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Hydraulic pressing of oilseeds: Experimental determination and modeling of yield and pressing rates

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ABSTRACT

The influence of pressure, temperature and moisture content on the oil yield and rate of conventional hydraulic expression of sesame and linseed is discussed as well as the influence of pressure and temperature for rapeseed, palm kernel, jatropha and dehulled jatropha. Yield increased with increase in pressure and with increase in temperature. For both sesame and linseed maximum oil yield was obtained at a moisture content of about 4 wt%. Maximum yields obtained were 45–55 wt% (oil/oil) for hulled seeds (linseed, rapeseed, palm kernel and jatropha) and 70–75 wt% (oil/oil) for dehulled seeds (sesame and dehulled jatropha). Rate of expression increased with an increase in temperature and a decrease in moisture content. Furthermore, the rate of pressing was described by the Shirato model. The increased creep, and thus decreased rate of pressing, observed with increased moisture content was satisfactorily described by the Shirato model.

1. Introduction

Vegetable oils have been used by mankind for centuries, for both food and non-food applications (Hasenhuettl, 1991). For most of this time, the only option to recover the oil from the seeds has been mechanical expression (pressing). The oil obtained via this method is of a high quality, but the attainable yield is limited to roughly 80 wt% of the oil originally present (Hasenhuettl, 1991). It is only in the last century that solvent extraction has been used in this field. The advantage of solvent extraction is the high yield that can be obtained economically with this method (>99 wt%), but this is at the expense of a reduced oil quality. This quality reduction is caused by the extensive solvent recovery processes that are necessary and the fact that the solvent co-extracts undesired components from the cell walls. Especially for high value added oils this quality reduction is unacceptable, limiting the production process to mechanical expression. Maximizing the yield is then limited to optimizing the preconditioning and maximizing the pressure. Since a cocoa filter press is able to achieve higher pressures (up to 100 MPa) than conventionally used presses (Khan and Hanna, 1983; Carr, 1997), the use of a laboratory scale cocoa press (Venter et al., 2006) was studied for its ability to attain high yields for oils from high value added seeds.

For this study, sesame, linseed, palm kernel and jatropha were chosen, because these seeds represent a wide range of physical properties and produce high value added oils. They range from soft to hard and from high to relatively low oil content. Furthermore rapeseed was included as a representative of the bulk oilseeds.

An overview of seed properties is given in Table 1. For the seeds used in this work, available pressing data is limited. Therefore the objective of this work is to extend the available pressing data for sesame, linseed, jatropha, palm kernel and rapeseed. The ranges for which experimental data are available in literature are extended for sesame (to include $P > 20$ MPa, $T = 100$ °C, <6 wt% moisture), linseed (to include $P < 66$ MPa, $T = 40$–100 °C), palm kernel (to include $P > 25$ MPa, $T = 40$ °C) and rapeseed (to include $P = 20$–50, 60–70 MPa, $T = 40$, 100 °C). These experiments were done to exclude the influence of the apparatus (Wu et al., 2000) when comparing the pressing properties of the seeds (Beveridge et al., 2005). To the best of the authors' knowledge data on hydraulic expression of jatropha is completely lacking in literature. Furthermore, the influence of moisture content and temperature on material properties obtained from the experimental data is discussed, which is also lacking at present.

To aid in the optimisation of the process a model previously used for cocoa expression (Venter et al., 2007b) is used to correlate the experimental data. Mathematical models previously used in oilseed expression are either empirical (Fasina and Ajibola, 1990),

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Table 1
Overview of seeds

Seed	Composition (wt%, d.b.)[a]				Oil point (MPa)	Hardness	World Market volume (10^6 ton) (2000)[b]	Source
	Oil content	Protein	Fiber	Ash				
Sesame	51.5	20–25	4–10	5		Soft	2.4	
Linseed	43.8	20–25	20–30	3–4		Hard	2.5	
Palm kernel	31.6	8	5	2	3.91	Hard	9.7	Faborode and Favier (1996) and Raji and Favier (2004)
Jatropha	37.2	19	38	5		Hard	Very low	
Rapeseed	46.7	25–35	30–50	5	6.7–8.4	Hard	44.7	Faborode and Favier (1996) and Sadowska et al. (1996)

[a] Bailey et al. (1964).
[b] US Department of Agriculture (2006).

based on the nature of cell structures (Lanoisellé et al., 1996) or Terzagi type models (Mrema and McNulty, 1985; Shirato et al., 1986). The first type is limited to specific seeds and equipment on which the measurements were done. The second type of models is the fundamentally most correct, but requires knowledge of difficult to measure properties. The Terzagi-type models provide a good compromise between general applicability and parameters that are easy to measure. The Shirato model (Shirato et al., 1986), which is an extended Terzagi type model originally developed for soil consolidation, has been shown to describe the expression of dry cocoa nibs quite well (Venter et al., 2007b). It was therefore decided to use it for other oilseeds as well in order to investigate the general applicability of the model. Material properties obtained from this model enable quantification of the terms “hard” and “soft” seeds commonly used in literature.

This paper presents a systematic study of the influence of pressure, pressure profile, temperature, time and moisture content on the pressing behavior of the small market volume oilseeds sesame, linseed, jatropha, palm kernel and rapeseed in a laboratory scale cocoa filter press. The pressing behavior is described as function of process conditions and material properties with the Shirato model.

2. Modelling of oilseed expression

Mathematical models previously used in oilseed expression are either empirical (Fasina and Ajibola 1990), based on the nature of cell structures (Lanoisellé et al., 1996)) or Terzagi type models (Mrema and McNulty, 1985; Shirato et al., 1986). The first type is limited to specific seeds and equipment on which the measurements were done. The second type of models is the fundamentally most correct, but requires knowledge of difficult to measure properties. The Terzagi-type models provide a good compromise between general applicability and parameters that are easy to measure. The Shirato model, which is an extended Terzagi type model originally developed for soil consolidation, has been shown to describe the expression of dry cocoa nibs quite well (Venter et al., 2007b). It was therefore decided to use it for other oilseeds as well in order to investigate the general applicability of the model.

