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Rheological properties of banana fruit in the creep test: Effect of variety and ripeness level

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Abstract: Banana quality is influenced by many factors, including variety and level of fruit ripeness. This quality can be evaluated from various points of view, one of which is the rheological consideration. Rheological properties are very important to study because they determine the design of equipment and processes, and minimise product damage. The aim of this research was to analyse and model the effect of variety and ripeness level on the rheological properties of banana fruit by applying a creep test. This research was carried out using a factorial experimental design 3 × 3 with 5 replications. Three varieties of banana, namely Ambon (*Musa parasidiaca* var. *sapientum* L. Kunt.), Raja (*Musa parasidiaca* L.), and Kepok (*Musa acuminata balbisiana* Colla) and each in three levels of ripeness, namely mature green, half ripe, and ripe. It was found that the parameters of the rheological properties of bananas changed according to the ripeness level ($P < 0.05$). The values of these rheological parameters decreased as the bananas ripened. Meanwhile, the variety and the interaction between variety and ripeness had no significant influence on the rheological parameters measured ($P > 0.05$). The constants of the four-element Burger model changed with the ripeness in all banana varieties. The Burger model with four elements could accurately predict the strain value of bananas tested in the creep test.

Keywords: Burger model; modulus elasticity; retardation time; strain; viscosity

Bananas are the most common and easiest fruit to find in almost every country in the world. Kumari et al. (2023) stated that the most easily available and affordable fruit in the world is the banana. High nutritional content, low price, and availability throughout the year make bananas very popular. As stated by several researchers that bananas are one of the most popular or common fruits in the world (Cho and Koseki 2021; Arunima et al. 2024). The average consumption of bananas globally is also quite high, reaching 12 kg per capita (Zaini et al. 2022).

Bananas grow well in tropical and subtropical countries around the world, where they are grown in more than 130 countries (Acevedo et al. 2021; Al-Dairi et al. 2023). The total production of bananas is very high, so that globally bananas are the fourth largest food after rice, wheat, and corn (Acevedo et al. 2021; Zaini et al. 2022). Although total banana production is already high, it still needs to be increased because banana consumption worldwide is reported continuously increased (Giuggioli et al. 2024). Global banana production reached 119 million tons, an increase of 10% from

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2010 to 2020 (Al-Dairi et al. 2023). This makes banana production rank second after oranges (Acevedo et al. 2021).

Bananas are included in the climacteric fruit group, namely a group of fruits that produce ethylene and experience an increase in respiration rate, which triggers the ripening process after being harvested (Khoozani et al. 2019; Cho and Koseki 2021; Maduwanthi and Marapana 2021). This causes bananas to deteriorate quickly because a large amount of their volume is lost during post-harvest (Vidigal et al. 2023). Bananas generally consist of a number of species in the genus *Musa* of the Musaceae family (Khoozani et al. 2019), and Indonesia is the third largest banana producing country in the world after India and China (Voora et al. 2023). There are various types of bananas in Indonesia. Three types of bananas that are very popular are Ambon bananas, Raja bananas, and Kepok bananas. These three types of bananas are generally served as fresh fruit and eaten or processed when they are ripe. To ensure that bananas are in accordance with consumer desires, maintaining the quality of bananas is very important (Arumina et al. 2024).

Banana quality can be evaluated based on physical, mechanical, physiological, chemical, and rheological parameters or a combination of these properties. Lately, physicochemical evaluation has become an important issue in relation to consumer acceptance levels (Sinanoglou et al. 2023). Therefore, at present, much research has been devoted to evaluating the quality of banana fruit and its derivative products based on physicochemical properties. To date, research related to evaluate the rheological properties of fresh agricultural products, including bananas, is still very rare. Rheology is defined as the science that studies the relationship between mechanical forces with deformation and flow in a material (Eissa et al. 2012; Martinez-Padilla 2024). If the result of the force exerted on a material results in deformation and flow, then the resulting mechanical properties are referred to as rheological properties.

Research dealing with the rheological properties of agricultural products is still limited due to difficulties in testing and analysing the parameters. However, rheological properties have very broad benefits for evaluating the quality of fresh agricultural products, especially related to the mechanical behaviour of the fresh product under loading. The use of rheological properties for evaluating the quality of agricultural products during storage has better results than measurements of physical property parameters (Eissa et al. 2012). Rheological assessment can be used to find the relationship between structure, texture, chemical composition, changes in product behaviour in various processes. These characteristics can be used as an index to assess product maturity, shelf life and processing conditions. Likewise, knowledge of rheological properties will be very helpful in optimising the design and construction of equipment or machines (Kamgar et al. 2017). A similar opinion is also expressed by several researchers (Singh and Patel 2014; Jahanbakhshi et al. 2020; Martínez-Padilla 2024).

