Mechanical behaviour of Arabica coffee (Coffea arabica) beans under loading compression

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Abstract. The uniformity of the product of the grinding process depends on various factors including the brittleness of the roasted coffee bean and it affects the extraction of soluble solids to obtain the coffee brew. Therefore, the reaching of a certain degree of brittleness is very important for the grinding to which coffee beans have to be subjected to before brewing. The aims of this study to show the mechanical behaviour of Arabica coffee beans from Tobasa (Indonesia) with roasted using different roasting time (40, 60 and 80 minutes at temperature 174 °C) under loading compression 225 kN. Universal compression testing machine was used with pressing vessel diameter 60 mm and compression speed 10 mm min\textsuperscript{-1} with different initial pressing height ranging from 20 to 60 mm. The results showed that significant correlation between roasting time and the brittleness.

1. Introduction
The importance of economical production of crops seeds such as coffee and cocoa beans as base materials of their technological processing are ever increasing. The behaviour of most crops seeds deviates essentially from that of the generally known elastic materials. Therefore, the mechanics of agricultural materials, as a scientific discipline, is still being developed at present, and in many cases has no exact methods as yet. However, the methods developed so far can already be utilized successfully for designing and optimizing machines and technological processes. By knowing mechanical behaviour of coffee in different types and condition can be increased on energy efficiency during processing.

A good quality cup of coffee is depended on many factors, such as the quality of green beans, the roasting conditions, the time since the beans are roasted, and the type of water used for brewing. The pleasant aromas released during the grinding of roasted coffee beans are as attractive as the aromas of fresh brewed coffee [2]. More than 800 volatile compounds have been identified in roasted coffee, whereof around 30 compounds are responsible for the main impression of coffee aroma [1, 3]. Coffee flavour is directly related to the volatiles compounds produced such as acids, alcohols, aldehydes, esters, furan, ketones, lactones, phenolic compounds and pyrazines. These compounds are responsible for the coffee aroma and also called key odorants [4]. The development of flavour compounds is influenced by temperature and time of roasting.
However, the uniformity of the product of the grinding process depends on various factors including the brittleness of the roasted coffee bean and it affects the extraction of soluble solids to obtain the coffee brew (Clo and Voilley, 1983; Clarke and Macrae, 1987). The changes in the textural and mechanical characteristics to which the coffee bean undergo during roasting play a relevant role in the quality of the roasted beans, these properties have been scarcely studied until now. The grinding of the coffee represents a loading process which is dynamic rather than static. It means the mechanical properties like crushing strength should be evaluated at the dynamic loading [7].

The knowledge of the strength and toughness of the coffee beans is necessary in order to evaluate brittleness of coffee beans. The reaching of a certain degree of brittleness is very important for the grinding to which coffee beans have to be subjected to before brewing. This study aims to describe mechanical behaviour of Arabica coffee from Tobasa (Indonesia) with roasted using different roasting time.

2. Materials and Methods
Arabica coffee beans were obtained from Tobasa, North Sumatera, Indonesia. The roasting process was conventional process at different time (40, 60 and 80 minutes) under temperature 174°C. The moisture content was determined using the procedure specified by [10]. The moisture content of beans for the compression test was determined by Equation (1) [11, 12]; where $M_c$ is the percentage moisture content on wet basis (% w.b.), $M_a$ is mass of coffee beans before heat-treatment (g) and $M_b$ is the mass of coffee beans after heat-treatment (g). A universal testing machine of type ZDM 50, Czech Republic together with a pressing vessel of diameter 60 mm with a plunger were used for recording the data points of force (N) and deformation (mm) of coffee beans of 20-60 mm measured pressing height [11]. A maximum force of 225 kN and speed of 10 mm/min were applied. The test was repeated three times. Minitab 16 statistical software (Minitab Inc, 2010) was used to analyse the statistical significance and correlation between parameters [13].

$$M_c = \left( \frac{M_a - M_b}{M_a} \right) \times 100 \quad (1)$$

The deformation energy and oil yield were numerically determined based on the equations proposed by the authors [14].

3. Results and discussion
Initial and roasting moisture content of coffee beans and energy deformation were determined (Tables 1 and 2). Increase roasting time with moisture content decreased (Table 1) while energy deformation increased (Table 2). Deformation energy of coffee beans was affected by roasting time and biological characteristics of coffee beans due to the changing slope of deformation (Fig. 1). The values of these mechanical characteristics are dependent on the loading orientation. The orientation used to leads to the maximum of the breaking force.

| Table 1. The values of moisture content of coffee beans |
|-------------------------------------------------------|
| $M_a$ (g) | $M_b$ (g) | $M_c$ (w.b, %) |
|-----------|-----------|----------------|
| Initial Moisture Content | 100 | 87.23±0.46 | 12.77±0.46 |
| $t_1$ = 40 min | 100 | 97.40±0.42 | 2.6±0.42 |
| $t_2$ = 60 min | 100 | 97.70±0.14 | 2.30±0.14 |
| $t_3$ = 80 min | 100 | 98.03±0.33 | 1.97±0.33 |
The dependence of the maximum of the loading (impact) force on the height $h$ enables to evaluate the force at which the bean is fractured. The values of this static loading breaking force (strength) are plotted in the Fig. 1.