The Shirato model is given in Eq. (1), which describes the consolidation ratio as a function of time, pressure and material properties. The consolidation ratio (U_c) is defined as the ratio of cake thickness decrease at time t and the final cake thickness decrease. This ratio can be used to compare the rates of pressing of different seeds. The total consolidation is divided in two parts: primary and secondary consolidation (creep). The relative contribution of creep to the total consolidation is given by the parameter B

$$U_c = \frac{l_0 - l_t}{l_0 - l_{\mathrm{end}}} = (1-B)\cdot\left(1-\exp\left(-\frac{\pi^2 i^2 C_e}{4\omega_0^2}\cdot t\right)\right) + B\cdot\left(1-\exp\left(-\frac{E}{G}\cdot t\right)\right) \quad \text{with} \quad C_e = \frac{P}{\mu_l \rho_s \alpha \frac{\partial e}{\partial P}} \tag{1}$$

with

U_c	compression ratio (–)
l_0	cake-thickness at the start of pressing (m)
$l(t)$	cake-thickness at time t (m)
l_{end}	cake-thickness at end of experiment (m)
B	relative contribution secondary consolidation
i	number of drainage surfaces (–)
C_e	consolidation coefficient (m^2/s)
ω_0	volume of solids per unit area (m^3/m^2)
t	time (s)
E/G	creep constant (s^{-1})
P	pressure (Pa)
μ_l	liquid viscosity (Pa s)
ρ_s	solids density (kg/m^3)
α	filtration resistance (m/kg)
e	void ratio (–)

$$(1-\varepsilon) = (1-\varepsilon_0)\cdot\left(1+\frac{P}{P_a}\right)^n \tag{2}$$

$$\alpha = \alpha_0\cdot\left(1+\frac{P}{P_a}\right)^\beta \tag{3}$$

$$\mathrm{Yield}(\mathrm{wt\%,\ o/o}) = \left(\frac{(1-F_o)\varepsilon\rho_o}{(1-\varepsilon)\rho_s F_o} - 1\right)\cdot 100\% \tag{4}$$

with

F_o	original oil content (wt%, d.b.)
ρ_o	oil density (kg/m^3)
ρ_s	solids density (kg/m^3)

By fitting Eq. (1) to the experimentally obtained U_c’s the filtration resistance (α), ratio of secondary consolidation to total consolidation (B) and creep constant (E/G) can be obtained. The yields can be related to the porosity according to Eq. (4). By fitting this equation to the experimental data the material constants (ε_0 and n) in Eq. (2) can be obtained. As is generally accepted in the field (Tiller and Yeh, 1987), filtration and porosity are functions of pressure as given in Eqs. (2) and (3). Density and viscosity of the oil are necessary inputs for the model and therefore these were measured as well.

3. Experimental procedure and equipment

3.1. Materials

Sesame seed and linseed were donated by Dipasa B.V. (Enschede, The Netherlands), rapeseed was donated by Noord Nederlandse Oliemolen B.V. (Delfzijl, The Netherlands), Jatropha by Diligent Energy Systems B.V. (Eindhoven, The Netherlands) and palm kernel from a local market in Tangerang, Indonesia. Unless stated otherwise, seeds used in the pressing experiments were dried overnight in an oven at 103 °C. Preliminary experiments showed that sample weight did not decrease anymore after this period.

3.2. Physical properties

3.2.1. Density and viscosity

Density of the oils was measured at 10 °C intervals between 20 and 90 °C with a density meter (DMA5000, Anton Paar, Graz, Austria). 1 ml samples were automatically inserted in the measuring cell with the help of the SHx/SCx sample changer. Samples were equilibrated to within 0.01 °C of the desired temperature. Measurement uncertainty was $1 \cdot 10^{-2}$ kg/m^3. Reported values are an average of three measurements.

Viscosity was measured at 10 °C intervals between 20 and 90 °C with an Ubbelodhe Capillary (No. II). This capillary had a capillary constant of 0.1004 mm^2/s ± 0.65% and is suited for kinematic viscosities between 10 and 100 mm^2/s. These measurements were also done in triplicate and the average is reported. Maximum deviation between consecutive measurements was less than 0.2 mm^2/s.

3.2.2. Moisture conditioning

For the pressing experiments at different moisture contents, batches of seeds were equilibrated with a constant humidity atmosphere in an exsiccator for at least a week. Constant humidity in the dissiccator was maintained by putting separate containers with saturated solutions of different salts in the dissiccator with the seeds. No temperature adjustment was done, since no influence of temperature was reported on moisture content of sesame seeds within 15–35 °C (Kaya and Kahyaoglu, 2006). Moisture content was determined according to Method B-I 4 of the German Standard Methods (DGF, 2002) by heating overnight at 103 °C.

For low moisture contents (below 2 wt%) the same procedure was used, but zeolite A4 was used instead of salt solutions. The zeolite was dried overnight at 200 °C before use.

3.3. Hydraulic pressing

A schematic representation of the hydraulic press used is shown in Fig. 1 and discussed in detail elsewhere (Venter et al., 2006). Seeds are placed on a sieve plate covered with fine wire mesh in a temperature controlled (30–100 ±1 °C) pressing chamber with a diameter of 30 mm. Pressures up to 100 MPa are exerted by a hydraulic plunger. The press is fitted with a thermocouple (±1 °C), pressure sensor and a position transducer (±0.01 mm), which measures the distance the plunger traveled. Measured values are automatically recorded every second.

In a typical experiment, 10 g of seeds was placed in the press-chamber, after which the piston was lowered on top of the seeds. The seeds were allowed to equilibrate to the pressing temperature for at least 30 min without mechanical pressure exerted on the seeds. After this, the mechanical pressure was raised up to 4 MPa for 10 s, providing a starting point for the compaction of the bed. Depending on the type of experiment, pressure was either increased in 2 s (to prevent pressure overshoot) to the desired value for the experiment or pressure was increased linearly at the desired speed until the final pressure was reached. For both types of experiment total pressing time was 10 min, except for the experiments to show the influence of pressing time.