Fresh agricultural products, such as fruits and vegetables are biological materials and are composed of solids and water. Such materials will have the properties of both solids and liquids simultaneously and are grouped as viscoelastic materials (Xu and Chen 2013). Viscoelastic materials will provide elastic and viscous responses to loading. During postharvest handling, bananas will go through several stages, such as cutting banana bunches from the tree, cleaning, transportation, ripening, cutting bunch combs, and serving. Various stages of these activities involve the use of mechanical force on bananas, which can cause damage to the fruit. Improper handling both during preharvest and postharvest will cause damage to agricultural products, which will result in losses (Yuri et al. 2019). Management to maintain fruit quality during distribution must begin with understanding activities from production to consumption that involve many mechanical operations. So that the factors that cause fruit damage can be identified, and the most appropriate handling technology can be selected (Zulkifli et al. 2020). The shelf life of fresh products can be extended when postharvest handling practices and appropriate treatment methods are applied. It is further stated that preserving quality and extending shelf life are the main objectives of postharvest technology, which are determined by proper handling, processing, storage, and transportation of harvested products (Strano et al. 2022). It is stated that the availability of fruits for consumption must be increased by reducing postharvest losses by improving the postharvest handling process (Chegere 2018). During postharvest activities,

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fruit can be damaged due to mechanical stress or heavy loads. This damage will result in decreased quality and increased losses (Jahanbakhshi et al. 2018). To avoid mechanical damage, various studies need to be conducted, including research on the characterisation of the rheological properties of fruit. Rheology will provide information related to the mechanical properties of fruit and provide a mathematical equation model that links mechanical loading with deformation or flow and time. This modelling will be very useful as information in improving postharvest handling processes that involve mechanical loading. Research related to the rheological properties of fresh fruit products is still very lacking. Therefore, globally, more rheological research is needed for fresh fruit products. In general, rheological modelling of agricultural products can be done in two ways, namely, creep test and stress-relaxation test. Briefly, a creep test is done by giving constant loading to the material being tested while measuring its deformation over time at constant pressure conditions. While a stress-relaxation test is done by giving a load to the material being tested at a certain value, then measuring the stress over time at a constant strain.

Creep test can provide more information than the stress-relaxation test, and data analysis can use the Burger model so that it is broader (Chakespari et al. 2010). It is further emphasised that creep testing under constant loading as a function of time can be used to estimate deformation that occurs in agricultural products, including vegetables, fruit, and others (Singh and Patel 2014). Creep test is a progressive increase in strain of a material that experiences a constant load over a long period of time (Fadiji et al. 2019). The creep test is widely applied in testing rheological properties of agricultural products. It has been applied for tomato fruit (Zheng et al. 2023; Apriyanditra et al. 2024), for cotton seed (Wei et al. 2024), for mango (Birch and Ekwue 2022), and for melon fruit (Xu and Chen 2013).

Mathematical models help describe a system, can be applied to develop and optimise many agricultural activities, and their use is growing rapidly (Ambaw et al. 2021). Mathematical models can also be used to predict the impact of various factors on the performance of many agricultural processes. Because developing mathematical models can be done at a very low cost compared to conducting research, this means that mathematical modelling will reduce research costs significantly. The rheological model of viscoelastic materials is generally based on mechanical models or spring and dashpot elements. The elastic properties of the material are represented by springs, while the viscous properties of the material are represented by dashpots (Moucka et al. 2023). If the two elements are arranged in series, it is known as the Maxwell model, and if they are arranged in parallel, it is the Kelvin model. This model can be developed further, where if one element of the Kelvin model is arranged in series with one Maxwell element, then the model is called the Burger model with four elements. Based on this arrangement, there are mathematical equations that describe each model. Equations (1) to (8) are the mathematical expressions for the Kelvin, Maxwell, and Burger models, respectively (Sahin and Sumnu 2006).

