Received: 24 August 2019 | Revised: 26 October 2019 | Accepted: 31 October 2019

DOI: 10.1111/jtxs.12496

RESEARCH ARTICLE

Journal of Texture Studies WILEY

Physical and viscoelastic properties of carrots during drying

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Funding information
National Science Foundation (NSF), Grant/Award Number: 1624812; Center for Advanced Research in Drying (CARD)

Abstract

It is essential to understand the physical and mechanical properties of a product since these properties affect the structure, texture, and ultimately consumer acceptance. The effect of drying conditions on dynamic viscoelastic properties, stress relaxation function and creep compliance, and physical properties, such as moisture distribution, color parameters, and shrinkage, was studied. An increase in drying temperature and duration resulted in a decrease in moisture content and volume, which were highly correlated (R = .988). Water evaporation followed the falling rate period, demonstrating that the water transport was limited by internal resistances. The decomposition of carotenoids led to a decrease in magnitude of color parameters (*L*, *a*, and *b*), between 30.1% and 51.6% with 4 hr drying. It was observed that the material shrinkage and moisture content highly affected the mechanical properties; increased stress relaxation modulus and decreased creep compliance values of the sample. The creep behavior, expressed with Burger's model ($R^2 \geq .986$), was highly dependent on moisture content. The linear viscoelastic region of carrots was found to be at strains lower than 3%. The three-element Maxwell model well fitted to describe the viscoelastic behavior of carrots ($R^2 \geq .999$, $RMSE \leq 2.08 \times 10^{-4}$). The storage moduli ($G'$) were higher than loss moduli (G''), indicating that samples presented solid-like behavior. The findings can be used to improve the textural attributes of carrots and carrot-based products.

KEYWORDS
carrots, color, creep behavior, drying, shrinkage, stress relaxation, textural properties

1 | INTRODUCTION

Carrots are widely cultivated for their high content of fibers and carotenoids, which are essential bioactive compounds in the human diet (Sharma, Karki, Thakur, & Attri, 2012). These high amounts of carotenes, especially β-carotene, make the carrots an excellent source of vitamin A (Karacabey, Turan, Ozcelik, Baltacioglu, & Kucukoner, 2016). They are also an excellent source for α-tocopherol; minerals like calcium, magnesium, and phosphate; and vitamins such as thiamine, riboflavin, C, B_6, and B_{12}. Some studies have reported that carotenes may help to prevent cancer, decrease cardiovascular diseases, lower cholesterol levels, improve antioxidant activity, and maintain body functions (Sharma et al., 2012; Xiao, Gao, Lin, & Yang, 2010).

Although carrots have rigid and firm structures, they are vulnerable to quality changes during shipping and storage due to high amount of water in their structure. Drying is one of the preferred methods to preserve the contents of carrots as it helps to minimize microbial activity; prevents biochemical, chemical, and physical deterioration; and decreases the costs of transportation, storage, and processing (Xiao et al., 2010). Advanced drying methods, including the combinations of different drying techniques, became popular to maintain the physical, chemical, and nutritional properties of foods. For example, Kumar, Joardder, Karim, Millar, and Amin (2014), developed intermittent microwave-convective drying (IMCD). Both experimental and modeling research of this group showed that intermittent heating

This article was published on AA publication on: 14 November 2019

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provides more uniform temperature distribution in the material (Joardder, Karim, & Kumar, 2013; Kumar, Joardder, et al., 2014). It was also shown that IMCD improves the preservation of nutrients in heat-sensitive food materials (Pham, Martens, Karim, & Joardder, 2018).

