
Published: 01/01/1985

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

29. EXPERIMENTAL AND THEORETICAL COMPRESSION STUDIES ON PORCINE SKIN

C.W.J. Oomens[1], D.H. Van Campen[1], H.J. Grootenboer[2] and L.J. De Boer[2]

[1] Eindhoven University of Technology, Eindhoven
The Netherlands
[2] Twente University of Technology, Enschede
The Netherlands

1. INTRODUCTION

Skin can be viewed upon as a biphasic material, consisting of a solid with a free movable fluid in it (Reddy et al., 1981). The solid matrix consists of collagen and elastin fibers, embedded in a ground substance that binds most of the water. The movable, interstitial fluid is not chemically bound and can flow when a pressure gradient is present. The biphasic character can explain a number of time dependent properties of the skin. In view of the above a model has been developed, which is based on the theory of mixtures (Bowen, 1976). The goal of the present study was to find a method to measure material properties of porcine skin, using a biphasic concept and to compare the results with theoretically obtained values. A suitable experiment which has been used with success on articular cartilage (Mow et al., 1984) is a confined compression test. It appears from this study that this test can be used for skin also and that it confirms our hypothesis about the biphasic nature of skin.

2. THE MODEL

The solid which constitutes the porous matrix is considered to be intrinsically incompressible and purely elastic. The fluid is assumed to be Newtonian and also incompressible. By means of an averaging procedure we are able to define a continuum for which the following set of equations hold:

equilibrium equations: $\underset{\sim}{\nabla} \cdot \underline{\sigma}_{eff} - \underset{\sim}{\nabla} p = \underset{\sim}{0}$ (1)

continuity equation: $\underset{\sim}{\nabla} \bullet \underset{\sim}{v}^s - \underset{\sim}{\nabla} \bullet (\underline{K} \bullet \underset{\sim}{\nabla} p) = 0$ (2)

In order to solve (1) and (2) these equations are written with reference to the undeformed configuration. A Galerkin weighted residual method is used to find an integral form suitable for a finite element model. After writing the equations in an incremental form they are solved with a Newton-Raphson iteration procedure.

As a constitutive model for the solid phase an expression for the strain energy A^s is used which is an exponential function of the Green strain (Fung, 1973). The one-dimensional representation we need for confined compression is given by:

$$A^s = \frac{1}{2} A\, E^2 + \frac{1}{2} B \exp\,(C\, E^2) \tag{3}$$

For articular cartilage it has been shown that there exists an exponential relation between the permeability of the tissue and the volume change (Mow et al., 1984).

$$K = K_0 \exp\{M(J_3-1)\} \tag{4}$$

Because we did not have similar data available for porcine skin we have assumed that (4) can also be applied to skin. Mow et al. (1984) have published an asymptotic solution for the transient problem just after load application for small displacements and for a linear solid:

$$u/u_{END} = \beta \sqrt{t} \quad \text{with: } \beta = \frac{2H}{L_0\sqrt{\pi}} \left(\sqrt{\frac{K_0}{H}}\right) \exp\left(-\frac{MP}{\pi H}\right) \tag{5}$$

$$\text{and : } H = A + BC$$

It can be seen that β is an exponential function of P, which we will use later to determine K_0 and M.

3. THE CONFINED COMPRESSION TEST

In a confined compression test a stepwise load is applied (Fig. 1) to a disc-shaped sample of porcine skin (radius: 3.70 ± 0.05 mm., thickness: 1.7 - 2.0 mm). The skin with the epidermis on top is placed in a tight fitting ring on a porous filter, so fluid can flow away in only one direction. Because of the ring the deformation is one-dimensional. We have cut 24 samples out of a square piece of skin (10 x 10 cm) out of the regio scapularis of a fully grown pig. The samples were kept frozen ($-35^{\circ}C$) until they were used. Just before the experiment is started the sample and ring are being placed in a saline solution. Then the loading shaft is lowered on the sample by means of a small weight (1 gf). The tissue swells in the saline solution for about 4 hours. To obtain unified conditions we have used the position of the loading shaft after 4 hours as a measure for the average, initial thickness of the sample. Then a stepwise load is applied between 30 and 500 gf during 18 hours.

The deformation after this time period is used for the determination of A, B and C in (11). The displacement curves during the first 120 seconds of the experiments are used for the determination of K_0 and M in (12).