$$\varepsilon = \frac{\sigma_0}{E}\left(1-\exp\left(-\frac{t}{\lambda_{ret}}\right)\right) \tag{1}$$

$$\lambda_{ret} = \frac{\mu}{E} \tag{2}$$

$$\sigma = \sigma_0 \exp\left(-\frac{t}{\lambda_{rel}}\right) \tag{3}$$

$$\lambda_{rel} = \frac{E}{\mu} \tag{4}$$

$$\varepsilon = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}\left(1-\exp\left(-\frac{t}{\lambda_{ret}}\right)\right) + \frac{\sigma_0 \times t}{\mu_0} \tag{5}$$

$$\frac{\varepsilon}{\sigma_0} = \frac{1}{E_0} + \frac{1}{E_1}\left(1-\exp\left(-\frac{t}{\lambda_{ret}}\right)\right) + \frac{t}{\mu_0} \tag{6}$$

$$J = J_0 + J_1\left(1-\exp\left(-\frac{t}{\lambda_{ret}}\right)\right) + \frac{t}{\mu_0} \tag{7}$$

$$\mu_1 = \lambda_{ret} \times E_1 \tag{8}$$

where: ε – the strain at any time; σ_o – the initial stress (MPa); E – the elastic modulus (MPa); E_0 – the instantaneous elastic modulus of the Maxwell unit (MPa); E_1 – the elastic modulus of Kelvin-Voigt unit (MPa); t – the time (s); λ_{ret} – the retardation time (s); λ_{rel} – the relaxation time (s); μ – the viscosity of the unit (MPa·s); μ_0 – the residual viscosity of the Maxwell unit (MPa·s); μ_1 – the internal viscosity of Kelvin-Voigt unit (MPa·s); J – the retarded compliance ($\varepsilon \cdot \sigma_o^{-1}$); J_0 – the creep compliance ($1 \cdot E_0^{-1}$); J_1 – the instantaneous compliance ($1 \cdot E_1^{-1}$).

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The Burger model is widely used to interpret the rheological properties of various agricultural products (Chompoorat et al. 2018). This model is clearly better and has wider applications than the constituent models. Several researchers have used the Burger model in testing the rheological properties of agricultural products, including Birch and Ekwue (2022) for mangoes and Eissa et al. (2012) for pears. Through creep testing, data will be obtained in the form of loading stress (σ_0), strain (ε), and time (t). Based on these data, analysis can be carried out to obtain the values of the Burger model constants. Where from the plot between $\varepsilon \cdot \sigma_0^{-1}$ and t, the values of J_0 and E_0 can be obtained. From the straight portion of the curve, the relationship between $J_t - J_0$ and t can be plotted to get the values of J_1, μ_0, and E_1. Then, from the curved portion of the curve, the relationship between $\ln\{1 - (J_t - J_0)/J_1\}$ and t can be plotted to find the values of λ_{ret}, and μ_1. Then, the values obtained can be used to calculate the Burger constants of $\sigma_0 \cdot E_0^{-1}$, $\sigma_0 \cdot E_1^{-1}$, $\sigma_0 \cdot \mu_0^{-1}$ and λ_{ret}, and finally, the Burger model with four elements could be formulated.

Bananas are harvested in a mature green condition before they are fully ripe, then ripened to produce ripe bananas that are ready to eat. Banana skin will change colour from green to yellow when ripe (Kumari et al. 2023). The change from mature green to ripe yellow will be followed by various changes in the physical, mechanical, chemical, and rheological properties of the banana. Therefore, to comprehensively evaluate the rheological properties of the banana, rheological testing needs to be carried out on the banana from mature green, half-ripe, and ripe conditions. Likewise, each banana variety will have different conditions in terms of dimensions, hardness, skin thickness, skin colour, proportion of components, and so on, which will result in different changes during the ripening process. Therefore, the aim of this research was to analyse the influence of variety and ripeness level on the rheological properties of banana fruit in the creep test.

MATERIAL AND METHODS

Material. In this study, the samples were three banana varieties, namely Ambon, Raja, and Kepok bananas, each at three levels of ripeness, namely mature green, half ripe, and ripe (Figure 1). Banana samples were purchased from a banana trader in Yogyakarta, Indonesia. Only intact, fresh, unblemished, and disease-free bananas were used as research samples. Upon arrival at the laboratory, bananas were cleaned, then cut to a length of 3 cm for research samples. The banana skin was left attached to the sample or the skin was not peeled. This was done so as not to disturb the initial condition of the sample. The diameter of the banana samples was then measured using a digital calliper before being used in the creep test.