Although some advanced drying methods have gained importance in the food industry as detailed above, hot air drying, which includes simultaneous heat and mass transfer mechanisms such as diffusion, convection, and capillary flow (Ozturk & Takhar, 2019), is still very popular for drying of fruits and vegetables (Link, Tribuzi, & Laurindo, 2017). It is widely reported that most drying processes lead to significant changes in chemical, nutritional, and physical properties of food materials (Pham et al., 2019). Longer drying times and crust formation on the surface due to elevated temperature (Kumar & Karim, 2019) and nonuniform airflow distribution in the drying chamber (Welsh, Kumar, & Karim, 2017) are main drawbacks of hot air (conventional) drying. In addition to these, changes in color, loss and development of flavor compounds, severe damage to nutrients, low rehydration capacity, and textural problems due to shrinkage are examples of unwanted effects of the drying process (Kumar, Karim, & Joardder, 2014; Sette, Franceschinis, Schebor, & Salvatori, 2017; Zhou et al., 2016; Zielinska & Markowski, 2007). Also, shrinkage and pore evolution in carrots during drying processes should be considered to explain the effects of drying process on textural properties (Joardder, Kumar, & Karim, 2017; Mahiuddin, Khan, Kumar, Rahman, & Karim, 2018). Due to these undesirable changes during drying process, it is essential to investigate the effect of drying conditions on physical and mechanical properties of carrots.

The mechanical properties, specifically viscoelastic properties, of a product change significantly during drying process and these changes have significant impact on structural and textural attributes, which can be used to determine consumer acceptability. Therefore, it is crucial to understand the nature of changes in viscoelastic properties (Mahiuddin, Khan, Duc Pham, & Karim, 2018). Although there is information on chemical composition and dehydration kinetics of carrots in the literature, the information on viscoelastic properties for carrots is lacking because the existing studies on textural properties of carrots only investigated the effects of rehydration process, not the effects of drying itself. Also, all the measured attributes in these studies are for the final products at the end of drying process although the drying time is an important factor to obtain the optimum conditions. Besides, instead of investigating basic textural properties such as maximum stress or strain, strength, and hardness as done by other studies, we conducted much complex analyses on stress relaxation, creep behavior, and frequency dependency to depict a broader picture, which was not done previously. Sanjuan, Hernando, Lluch, and Mulet (2005), for example, investigated the effects of stepwise blanching on texture of carrots. They found that pectin methyl esterase could be activated and inactivated at different blanching temperatures, which would improve the textural properties. Marabi, Thieme, Jacobson, and Saguy (2006) carried out a sensory texture analysis on carrot particulates and reported the effect of rehydration time on overall acceptability of hot air-dried samples. Markowski and Zielinska (2013) showed that rehydrated carrots exhibited lower relaxation values than raw and blanched samples. However, as stated above, these studies have investigated only a few textural properties after rehydration process. Therefore, the first objective of this study was to investigate the changes in textural properties directly arising from drying with different measurements like stress relaxation, creep behavior, and frequency sweep. The second objective was to observe how the textural properties change during drying as a function of drying time, which would allow improving the quality of carrots-based products.

2 | MATERIALS AND METHODS

2.1 | Materials and drying procedure

Fresh carrots (*Daucus carota* L.) were obtained from a local supermarket and stored at 4°C. Sample preparation and drying procedure of Ozturk and Takhar (2019) was used with slight modifications. Carrots were cut into cylindrical-shaped samples with 18 mm diameter and 4 mm thickness for the drying process. Blanching, in hot water without chemicals, was performed at 70°C for 3 min. An environmental chamber (Associated Environmental Systems, Ayer, MA) providing an air flow of 5.15 m/s at 40% relative humidity was used for drying of carrots up to 9 hr. Three drying temperatures (50, 60, and 70°C) were selected to see the effect of drying temperature.

2.2 | Drying profile analysis

For rapid moisture measurement, a moisture analyzer (OHAUS MB35, Parsippany, NJ) was calibrated against a hot air convection oven based on AOAC Method No. 934.06 (AOAC, 1990) as described by Ozturk and Takhar (2019). Seven replications were performed for each condition. From the moisture data, drying rate was calculated using the following equation (Doymaz, 2015).

$$\text{Drying rate} = \frac{M_t - M_{t+\Delta t}}{\Delta t}, \quad (1)$$

where M_t (kg water/kg solid) is the moisture content at time t, $M_{t+\Delta t}$ (kg water/kg solid) is the moisture content of the sample at $t + \Delta t$, and Δt is the time difference between the measurements.