3.4. Soxhlet analysis

Residual oil contents were determined by soxhlet extraction, based on method B-I 5 of the German standard methods. Whenever necessary, samples were dried overnight at 103 °C before

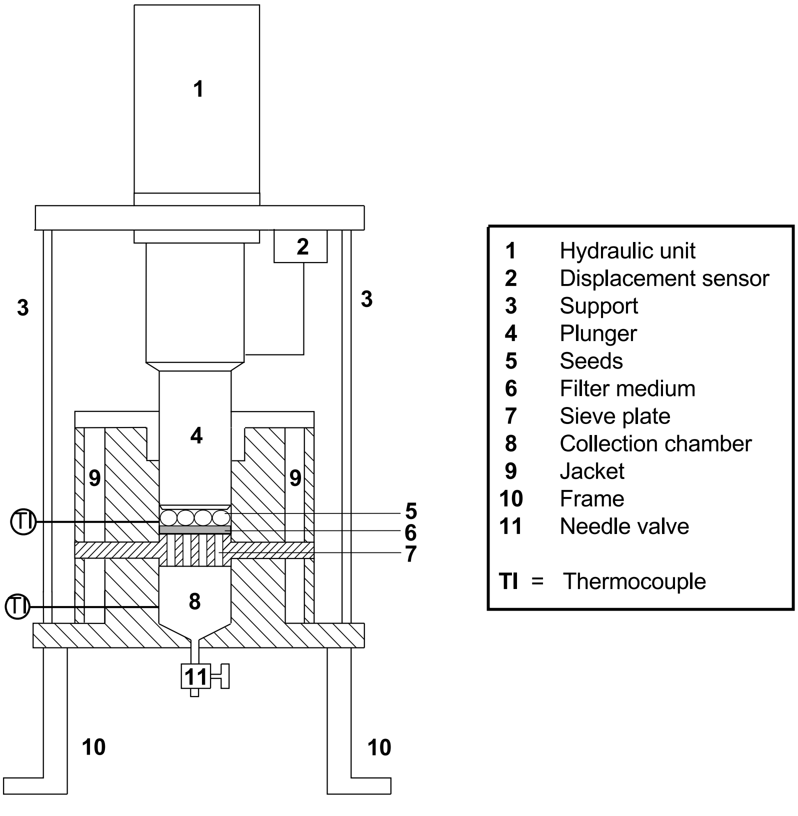

Fig. 1. Schematic representation of the hydraulic press (Venter, 2006).

analysis. For each analysis, approximately 5 g of sample was weighed with an accuracy of 0.0001 g. This was ground in a ball mill (Retsch, MM301, Haan, Germany) together with a small volume of petroleum benzene (boiling range 40–60 °C, VWR International B.V., Amsterdam, The Netherlands) for 20 s at 25 Hz. This was qualitatively transferred to a soxhlet thimble, covered with two wads of cotton wool and extracted with petroleum benzene for at least 4 h (sesame, linseed) or overnight (jatropha, rapeseed, palm kernel). After evaporation of the solvent, samples were put in an oven at 103 °C overnight or until constant weight. The residual oil content is reported as gram oil per gram sample on a dry basis.

3.5. *Data analysis*

Yields and compression ratios (U_c) were calculated for all experiments. Yield is defined as the oil recovered from the seeds as percentage of the amount originally present in the seeds. The compression ratio is defined in Eq. (1) and is used as an indication for the rate of pressing. It is defined as the ratio between cake thickness decrease at time *t* and the final cake thickness decrease.

3.6. *Repeatability – analysis and press*

In order to draw conclusions from the experiment, the repeatability of the experiments have to be tested. For the soxhlet extraction, the DGF-standard methods (DGF, 2002) report a repeatability for two analysis from one sample on the same day, by the same person to be within 0.4 wt% in oil content. For measurements on different days, this is reported to be within 1 wt%, which was confirmed by experiments.

To test the reproducibility of the complete procedure, duplicate experiments were done for sesame seed at 40 °C, with a linear increase in pressure of 0.1 MPa/s to 15 MPa and a total pressing time of 10 min. Yields were 40.7 and 40.3 wt%. Repeatability for cocoa was 1 wt% and therefore overall experimental error was taken as 1 wt% for all the seeds. This is shown as error bars in all yield related graphs. Error bars in the other graphs represent the standard deviation for at least five samples.

3.6.1. *Default press settings*

Several factors were identified to limit the experimental study by using standard parameters that were chosen for the majority of the experiments. First of all, it was shown previously that below a bed depth of 35 mm, the influence of press cake thickness on the oil yield was negligible for groundnut seeds (Hamzat and Clarke, 1993) and cocoa (Venter, 2006). Experiments were done with 5, 10 and 15 g of both sesame seed and jatropha to test the validity of this statement for other seeds under the conditions used in this work. These amounts resulted in a maximum bed depth at the end of the experiment of roughly 15 mm, well below the limit reported in literature. These experiments showed no influence of the amount of seeds on the oil yield. Therefore the amount of material was fixed at 10 g.

Secondly, it is reported in literature that the majority (>95%) of the oil is expressed in the first ten minutes of pressing (Ajibola et al., 1993; Venter, 2006). Again, a limited series of experiments was done for sesame to validate this in the present situation. Indeed for the first ten minutes yield increased with time and thereafter remained approximately constant. Therefore 10 min was taken as a representative time for the rest of the experiments.

Furthermore, since oil quality is reported to be higher at lower temperatures (Bailey et al., 1964), the major part of the experiments was done at 40 °C. Therefore, unless otherwise stated, all experiments were performed with approximately 10 g of seed at 40 °C with a pressing time of 10 min. Data for cocoa were taken from a previous study (Venter, 2006).