![Graph showing mechanical behaviour of coffee at various height vessel press (H) with roasting time (t)](image)

**Fig 1.** Mechanical behaviour of coffee at various height vessel press (H) with roasting time (t)

One can see that the coffee beans resistivity against to fracture is higher at the dynamic (impact) loading. The experimental points can be fitted by a linear function with a relatively good correlation. The increase the strength at transition from static to dynamic loading is observed for many technical materials including metals and their alloys, polymers etc [7]. This increase can be explained in terms of material structure. It means the explanation of this phenomenon in coffee beans must be based on the detail study of the microstructure of this material.

**Table 2.** The values of deformation and energy at various vessel press height and roasting time

| Time (min) | H (mm) | Deformation (mm) | Energy (J) |
|-----------|--------|-----------------|------------|
| $t_1=40$  | 20     | 12.26           | 579.43     |
|           | 40     | 23.04           | 1007.87    |
|           | 60     | 31.22           | 1418.87    |
| $t_2=60$  | 20     | 10.98           | 541.16     |
|           | 40     | 21.98           | 1032.10    |
|           | 60     | 30.69           | 1477.33    |
| $t_3=80$  | 20     | 15.06           | 691.76     |
|           | 40     | 26.11           | 1169.99    |
|           | 60     | 34.36           | 1606.62    |

4. Conclusions

Increase roasting time with moisture content decreased while energy deformation increased. Deformation energy of coffee beans was affected by roasting time and biological characteristics of
coffee beans due to the changing slope of deformation. Correlation between roasting time and the brittleness was significantly

References
[1] Baggenstoss J, Poisson L, Kaegi R, Perren R. And Escher F 2008 Coffee Roasting and Aroma Formation: Application of Different Time temperature Conditions Journal of Agricultural and Food Chemistry 56 (14) 5836-46
[2] Baggenstoss J, Thomann D, Perren R and Escher F 2010 Aroma Recovery from Roasted Coffee by Wet Grinding Journal of Food Science 75 (9) 697-702
[3] Ku Madiah K Y, Zaibunnisa A H, Norashikin S, Rozita O and Misnawi J 2013 Optimization of roasting conditions for high-quality Arabica coffee International Food Research Journal 20 (4) 1623-27
[4] Brohan M, Huybrighs T, Wouters, C. and Bruggen, B. V. 2009. Influence of storage conditions on aroma compounds in coffee pads using static headspace GC-MS. Food Chemistry 116: 480-483.
[5] Akimaya M, Murakami K, Ohtani N, Iwatsuki K, Sotoyama K, Wada A, Tokuno K, Iwabuchi H and Tanaka K 2003 Analysis of Volatile Compounds Released during the Grinding of Roasted Coffee Beans Using Solid-Phase Microextraction J. Agric. Food Chem. 51 1961-69
[6] Caprioli G, Cortese M, Sagratini G and Vittori S 2015 The Influence of different types of preparation (espresso and brew) on coffee aroma and main bioactive constituents Int. J. Food Sci. Nutr. 1-9
[7] Nedomova S, Trnka J, Stoklasa P and Buchar J 2013 Strength of Coffee Beans Under Static and Dynamic Loading ACTA University Agriculturae et Silviculturiae Mendelianae Brunensis LXI (3) 743–49
[8] Uman E, Colonna-Dashwood M, Colonna-Dashwood L, Perger M, Klatt C, Leighton S, Miller B, Butler K T, Melot B C, Speirs R W and Hendon C H 2016 The Effect of Bean Origin and Temperature on Grinding Roasted Coffee Scientific Report 6 1-7 https://www.nature.com/articles/srep24483
[9] Waters D M, Moroni A V and Arentd 2015 Biocgemistry, Germination and Microflora Associated with Coffea Arabica and Coffea canephora Green Coffee Beans Food Science and Nutrition
[10] ISI 1966 Indian standard methods for analysis of oilseeds IS:3579 New Delhi Indian Stand. Ins.
[11] Sigalingging R, Herak D, Kabutey A, Dajbych O, Hrábe P and Mizera C Application of a tangent curve mathematical model for analysis of the mechanical behaviour of sunflower bulk seeds Int. Agrophys 29(4) 517–524.
[12] Kabutey A, Herák D, Chotěborský R, Sigalingging R, Mizera, Č 2015 Effect of compression speed on energy requirement and oil yield of Jatropha curcas L. bulk seeds under linear compression Biosystems Engineering 136 8–13
[13] Minitab Inc (2010): Minitab® 16 Statistical Software, State College, Pa.
[14] Herak D, Kabutey A, Sedlacke A and Gurdil G 2012 Mechanical behaviour of several layers of selected plant seeds under compression loading Res. in Agric. Eng. 58(1) 24-29