Journal of Cereal Science 47 (2008) 438–444

Journal of
CEREAL
SCIENCE

www.elsevier.com/locate/jcs

Use of mechanics of cohesive granular media for analysis of hardness and vitreousness of wheat endosperm

J.Y. Delenne[a,*], Y. Haddad[a], J.C. Bénet[a], J. Abecassis[b]

[a]*Laboratoire de Mécanique et Génie Civil, UMR CNRS 5508, Université Montpellier II, cc 034, Place E. Bataillon, 34095 Montpellier cedex 5, France*
[b]*ENSA-INRA, Unité de technologie des céréales et agropolymères, 2 Place Viala, 34080 Montpellier cedex 1, France*

Received 21 October 2006; received in revised form 17 April 2007; accepted 23 May 2007

Abstract

The characterisation of the wheat endosperm by mechanical tests of compression highlighted a relation between the rupture energy and the elasticity modulus for different varieties of wheat; this relation allows us to distinguish mealy and vitreous endosperms. An approach based on the micromechanics of cohesive granular materials is used to analyse these experimental results. A geometrical model of the wheat endosperm made of grains linked by cohesive bonds is proposed. We introduced two parameters, the first one α represents the percentage of active bonds (bonds where the stiffness and strength are non-zero), and the second one β represents the threshold of the bond's rupture. The parameter β can be related to the cross-section of the bond. This model successfully describes the mechanical tests on the wheat endosperm. The comparison with the experimental tests makes it possible to clearly differentiate vitreous wheats and mealy wheats and then attribute this property to the parameter β. The model shows the same tendency as regards the evolution of the rupture energy and the elastic modulus with the parameter α. The modelling of endosperm by the mechanics of cohesive granular media provides a new theoretical framework to interpret the rheology of endosperm. This approach allows us to connect this rheology to the mechanical actions at the scale of the granules.

Keywords: Wheat endosperm; Rheology; Hardness; Vitreousness; Cohesive granular media; Numerical simulation

1. Introduction

Rheological tests have been performed, only recently, on samples taken from wheat grain endosperm. In work by Glenn et al. (1991), cylindrical test samples were subjected to tractive force and compression. A technique for milling parallelepipedal samples was developed more recently (Haddad et al., 1998). The rapidity of the method based on machining the faces of the sample by abrasion (Haddad et al., 1999) made it possible to increase the number of compression, creep and relaxation tests on samples measuring 1.6 mm long, 0.6 mm wide and 1.1 mm high. The work of Glenn and Haddad also revealed the effect of the variety and of vitreousness on rheological behaviour.

These results deal with macroscopic tests. At the moment, the mechanical forces between starch granules are a major stake for understanding the behaviour during grinding processes. However, the experimental techniques for the measurement of these forces and other local variables are not available. On the other hand, the link between the biochemical studies dealing with protein–starch mechanical interaction and the rheological tests are not established. The main objective of this work is to propose a suitable framework in this direction in order to enrich the description of the mechanical behaviour and failure of wheat endosperm.

This framework is offered by the mechanics of cohesive granular media. It presents the advantage to account for the microstructure composed of granules interacting through cohesive bonds. This type of modelling is obviously more suitable than continuum mechanics since it allows us to incorporate the representative local scale

*Corresponding author. Tel.: +33 4 67 14 39 90; fax: +33 4 67 14 45 55.
E-mail address: delenne@lmgc.univ-montp2.fr (J.Y. Delenne).

0733-5210/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcs.2007.05.009

parameters of the real structure that we can hope to connect with biochemical considerations.

The presentation of available results from mechanical tests is followed by interpretation using the mechanics of cohesive granular media. This model is then used to bring out the microscopic parameters that are significant for the description of the rheology of the wheat endosperm.

2. Mechanical tests on wheat endosperm

In spite of the heterogeneous, granular structure of endosperm, the rheological behaviour observed could be interpreted using the rheological models developed in the mechanics of materials. This applies to compression, creep and relaxation tests (Lemaitre and Chaboche, 1994). As an example, the stress–strain curves for various wheat and rice varieties are shown in Fig. 1(a) (Haddad et al., 1998). The effect of the moisture content during compression has also been demonstrated (Delwiche, 2000; Haddad et al. 2001); the plasticising effect of water is shown in Fig. 1(b). The curves in Fig. 1(a) make it possible to determine Young's modulus in the linear part and the failure energy represented by the area beneath the curve calculated to the failure point; this is identified as the maximum loading applied during the test.