4. Results and discussion

4.1. *Physical properties*

4.1.1. *Density*

Density for sesame, linseed and rapeseed oil for temperatures ranging from 30 to 90 °C are given in Fig. 2. Densities are well within the boundaries given by Bailey et al. (1964), as are the slopes of density vs. temperature ($6.7 \cdot 10^{-4}$ g/cm^3/°C experimentally for all oils vs. $6.4 \cdot 10^{-4}$ g/cm^3/°C from Bailey). The slightly higher density of linseed oil compared to sesame and rapeseed can be explained by the fact that it has a high degree of unsaturation, which raises the density. Densities were fitted using the linear equation given in Eq. (5), for which the fit values are given in Table 2. Regression coefficients for all oils were 0.999 or better.

$$\rho = \rho_1 - \rho_0 \cdot T_1 \qquad (5)$$

with

ρ density (g/cm^3)
T temperature (°C)
ρ_0, ρ_1 fit parameters (g/cm^3/°C and g/cm^3)

4.1.2. *Viscosity*

The viscosity of all oils, as shown in Fig. 3, is in agreement with the values specified in Bailey et al. (1964). Viscosity can be described as a function of temperature by the modified Riedel equation, given in Eq. (6) (Green, 1999). Regression coefficients for all oils were 0.997 or better. The μ_1-values obtained for sesame seed and rapeseed are similar (25.8 and 26.0 kJ/mol), whereas for

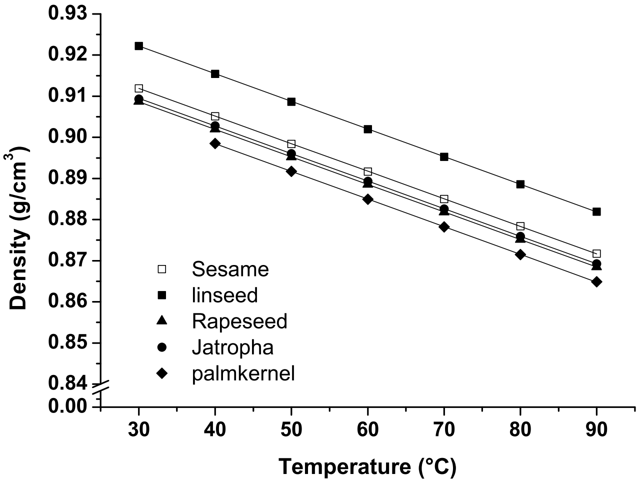

Fig. 2. Density of sesame, linseed, palm kernel, jatropha and rapeseed oil at different temperatures. Lines represent fits with Eq. (5) with values for parameters given in Table 2.

Table 2
Value of fit parameters in Eqs. (5) and (6)

Oil	ρ_0 (g/cm^3/°C)	ρ_1 (g/cm^3)	μ_0 (MPa s)	μ_1 (kJ/mol)
Sesame	$6.71 \cdot 10^{-4}$	1.115	1.55	25.8
Linseed	$6.73 \cdot 10^{-4}$	1.126	3.38	23.0
Rapeseed	$6.70 \cdot 10^{-4}$	1.112	1.40	26.0
Jatropha	$6.71 \cdot 10^{-4}$	1.113	1.56	25.7
Palm kernel	$6.73 \cdot 10^{-4}$	1.109	1.17	26.9

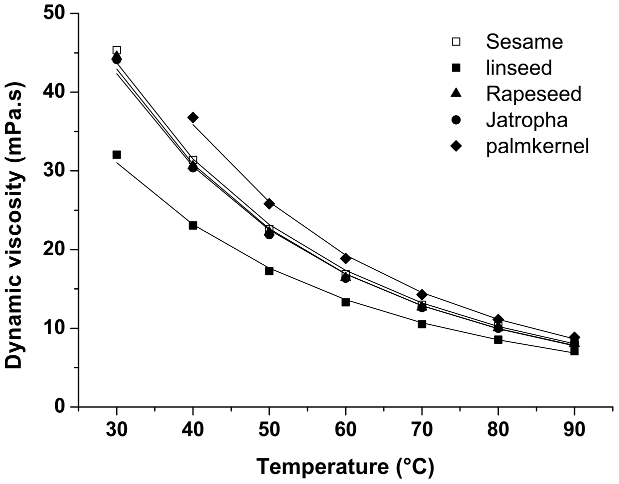

Fig. 3. Dynamic viscosity of sesame, linseed, palm kernel, jatropha and rapeseed-oils as function of temperature. Lines represent fits of Eq. (6) with values from Table 2.

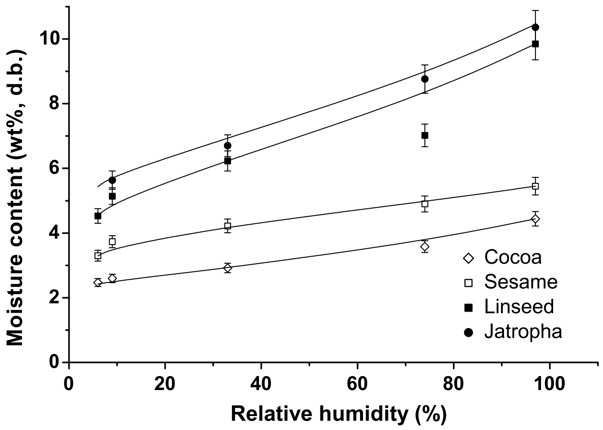

Fig. 4. Moisture content of sesame, linseed, cocoa and jatropha as function of relative humidity at room temperature. Lines present fit by Eq. (7).

linseed it is lower (23.0 kJ/mol). Agreement with literature values is excellent for rapeseed (lit: 26.3 kJ/mol (Coupland and McClements, 1997)) and linseed (lit: 26.1 kJ/mol (Arissen, 1996)) and for sesame (lit: 28.2 kJ/mol (Coupland and McClements, 1997)) it is reasonable. Again the notable difference between linseed and the other oils is explained by its high degree of unsaturation (Bailey et al., 1964)

$$\mu = \mu_0 \exp(-\mu_1/(RT)) \tag{6}$$

with

μ	dynamic viscosity (Pa s)
μ_0, μ_1	fit constants (Pa s and J/mol)
R	universal gas constant (J/(mol K))

4.1.3. Moisture sorption isotherms

The sorption isotherms of water for cocoa, sesame, linseed and jatropha are given in Fig. 4. As can be seen from the graph, the dehulled seeds (cocoa and sesame) have lower moisture contents than the seeds with hull. This suggests that moisture uptake in the hull is higher than in the kernel itself. To validate this, jatropha seeds were separated into hulls and kernels and these were dried separately. The measured moisture content of the kernel was 4.7 wt% (d.b.), whereas the hull contained 9.7 wt% (d.b.) moisture.