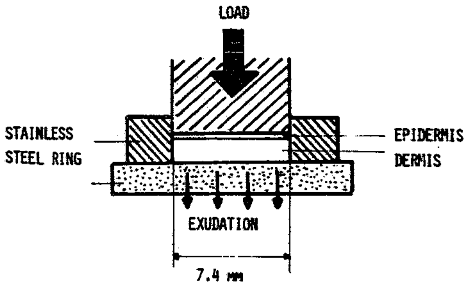

Fig. 1

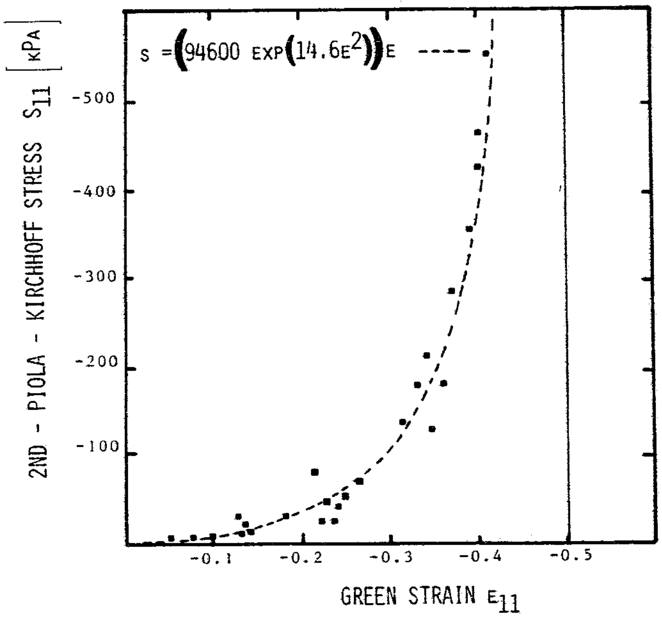

Fig. 2

4. RESULTS

In Fig. 2 the effective 2nd-Piola-Kirchhoff stress is given for the 24 tissue samples as a function of the Green strain after 18 hours. Because of the shape of the curve we have done a regression analysis, assuming that A = 0. This leads to the following values of B and C with their 95-% confidence intervals: B = (0.648 ± 0.006) x 10^4 N/m^2 ; C = 14.6 ± 2.5. Fig. 3 shows that in a time period immediately after load application a linear relationship exists between u/u_{end} and $\sqrt{t}$, even for high loads. For low loads this has already been predicted by Mow et al. Our numerical calculations have shown that theory predicts that this linearity also exists for high loads. Fig. 3 also shows that there is an initial displacement which cannot occur in an ideal confined compression experiment. This can be caused by deflections from the perfect disc shape, a not exactly fitting ring or a not perfectly smooth surface of the porous filter. It is also not certain whether the solid matrix is really intrinsically incompressible. The striking

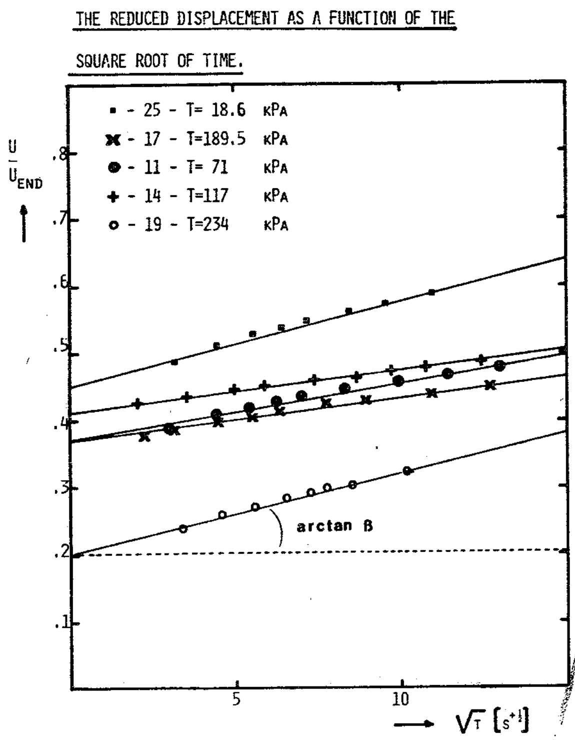

Fig. 3

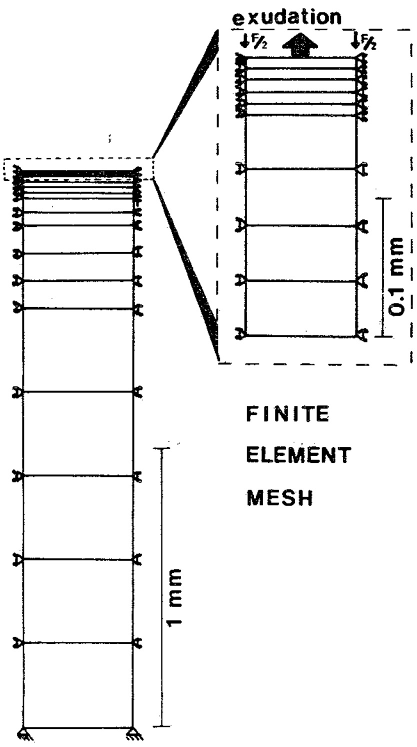

Fig. 4

linearity after the initial deformation points out that we still have a confined compression experiment, but with an initial deformation which is not one-dimensional. Unfortunately this leads to a rather large systematic error in B and C. In Fig. 5 the tangents β of the reduced displacements with their 95-% confidence intervals are given as a function of the load. It can be seen that for low loads β descends rapidly but at higher loads becomes nearly a constant. We have done some numerical calculations, using the geometrically non-linear theory and an exponential strain energy law. We have used the measured values of B and C and estimated values of K_0 and M of 1.4×10^{-14} Nm^4/s and 10 respectively. Te latter estimates have been determined by combining theoretical and experimental results. The element mesh is given in Fig. 4. These calculations lead to the dotted line in Fig. 5. If we substitute the same values of K_0 and M in the analytical solution, based on the geometrically linear theory and a linear strain energy we obtain the solid line. It is obvious that for porcine skin introduction of additional non-linear aspects such as a non-linear constitutive law for the solid, changes the obtained material properties.