The representative points in the tests conducted by Glenn and Haddad are shown in Fig. 2 in Young's modulus E (GPa) against failure energy W (MJ/m^3). Haddad specified the hardness and the vitreous or mealy nature whereas Glenn did not. Two families of points grouped around two lines can be seen in the diagram. In the light of the information provided by Haddad, they represent the vitreous and mealy wheats. Most of the points for Glenn's test are for mealy wheats and appear to represent durum hardness in three tests. Three points cannot be grouped in the vitreous field. However, it is noted that Haddad (1999) reported difficulty here in the measurement of Young's modulus because of the rigidity of the test machine.

The diagram clearly shows that mechanical tests can be used to distinguish between vitreousness and hardness of wheat endosperm.

The aim of the work described here is to interpret these results using a mechanical model of wheat endosperm. As a first approximation, endosperm can be considered as a network of starch grains linked by proteins (Haddad et al., 2001). This structure (Fig. 3) leads us to propose modelling based on the mechanics of cohesive granular media (Delenne et al., 2002, 2004).

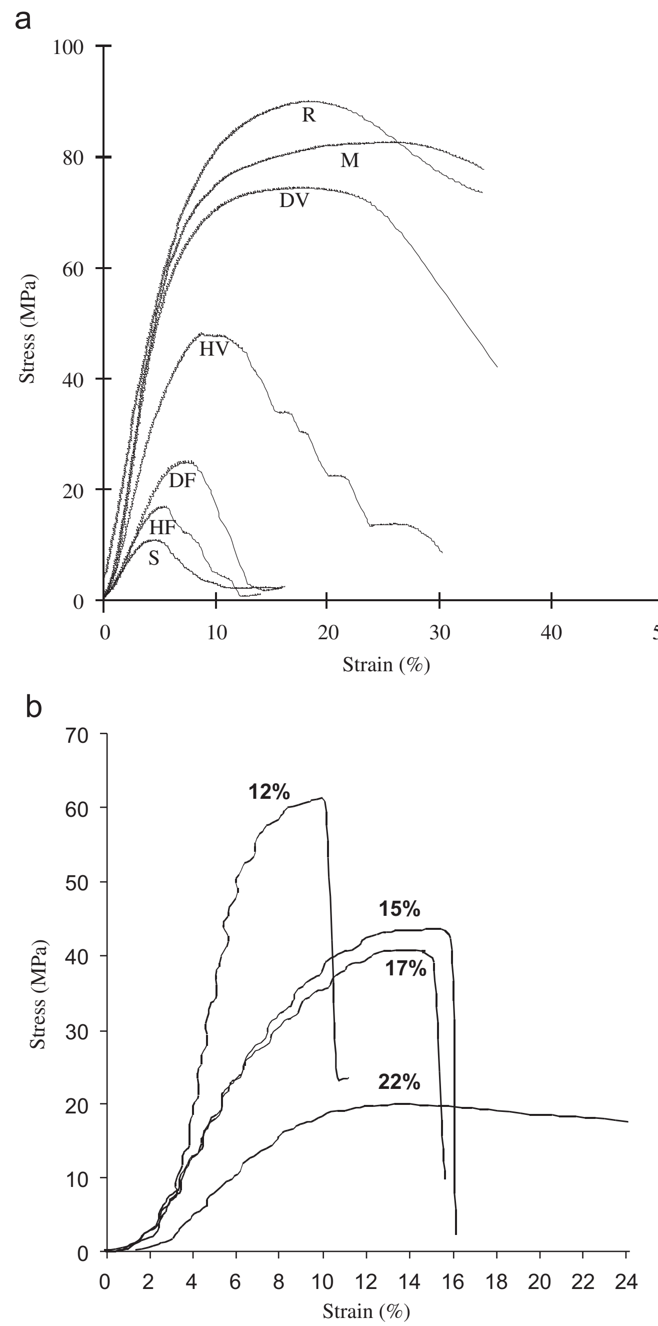

Fig. 1. (a) Average stress–strain curves of endosperm of starchy soft wheat (s), of floury durum wheat (HF), mealy durum wheat (DF), vitreous durum wheat (HV), vitreous durum wheat (DV), maize (M) and rice (R) (Haddad, 1999). (b) Average curves of the compression of vitreous endosperm of Baroudeur (hard) at moisture contents of 12%, 15%, 17% and 22% (Haddad et al., 2001).

3. Modelling cohesive granular media

Starting with the work of Cundall and Strack (1979), methods based on the discrete representation of the microstructure of granular media have developed strongly (Moreau, 1994; Radjai, 1999). In this approach, the mechanical behaviour between grains is described by contact and friction actions.

More complex models of interactions between grains were implemented by several authors, particularly for the study of mediums using capillary or electrostatic interactions (Lian et al., 1998; Thornton and Ning, 1998). These models were extended in order to take into account cohesive forces due to the presence of a solid body (such as a protein) between grains (Delenne et al., 2002). A synthetic presentation of this model is given in what follows.