In general, the characteristics of banana samples at the three levels of ripeness are as follows. In the mature green condition, the banana skin was still green, the banana skin could not be peeled, the fruit flesh was still hard, and the banana could not be eaten. In the half-ripe condition, the banana skin was yellowish green, the banana skin could be peeled but was still difficult, the fruit flesh was softer, but the banana still could not be eaten because it was still hard and felt astringent. In the ripe condition, the banana skin would be yellow, the banana skin could be peeled easily, the flesh was soft, the banana was ready to be eaten, it tastes sweet and there was no more astringent taste.

Apparatus. The main equipment used in this study was the creep test apparatus (Figure 2). Basically, this apparatus consisted of several main parts: (1) main frame of the equipment, (2) slider

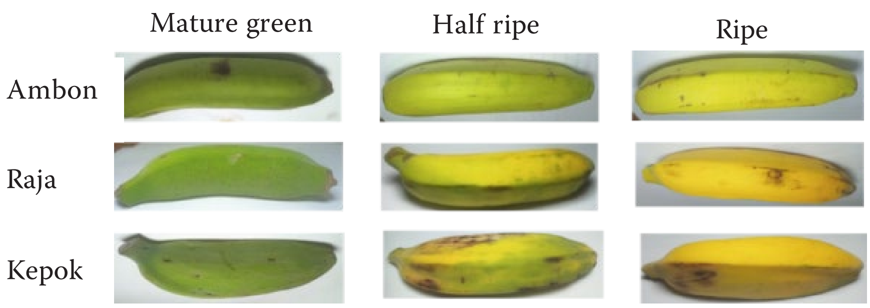

Figure 1. Photos of banana samples used in the research

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rod, (3) loading plate, (4) compression plate, (5) linear variable displacement transformer (LVDT, Model KTC-50L, MILLAY, China), (6) LVDT stand, (7) analog digital converter (ADC, Labjack U3-HV, Labjack Corporation, US), (8) computer, (9) flesh of banana sample, and (10) skin of banana sample. This creep test apparatus could provide constant loading to the tested sample so that deformation occurred in the sample. Loading was done manually while sample deformation was measured electronically and stored in a computer.

Procedures. The creep test apparatus was prepared so that the apparatus and other supporting equipment were ready to use. Before the creep test was carried out, the surface diameter of the banana samples was measured at four positions using a digital calliper. Then the banana sample was placed on the base of the creep test equipment. The pressure plate of the creep apparatus was lowered to touch the top surface of the sample, then a known load was placed on the loading plate manually. This sudden load would cause deformation of the banana sample. The value of deformation was measured by using the LVDT and then transferred to the computer through the ADC. In this study, a creep test was carried out with a constant load of 3.5 kg (34.3 N) for 10 min, and each variety and ripeness of banana sample was tested five times. Therefore, in this creep test, the increase of sample deformation during constant loading was measured as a function of time, the same as done by Zulkifli et al. (2020). In this study, three types of bananas were tested at three levels of ripeness, namely mature green, half-ripe, and ripe. To obtain banana samples in half-ripe and ripe conditions, banana samples were stored in open space conditions or at ambient temperature. This storage method was carried out to represent storage conditions that were generally carried out at the farmer level and local markets. When the bananas had reached half-ripe or fully ripe conditions, the creep test was carried out again with the same procedure.

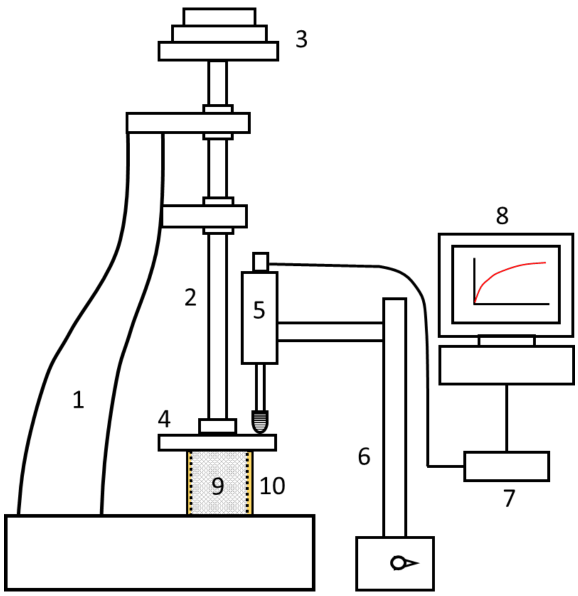

Figure 2. Schematic diagram of creep test apparatus used in the research

1 – main frame of the equipment; 2 – slider rod; 3 – loading plate; 4 – compression plate; 5 – linear variable displacement transformer (LVDT, Model KTC-50L); 6 – LVDT stand; 7 – analog digital converter (ADC, Labjack U3-HV); 8 – computer; 9 – flesh of banana sample; 10 – skin of banana sample

