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Experimentation and simulation of double spherical compression on agar gel toward multiphysical measurements

Emilien Schall

Université de Lorraine, DCAC, Nancy, France

Adrien Baldit

Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, Metz, France

Anne-Sophie Bonnet

Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, Metz, France

Marie-Reine Losser

Université de Lorraine, DCAC, Nancy,

CHR Metz-Thionville, Metz, France

Serge Le Tacon

CHR Metz-Thionville, Metz, France

Corresponding author.

Email: emilien.schall@univ-lorraine.fr

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1. Introduction

Biomechanical characterization of soft biological tissues with or without injuries (Kawałkiewicz et al., 2023) is a recurrent need for the development of medical devices but these tissues often involve a diversity of layers with complex structures. Two contact points tests allow assessing the structural variations of tissues between the contact probes through multiphysical measurements such as mechanical as well as electrical ones. To analyse and understand the behaviour of skin, customizable agar gel can be used as a skin substitute (Mathieu et al., 2023) but needs to be characterized depending on the gel concentration and additives. The present work focuses on the mechanical characterization of agar hydrogels through double compression tests combined with finite element analyses.

2. Methods

2.1 Agar samples

Agar samples were prepared by mixing agar powder, and water. Three different concentrations of agar

have been tested: 1%, 1.5% and 2%, respectively named group A, B and C. Sodium chloride solution was used to analyse its concentration incidence on the sample mechanical response. The mixture was then poured into 100 mm diameter Petri dishes resulting in 10 mm thick samples. During the procedure, special care was given to guaranty homogeneous samples.

2.2 Tests on agar samples

Spherical compression tests were made with a double spherical probe featuring 2 spheres of 6 mm diameter and spaced of 10 mm centre to centre. It was previously demonstrated that this distance between the spheres prevented mechanical interference in the tested material. (Mathieu et al., 2023).

Plate-plate compression with digital image correlation was performed on the same specimen. 8 mm-diameter cylindrical samples with 10 mm height were harvested thanks to a surgical trephine to determine Poisson ratio and Young's modulus within the framework of linear elasticity. All tests were performed 3 times with a universal tension-compression machine (Zwicky0.5) equipped with a 10N load cell and at 0.01 mm/s velocity to satisfy quasi-static conditions and reduce viscous effects.

2.3 Finite element modelling

3D finite element modelling of the sample was made using Abaqus/CAE 2022[®]. The sample was represented by a cylinder of 100 mm in diameter and 10 mm in height. It was meshed using hexahedral elements whose size progressively went from 0.3 to 5 mm from the centre to the border and from 0.3 to 1 mm top to bottom (*Figure 1*). The spheres were both considered as discrete rigid solids and meshed with an element size of 0.4 mm. The test was displacement-controlled and a value of 1.80 mm was imposed. The contact was considered frictionless due to the well hydrated surface of the agar samples. A linear constitutive law was chosen to reproduce the experimental response. Thanks to the plate-plate compression tests, the Poisson ratio have been set and kept constant to 0.3 within the simulation. The Young's moduli obtained from the plate-plate tests (*Table 1*) were adjusted using the maximal force ratio between experiments and simulation.

3. Results and discussion

As expected the force value increased with the agar concentration as presented in *Figure 1*. For conditions A and C, curves resulting from 3 identical test samples are shown, pointing out the repeatability

and the reliability of the experimental bench. Focusing on condition B, the impact of salt on mechanical response appears to be negligible. Similar observations were made with other agar concentrations but are not presented here.

Table 1. Properties of agar samples
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Agar sample	A	B	C
Agar concentration (%)	1	1.5	2
Plate-plate			
Young's modulus (kPa)	18±1	42±3	66±3.5
Identified			
Young's modulus (kPa)	22	45	70
Poisson ratio	0.3	0.3	0.3
Salt concentration (%)	0	0	6
	9	0	

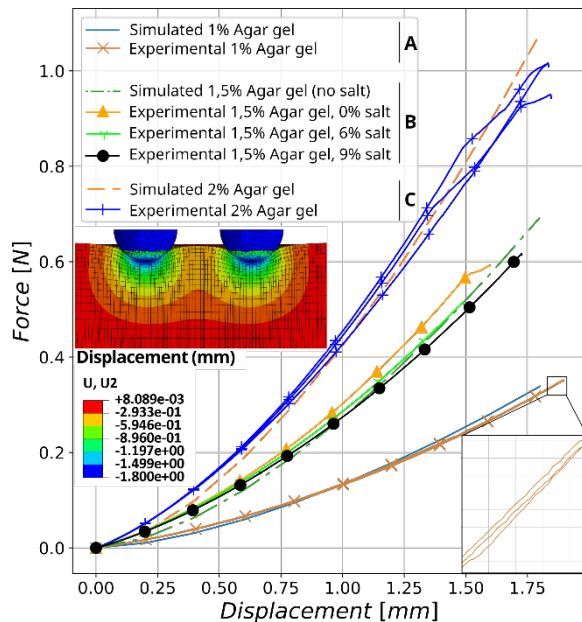


Figure 1. Force-displacement curves for experimental and simulated data. The impact of salt is shown for the 1.5% percent agar samples as well as a cross-section of the vertical displacement field within the sample for 1.80 mm compression with solid rigid spheres.
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The proportional fitting procedure allowed to identify the values of Young's modulus reported in Table 1. These values are inside the range of variation of the ones obtained by plate-plate compression.

The limit of non-influence between the spheres is a displacement of 1.20 mm. Above, an interaction becomes visible between the two compression sites, making an arch shape with a 0.3 mm vertical

displacement located between the two spheres, obtained for a 1.80 mm prescribed displacement (Figure 1). It is important to take into consideration that in practice, the sphere displacement is never equal to the contact depth (Geerligs et al., 2011).

A limit for the simulation is that the force measurements start precisely when contact between probe and sample is initiated. In the experimental setup, the load cell tends to detect a contact before the probe gets in touch with the sample. This is due to the wet layer naturally present on the agar which creates a surface tension between the sample and the spheres, before the actual start of the spherical compression test (Pailler-Mattéi & Zahouani, 2004).

4. Conclusions

We showed that the elastic properties of agar gel identified through double spherical compression and finite element simulation are close to those provided by classical plate-plate compression tests. Even though agar samples are homogeneous, 1% agar is a good candidate as a customizable skin substitute in terms of mechanical properties, such as a Young Modulus of 9.5 kPa on a in vivo study with a Ø6.35 mm sphere (Pailler-Mattéi & Zahouani, 2004). It gives promising perspectives to conduct multiphysical measurements such as electro-mechanical couplings (Mathieu et al. 2023). The presence of NaCl showed no impact on the mechanical properties of the samples but the influence on hydro-chemo-mechanical couplings is under investigation.

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Conflict of Interest Statement

None.

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