Table 3
Fit values for Eq. (7)

Seed	MC_0 (wt%)	B (1000/%)	C (–)
Sesame	3.96	2.9	250
Linseed	5.55	4.6	137
Jatropha	5.83	4.5	250
Cocoa	2.52	4.5	524

The moisture content of the original seeds was 6.6 wt% (d.b.) at a relative humidity of 33%. It can therefore be concluded that the majority of the moisture is located in the hull. The same was concluded by others for candle nut (Tarigan et al., 2006) and sesame (Kaya and Kahyaoglu, 2006).

The Guggenheim-Anderson-de Boer (Eq. (7)) model was fitted the sorption isotherms, parameter values for this fit are shown in Table 3. This model was used, because it generally describes the sorption of seeds very well (Tarigan et al., 2006). The higher monolayer factors (MC_0) for the hulled seeds clearly show the increased moisture uptake for linseed and jatropha.

$$\frac{M}{MC_0} = \frac{MC_1 \cdot MC_2 \cdot RH}{(1 - MC_1 \cdot RH) \cdot (1 - MC_1 \cdot RH + MC_1 \cdot MC_2 \cdot RH)} \tag{7}$$

with

MC	moisture content (wt%, d.b.)
RH	relative humidity (%)
MC_0, MC_1, MC_2	fit parameters (wt%, 1/% and –)

4.2. Influence of pressing factors

4.2.1. Influence of pressure: constant pressure

As can be seen in Fig. 5, the yield increased for all seeds with increasing mechanical pressure, approaching a limit at higher pressures. The low yield for rapeseed at 10 MPa is due to operation near the reported oil-point for this seed (8.5–9.1 MPa) (Faborode and Favier, 1996).

Furthermore, this figure shows that maximum yields are limited to 45–55 wt% for the hulled seeds (linseed, rapeseed and jatropha) and to about 70–75 wt% for the dehulled seeds (sesame and cocoa) in the pressure range investigated. It is assumed that this is caused by the fact that the hull does not contain significant amounts of oil (Wakelyn and Wan, 2004) and the fiber in the hull absorbs oil during the expression, thereby lowering the overall yield. To support this assumption, jatropha seeds were manually

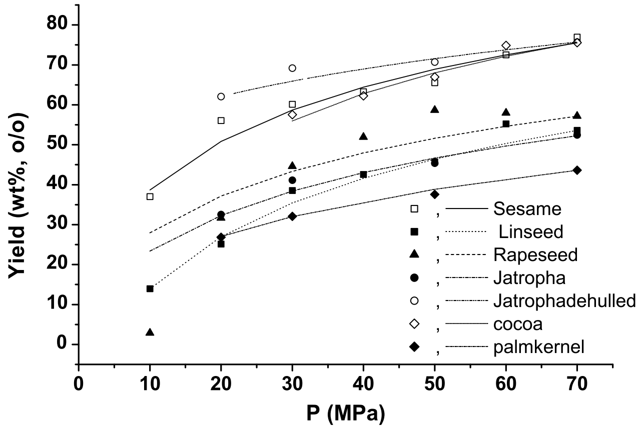

Fig. 5. Influence of constant pressure on yield for different seeds (T = 40 °C, time of pressing: 10 min, dry seeds), symbols are experimental, lines are fits with Eq. (2), sesame, linseed, rapeseed, jatropha, palm kernel and cocoa (Venter et al., 2007a).

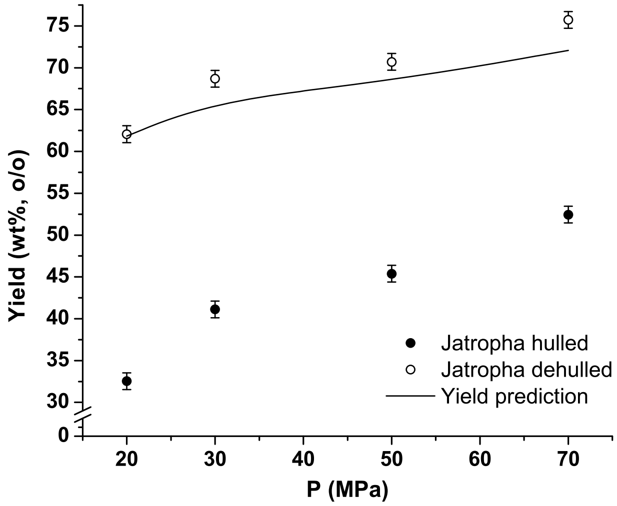

Fig. 6. Experimental yield and prediction for dehulled jatropha, hulled experimental, dehulled experimental and dehulled predicted.

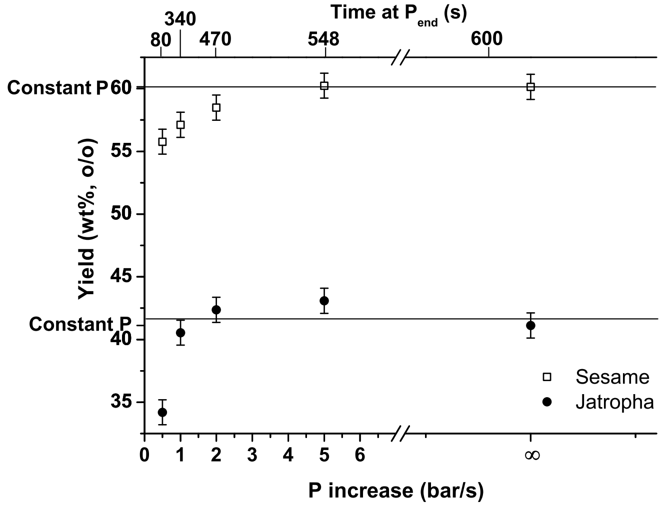

Fig. 7. Yields for sesame and jatropha for linear increase in pressure at different speeds (P_{end} = 30 MPa, T = 40°C, time of pressing: 10 min, 10 g of dry seeds).

dehulled and pressed under the same conditions as non-dehulled seeds. Mass fraction of hull was calculated (35.4 wt% d.b.) and the oil content of the hull was verified to be negligible by soxhlet extraction. Assuming that the press cake of non-dehulled jatropha has a uniform oil content, the amount of oil absorbed by the hulls can be calculated. Adding this amount to the determined yield for non-dehulled seeds should give a good correlation with experimental data for dehulled seeds. As is shown in Fig. 6, correspondence between the predicted and experimental yields is very good, supporting the assumption of oil absorption by the hulls.