Data analysis. As mentioned above, based on the research data, the values E_0, μ_0, E_1, λ_{ret}, and μ_1 would be obtained for each variety and ripeness of banana samples. These data were then analysed statistically according to the research design, which was a repeated measures design with five replications. Further analysis for mean comparison was carried out using the Bonferroni test.

Meanwhile, from the resulting Burger model, it was then used to calculate the strain value as a function of time and compared with the strain value from the measurement results. To determine the goodness of fit of the Burger model obtained the accuracy was evaluated based on the values of the coefficient of determination (R^2), root means square error (RMSE), and percentage error (PE). The Burger model was said to be accurate if the R^2 value was close to one accompanied by low RMSE and PE values.

RESULTS AND DISCUSSION

The creep test results showed that the strain consistently increased with time for all banana varieties and ripeness levels (Figure 3). At the beginning of the creep test, the rate of increase in strain was quite large, then decreased with time. This pattern of increasing strain as function of time was a typical pattern that was generally obtained in creep testing of a material. Similar phenomena were also reported for tomato fruit (Apriyanditra et al. 2024); porcine skin and its gelatin-based sur-

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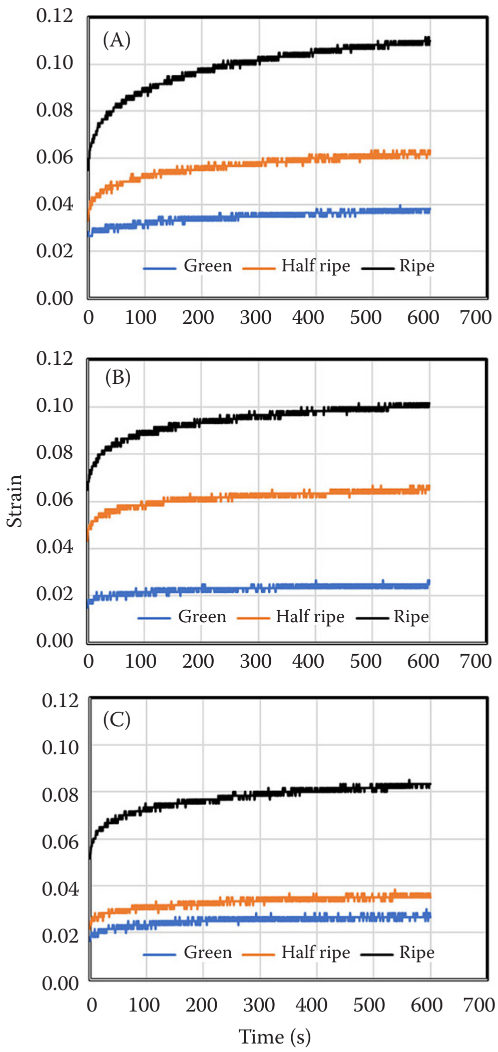

Figure 3. Observed strain curve as the function of time in creep test: (A) Ambon banana, (B) Raja banana, and (C) Kepok banana

rogates (Moucka et al. 2023), quinona (Polo-Muñoz et al. 2023), and date fruit (Kamgar et al. 2017). Creep test curve could be divided into three main parts, that were instantaneous elastic, retarded elastic, and Newtonian flow.

Based on the results of this creep test, the rheological properties of E_0, μ_0, E_1, $\boldsymbol{\lambda}_{ret}$, and μ_1 could be calculated and the results are shown in Table 1. Then, from these rheological properties, the constant values of the Burger model could be obtained.