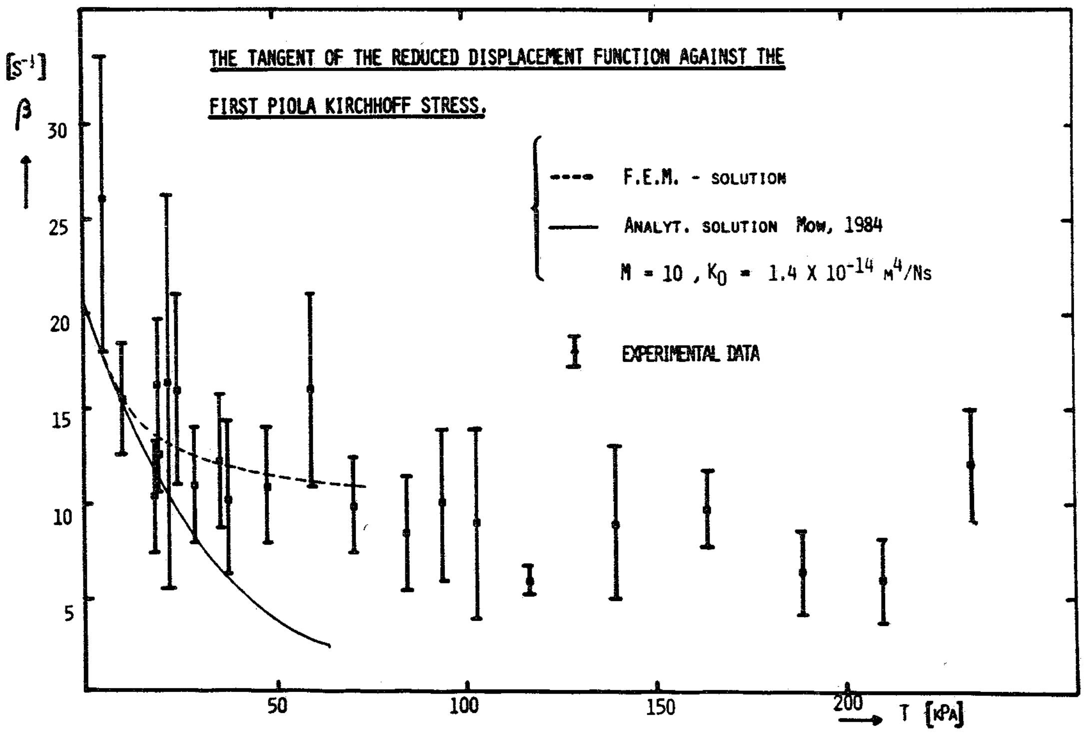

Fig. 5

5. CONCLUSIONS

The confined compression experiments seem to confirm the biphasic nature of porcine skin. Because of its mathematical simplicity confined compression is an attractive way to determine some material properties of biphasic material, but the difficulties to approach the ideal experiment make it a rather inaccurate one for skin. However from the performed experiments it has become evident that a fair agreement can be found between theory and experiment and a first estimate of some material properties has been made.

6. NOMENCLATURE

$\underset{\sim}{\nabla}$: gradient operator with regard to the deformed configuration

$\underline{\sigma}_{eff}$: stress in the solid matrix due to elastic contact.

$\underset{\sim}{v}^{\alpha}$: real volume average of the velocity of phase α.

A^s : Helmholtz free energy for the solid matrix.

$\underline{E}$: Green strain

t : time

P : the load devided by the original sample.

T : 1st-Piola-Kirchhoff stress crosssection.

$\underset{\sim}{x}^{\alpha}$: deformed position vector of phase α.

$\underline{\sigma}^{\alpha}$: bulk volume averaged or apparent stress tensor of phase α.

p : real volume average of the hydrodynamic pressure.

ρ^s : apparent density

$\underline{K}$: permeability

J_3 : third strain invariant

L_0 : original thickness of tissue

7. REFERENCES

1. Bowen R.M., 1976. Theory of mixtures - in: Continuum physics (ed. Eringen AC). Acad. Press, New York.
2. Fung Y.C., 1973. Biorheology of soft tissues. Biorheology, 10, 139-155.
3. Mow V.C., Holmes M.H., Lai W.M., 1984. Fluid transport and mechanical properties of articular cartilage: a review. J. Biomech. 17, 5, 377-394.
4. Reddy N.P., 1981. Subcutaneous interstitial pressure during external loading. Am. J. Physiol. R 327-329.