The fits of porosity, shown as lines in Fig. 5, show that apart from the 10 MPa data, yields can be adequately described with Eq. (2). Values for the fit parameters are given in Table 4. The variation of porosity with pressure for the dehulled seeds is significantly higher than for the hulled seeds, reflecting the higher compressibility of the dehulled seeds.

4.2.2. Influence of pressure: pressure profile

In industry, the applied pressure profile is regarded as an important parameter in the expression of cocoa mass (Landelijke organisatie beroepsopleidingen agrarische sectoren, 1997). Fig. 7 shows the yields for sesame and jatropha for a linear increase in pressure at different rates. For all experiments, the total pressing time was 10 min and the final pressure was 30 MPa. Yields increase with increasing rates, but do not exceed the yield for constant pressure (infinite rate of pressure increase). Since a slower rate results in a shorter time the seeds experience the final pressure (given a constant pressing time), yields are lower at these rates. Since cocoa showed similar results (Venter, 2006), the influence of pressure profile was not investigated further.

4.2.3. Influence of temperature

Experiments were performed for all seeds at temperatures of 40, 80 and 100 °C and a constant mechanical pressure of 30 MPa. Yields for these experiments are shown in Fig. 8. As can be clearly seen from this graph, temperature only has a significant influence around 100 °C. Raising the temperature from 40 to 80 °C does not have a significant influence on the oil yield. Around 100 °C cooking takes place, which coagulates the protein and the oil globules (Bailey et al., 1964). These factors increase the yield. Temperature does have an influence on the rate of pressing for all seeds, linseed is shown as an example in Fig. 9. The influence of temperature can be caused by two effects: lowering of the viscosity of the oil or a change in the solid structure. As was previously shown (Venter et al., 2006), lowering the viscosity by dissolving of CO_2 at constant temperature resulted in the same displacement as a function of time as for the conventional experiments. It can therefore be concluded that the main factor of influence is the softening of the solids structure.

4.2.4. Influence of moisture content

Preliminary experiments were done to check whether moisture was lost during the pressing experiments, either by evaporation or by expression. The ratio between water and solid (W/S) was taken as indicator. These experiments showed that moisture loss during the experiments (including thermal equilibration) at 40 °C was negligible (W/S reduced from 0.1143 to 0.1123 (linseed)), whereas at 100 °C moisture loss was significant (W/S reduced from 0.0723 to 0.0576 (sesame)). Therefore it can be concluded that moisture is not removed by expression, but losses are due to evaporation.

Results for sesame and linseed at different moisture contents are given in Fig. 10. The experimental values for sesame show a slight increase in yield compared to dry seeds, from 60.2 to 62.3 wt% at a moisture content of 2.1 wt% d.b. It also showed that there is an optimum in the lower moisture content region as was reported earlier for cocoa and other seeds (Dedio and Dorrell, 1977; Singh et al., 2002; Venter, 2006).

Table 4
Value of fit parameters for constitutive Eqs. (2) and (3) for dry seeds at 40 °C P_a was taken as 10 MPa for each seed

	ε_0 (−)	n (−)	R^2	α_0 (10^{-10} m/kg)	β (−)	R^2	B_{avg} (−)	E/G (10^{-3}/s)
Sesame	0.57	0.25	0.96	0.37	1.36	0.98	0.11 ± 0.04	6–8
Linseed	0.56	0.19	0.97	0.28	1.55	0.99	0.12 ± 0.06	6–8
Rapeseed	0.54	0.16	0.92	1.04	1.05	0.95	0.36 ± 0.09	4–8
Cocoa(Venter et al., 2006)	0.67	0.36		1.84	2.28		0.11 ± 0.04	7
Jatropha	0.45	0.12	0.97	2.06	0.34	0.97	0.06 ± 0.02	6–12
Jatropha dehulled	0.32	0.09	0.94	6.8	0.48	0.63	0.64 ± 0.08	5–6
Palm kernel	0.39	0.08	0.99	1.24	1.0	0.83	0.16 ± 0.04	4–8

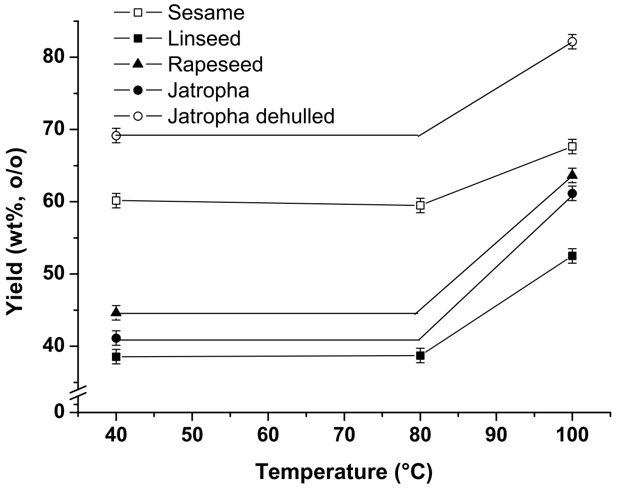

Fig. 8. Influence of temperature on oil yield for sesame, linseed, rapeseed, jatropha and jatropha dehulled ($P = 30$ MPa, time of pressing: 10 min, 10 g of dry seeds) Lines only serve as visual aid.