It could be observed that E_0, μ_0, E_1, $\boldsymbol{\lambda}_{ret}$, and μ_1, which were the rheological properties of banana fruit, changed according to variety and ripeness level. In the same banana variety, the values of E_0, μ_0, E_1, $\boldsymbol{\lambda}_{ret}$, and μ_1 in the mature green condition consistently had the largest values, and the ripe banana had the smallest ones. In other words, the values of the rheological properties of bananas would decrease as the bananas ripen. This finding was in accordance with visual observations, that the riper the banana was, the smaller the mechanical strength of the banana would be. In the ripening process changes occurred in the cell walls involving various complex chemical processes such as depolymerization, solubilization, loss of sugar from pectin, this would weaken the cell walls and increased the separation of cells which finally weaken the texture of the cells and made the product texture soft (Posé et al. 2019). During ripening, the cell walls deteriorated, as well as a loss of water from the product, which would reduce turgor tension of the cells, resulting in texture changes and softening of the product (Farcuh and McPherson 2021). It was also observed that,

Table 1. Rheological properties of the investigated bananas

Variety	Ripeness	E_0 (MPa)	μ_0 (MPa.s)	E_1 (MPa)	λ_{ret} (s)	μ_1 (MPa.s)
Ambon	mature green	1.402[a]	6 666.667[a]	6.797[a]	44.173[a]	308.619[a]
	half ripe	0.969[b]	2 133.333[b]	2.923[b]	35.787[b]	104.475[b]
	ripe	0.554[c]	1 008.081[c]	0.947[c]	34.191[c]	32.404[c]
Raja	mature green	1.694[a]	9 000.000[a]	6.830[a]	39.147[a]	264.688[a]
	half ripe	0.787[b]	3 000.000[b]	2.659[b]	36.744[b]	98.682[b]
	ripe	0.505[c]	1 866.667[c]	1.500[c]	34.067[c]	50.678[c]
Kepok	mature green	1.610[a]	8 555.556[a]	7.107[a]	53.690[a]	394.247[a]
	half ripe	0.826[b]	3 233.333[b]	3.256[b]	36.296[b]	117.461[b]
	ripe	0.611[c]	1 852.381[c]	1.800[c]	34.125[c]	61.522[c]

E_0 – the instantaneous elastic modulus of the Maxwell unit (MPa); E_1 – the elastic modulus of Kelvin-Voigt unit (MPa); μ_0 – the residual viscosity of the Maxwell unit (MPa·s); μ_1 – the internal viscosity of Kelvin-Voigt unit (MPa·s); λ_{ret} – the retardation time (s); numbers in the same column followed by the same letter are not significantly different at $\alpha = 0.05$

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based on the analysis results, it was consistently obtained that the E_1 (elastic modulus of Kelvin-Voigt) value was greater than E_0 (instantaneous elastic modulus of the Maxwell). This indicates that bananas had a stronger tendency towards elastic behaviour than viscoelastic behaviour. Similar results were also reported by Ma et al. (2024) for corn straw particles; Soliman and El-Sayed (2017) for potato tubers; Mosiewicki et al. (2011) for wood flour composites; and Alvares et al. (1998) for potatoes. Likewise, the value of μ_0 (residual viscosity of the Maxwell) was consistently greater than μ_1 (internal viscosity of the Kelvin-Voigt). This condition indicated that bananas had a higher primary bond than secondary bond, or had a higher degree of mechanical strength or a tendency to resist permanent deformation under stress. Similar results were also reported by Dakogol et al. (2015) for lime fruit; Dzadz et al. (2015) for chicken meat frankfurters, and Dolz et al. (2008) for low oil content food emulsions. Further, the λ_{ret} (retardation time) value indicates the time required to achieve deformation of 63.21% of the total deformation in the creep test. Therefore, the stronger a material is, the greater the λ_{ret} value will be and vice versa. In this study, it was found that the λ_{ret} value ranged from 34–54 s and decreased with increasing ripeness of the banana. This showed that the riper the banana, the easier it was to deform, due to the softening of the banana tissue. The λ_{ret} value obtained in this study was in the range of λ_{ret} values generally reported in various other similar studies. Soliman and El-Sayed (2017) obtained a λ_{ret} of 621 ± 5 s for potato tuber; Melito et al. (2012) reported λ_{ret} ranging from 1.4–33.6 s for protein isolate/κ-carrageenan gels; and Chakespari et al. (2010) obtained λ_{ret} values of 12 and 15 s for Shafi Abadi and Golab Kohanz apple varieties, respectively.

Analysis of variance using repeated measures showed that ripeness level significantly affected all rheological property parameters which were expressed as E_0, μ_0, E_1, λ_{ret}, and μ_1 ($P < 0.05$). These differences in rheological properties would also be reflected by differences in other properties of a material. Several researchers also reported that ripeness level had a significant effect on the physical, mechanical or rheological properties of the material. It was reported that ripeness level had a significant effect on the penetration force of Nipah banana (Abidin et al. 2019); it also significantly affected colour, firmness, pH, and total soluble solid content of Berangan banana (Zulkifli et al. 2016). This meant that at the same level of banana maturity, the rheological parameters resulting from this research were valid for the three banana varieties tested, so that there was no need to consider differences in banana varieties in the application of these rheological properties in designing the processes and machine required. Meanwhile, variety and interactions between variety and ripeness were found to have no significant influence on the measured rheological parameters ($P > 0.05$). Several researchers also reported that variety had no significant effect on the mechanical or rheological properties of the material. It was reported that there was no significant difference for mostly the values of elasticity index of a mixture of wheat flour and eight varieties of sorghum flour (Rumler et al. 2024). Meanwhile, firmness, hardness and adhesion were not influenced by the variety of kiwi fruit (Vivek et al. 2019). This phenomenon indicated that the ripeness was more important to consider, because it had a real influence on the rheological characteristics of bananas compared to variety, as well as its interaction. This finding proved that for the three banana varieties tested, the characterisation of the rheological properties of bananas and the application of these rheological properties in the processes and machine designs had to take into account the ripeness level of bananas and didn't need to consider the differences in varieties. At the mature green condition, all tested banana varieties had the highest E_0, μ_0, E_1, λ_{ret}, and μ_1 values and were significantly different from all other evaluated ripeness levels. Meanwhile, at the ripe condition, all tested banana varieties had the lowest values of E_0, μ_0, E_1, λ_{ret}, and μ_1 than those in the mature green and half-ripe conditions. This illustrated that the three banana varieties had high rheological characteristics in the mature green condition and would decrease as the ripening process progressed.

Based on the rheological parameters obtained above, Burger model of four elements could be formulated as presented in Table 2. These models could be used to predict the strain values of the three bananas at the three levels of ripeness. From these models, it could be observed that the first term (σ_0/E_0), the second term (σ_0/E_1), and the third term (σ_0/μ_0) increased with the level of ripeness, while the value of λ_{ret} decreased for

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Tabel 2. The results of the Burger model for the three banana varieties along with R^2, RMSE, and PE values

Variety (ripeness)	Burger Model	R^2	RMSE	PE
Ambon (mature green)	$\varepsilon = 0.0235 + 0.005\left\{1 - \exp\left(-\frac{t}{44.173}\right) + 5.89x10^{-6}t\right\}$	0.94	0.0004	1.116
Ambon (half ripe)	$\varepsilon = 0.0384 + 0.0154\left\{1 - \exp\left(-\frac{t}{35.787}\right) + 1.77x10^{-5}t\right\}$	0.99	0.0008	1.049
Ambon (ripe)	$\varepsilon = 0.0576 + 0.0360\left\{1 - \exp\left(-\frac{t}{34.191}\right) + 3.29x10^{-5}t\right\}$	0.99	0.0016	1.176
Raja (mature green)	$\varepsilon = 0.0233 + 0.00568\left\{1 - \exp\left(-\frac{t}{39.147}\right) + 4.37x10^{-6}t\right\}$	0.99	0.0004	1.351
Raja (half ripe)	$\varepsilon = 0.0459 + 0.0131\left\{1 - \exp\left(-\frac{t}{36.744}\right) + 1.14x10^{-5}t\right\}$	0.99	0.0007	0.816
Raja (ripe)	$\varepsilon = 0.0682 + 0.0232\left\{1 - \exp\left(-\frac{t}{34.067}\right) + 1.85x10^{-5}t\right\}$	0.99	0.0010	0.823
Kepok (mature green)	$\varepsilon = 0.0186 + 0.004307\left\{1 - \exp\left(-\frac{t}{53.690}\right) + 4.43x10^{-6}t\right\}$	0.99	0.0005	1.560
Kepok (half ripe)	$\varepsilon = 0.0359 + 0.0084\left\{1 - \exp\left(-\frac{t}{36.296}\right) + 8.99x10^{-6}t\right\}$	0.99	0.0005	0.860
Kepok (ripe)	$\varepsilon = 0.0466 + 0.01644\left\{1 - \exp\left(-\frac{t}{34.125}\right) + 1.53x10^{-5}t\right\}$	0.99	0.0009	0.968