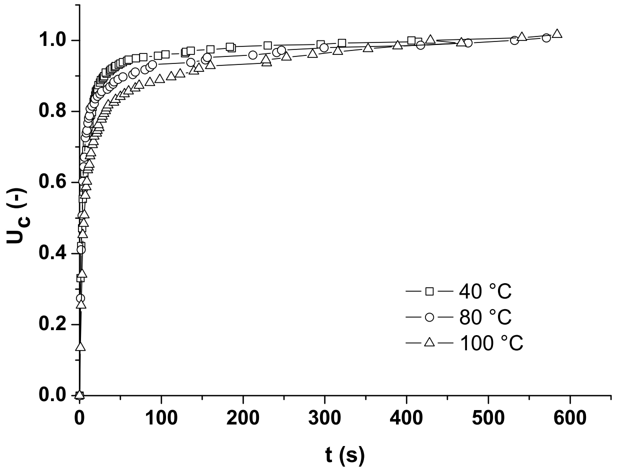

Fig. 9. U_c versus time for linseed at different temperatures: 40 °C, 80 °C and 100 °C (P=30 MPa, time of pressing: 10 min, 10 g of dry seeds).

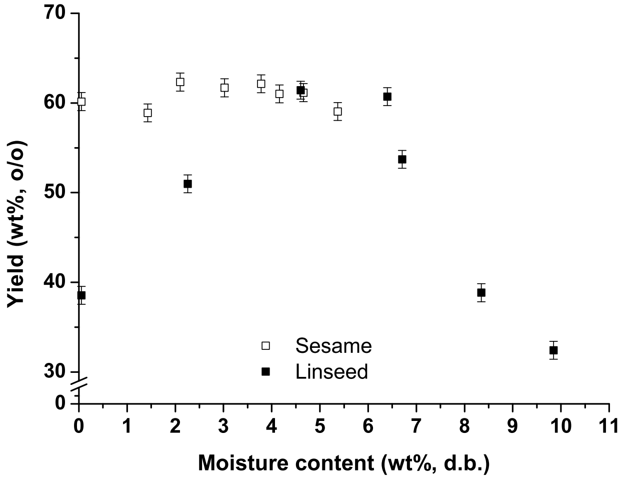

Fig. 10. Yield of sesame and linseed as function of moisture content ($P = 30$ MPa, $T = 40$ °C, time of pressing: 10 min).

The yields for linseed show a similar dependency on moisture content to the sesame seeds. However, the increase in yield of the optimum yield compared to dry seeds is a lot larger: 22 wt% for linseed versus 2 wt% for sesame.

4.3. Qualification of material properties

The Shirato solution (Eq. (1)) was fitted to the U_c-profiles for all seeds in the pressure range investigated by adjusting the α, B and E/G values. The values obtained for α were then correlated using Eq. (3). Results are given in Table 4. The Shirato model describes the U_c profiles for all seeds reasonably well, as can be seen from Fig. 11.

Cocoa has a filtration resistance that increases strongly with increasing pressure, represented by a high value of β. This hardening phenomenon is well known in industry. Dehulled jatropha forms a very dense cake at all pressures investigated, which results in the relatively high filtration resistance. All other seeds show relatively low filtration resistances compared to dehulled jatropha and cocoa. The low correlation coefficient for palm kernel and dehulled jatropha is caused by the low number of experiments in these series.

The similar values for B show that the contribution of secondary consolidation to the total process for sesame, linseed and cocoa is

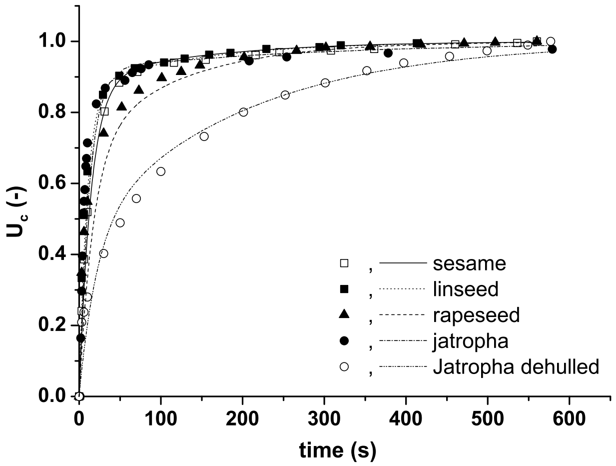

Fig. 11. U_c for different seeds: sesame, linseed, rapeseed, jatropha and dehulled jatropha ($P = 30$ MPa, $T = 40$ °C, 10 g of dry seeds).

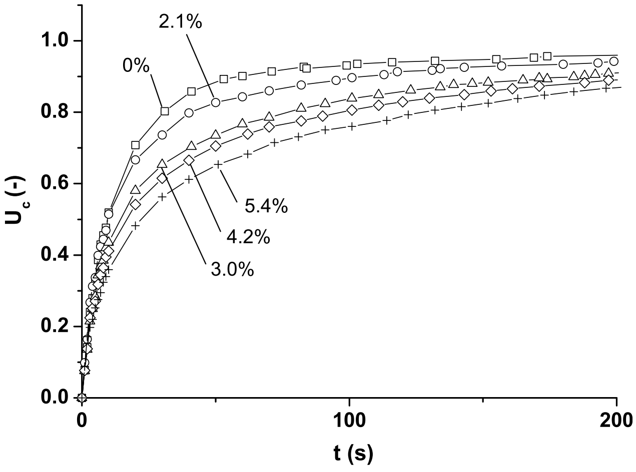

Fig. 12. U_c as function of time for sesame at different moisture contents. ($P = 30$ MPa, $T = 40$ °C).

similar and remains almost constant at different pressures, but for hulled jatropha it is smaller because of the hard and brittle hulls. Dehulled jatropha shows a large contribution of secondary consolidation, indicating very elastic solids. For rapeseed the results for secondary consolidation are inconsistent as can be seen from the larger error in the *B*-value.