R^2 – coefficient of determination; RMSE – root mean square error; PE – percentage error; ε – the strain at any time; t – the time

all banana varieties in all ripeness levels. Increasing the values of σ_0/E_0, σ_0/E_1, and σ_0/μ_0 along with decreasing the value of λ_{ret} would result in an increase in the calculated strain value. This phenomenon showed that the predicted strain value of the banana would increase as the banana ripens. Likewise, the values of these constants were different for each variety and level of ripeness of banana, indicating that changes in the constant of the Burger model varied according to the variety and ripeness level.

Figure 4 shows validation by curve fitting between measured and predicted strain values for the three banana varieties at the three ripeness levels studied. The predicted strain was calculated using the mathematical equations of the Burger model, which were presented in Table 2. Clearly, it could be observed that the predicted strain could accurately follow the measured one. The accuracy of this prediction was strengthened by the high R^2 value and low RMSE and PE values. These results showed that the Burger model with four elements could accurately predict the strain value in the creep test. This finding was in accordance with the results reported for several other agricultural products, such as seed cotton (Wei et al. 2024), kiwi fruit (Xie et al. 2023), and St. Julian Mango (Birch and Ekuwue 2022).

CONCLUSION

Based on the results of this research, it could be concluded that the rheological properties of banana fruit, expressed as E_0, μ_0, E_1, λ_{ret}, and μ_1, changed according to ripeness level ($P < 0.05$). Rheological parameters of the evaluated banana decreased significantly as the banana became ripe. Meanwhile, varieties and interactions between varieties and maturity levels were found to have no significant influence on the measured rheological parameters ($P > 0.05$). The constants of the four-element Burger model, namely σ_0/E_0, σ_0/E_1, and σ_0/μ_0, increase, while the λ_{ret} value decreases with the ripeness level in all banana varieties.

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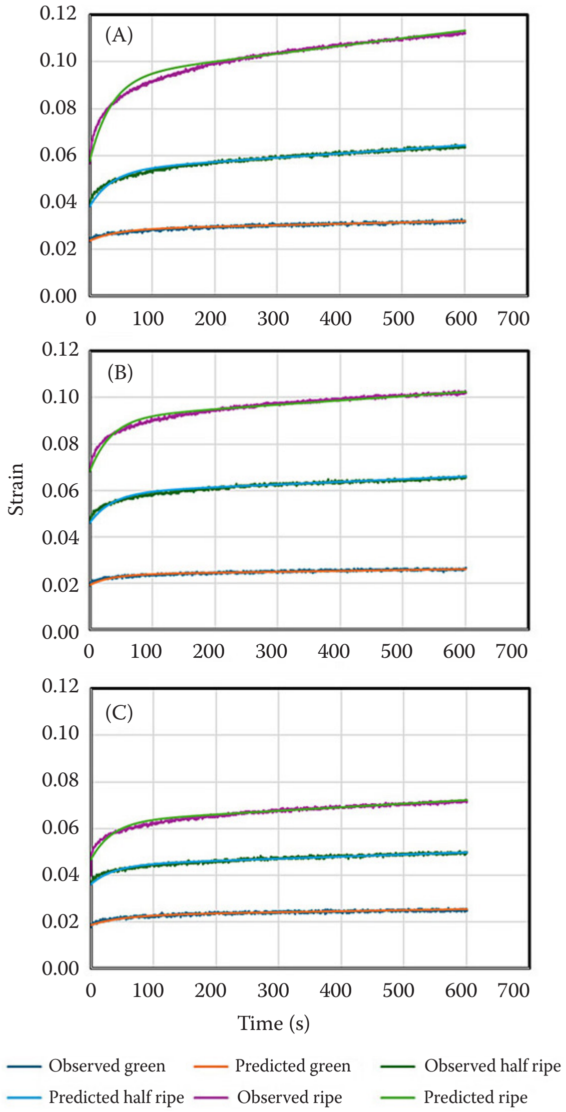

Figure 4. Strain comparison between measured and predicted values: (A) Ambon banana, (B) Raja banana, and (C) Kepok banana

The four-element Burger model could predict the strain values of the tested banana accurately.

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