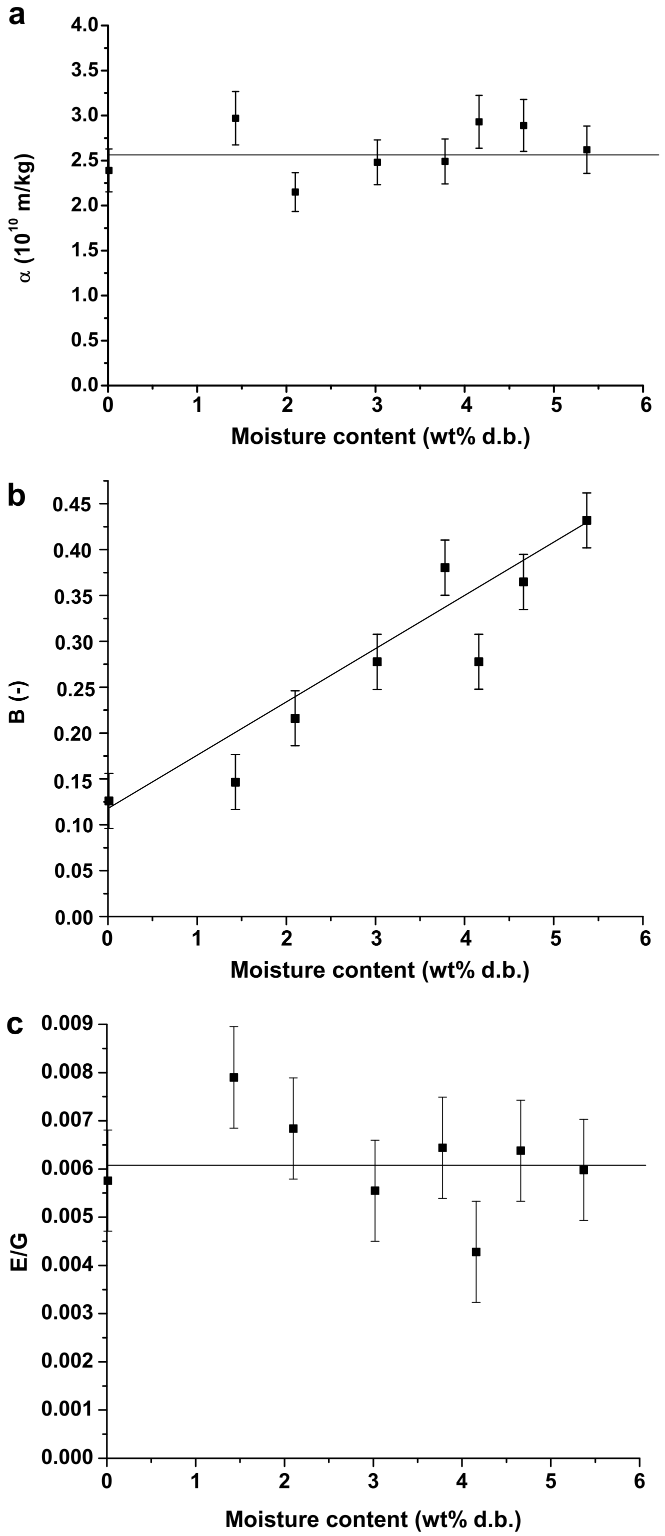

Fig. 13. Material properties of sesame as function of moisture content ($P = 30$ MPa, $T = 40$ °C): (a) specific filtration resistance, (b) contribution of secondary consolidation and (c) creep constant.

No clear distinction can be made between the *E*/*G*-values for the different seeds, especially considering that these values are obtained from a very small part of the U_c-graph.

The values for n are higher for dehulled seeds (sesame, cocoa and dehulled jatropha) than for the hulled seeds (linseed, rapeseed and jatropha). This shows a stronger dependency of the porosity on pressure for the dehulled seed. When using hulled seeds, the hulls carry part of the pressure, whereas for dehulled seeds, all the energy is used to express the oil.

4.3.1. Moisture content

As can be seen from Fig. 12 increasing the moisture content for sesame does slow down the rate of compaction at 30 MPa and 40 °C. This indicates that the material shows more creep by the addition of moisture. Fitting of the Shirato solution to the experimental U_c-graphs (material properties are shown in Fig. 13) nicely illustrates this effect by an increase in the relative contribution of secondary consolidation (*B*, Fig. 13b), whereas the filtration resistance (α, Fig. 13a) and the creep constant (*E*/*G*, Fig. 13c) remain close to the value for dry seeds. The same was observed for the experiments at 50 MPa, showing that pressure dependency of the filtration resistance (exponent β in Eq. (3) is not affected by a change in moisture content.

5. Conclusions

This works shows the influence of pressure (-profile), temperature, cake thickness and moisture content on the oil yields and rate of pressing for a variety of seeds as determined in a laboratory press. Increasing the pressure, using a temperature of 100 °C and using the optimum moisture content increased the yield obtained for all seeds. Applying a pressure profile or changing the amount of seeds did not influence the yield significantly. The yields obtained for hulled seeds (linseed, rapeseed and jatropha) were limited to 45–55 wt%, for dehulled seeds (sesame, cocoa and dehulled jatropha) the limit was around 70–75 wt%. This difference could be attributed to the absorption of oil by the fibers in the hulled seeds. It shows that dehulling is crucial when high yields are desired in conventional expression. This work also shows that using a press capable of higher pressures (>45 MPa) does improve the oil yield by up to 15 wt% (oil/oil) compared to conventional presses. The limited yields obtained with conventional expression clearly show a need for an improved process.

The Shirato model describes the expression process reasonably well for all seeds tested, except rapeseed and can be used in practical applications. The pressure dependent filtration resistance and porosity show good agreement with the classification into soft (high *n*, low filtration resistance) and hard (low *n*, mostly high filtration resistance) seeds. For dry seeds, the contribution of secondary consolidation ranged from 10% to 20% and *E*/*G*-values did not show a significant difference between the seeds. The contribution of secondary consolidation increased with an increase in moisture content in sesame seed and cocoa, consistent with a more viscoplastic material.

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