2.3 | Shrinkage

The volume of samples was measured by immersing the samples in toluene. Then, shrinkage during drying was calculated using the following equation (Zielinska & Markowski, 2007).

$$S = \frac{V_i - V_f}{V_i}, \quad (2)$$

where V_i and V_f are the initial and final volume of carrots, respectively. Eight replications were conducted for each condition.

2.4 | Color analysis

CIE L^*, a^*, and b^* color values on the surface of dried carrots were measured using a LabScan XE colorimeter (HunterLab, Reston, VA).

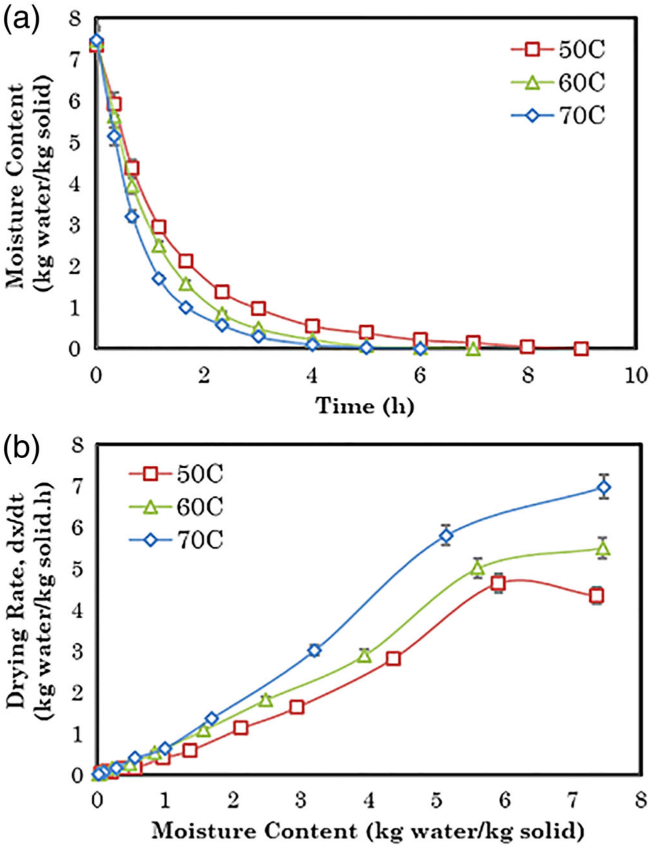

FIGURE 1 Moisture content (a) and drying rate (b) at different drying temperatures

For each drying condition, after calibration, L^* (lightness), a^* (greenness-redness), and b^* (blueness-yellowness) values were measured by averaging the values at four locations on the top and four locations on the bottom surfaces of carrots. Six replications were performed to obtain the averaged values of L^*, a^*, and b^* for each condition.

2.5 | Analyses on viscoelastic properties

Selected viscoelastic properties (creep behavior, stress relaxation, and frequency dependency) were measured using a dynamic mechanical analyzer (DMA) (Q800series, TA Instruments, New Castle, DE) as described by Ozturk and Takhar (2019) with slight modifications. All viscoelastic measurements were conducted at the same temperature with drying. For fitted models to creep and stress relaxation behavior, the model parameters were determined by nonlinear fitting in R (R Core Team, 2016).

2.5.1 | Stress relaxation measurements

The procedure of Ozturk and Takhar (2019) was followed for this analysis with a slight change on strain level, which was chosen as 3% after the determination of linear viscoelastic region (LVR) of carrots. The relaxation time to maintain the imposed strain was determined as 3 min based on preliminary experiments by observing the time needed for the decay of stress. Five replications were performed for each drying condition.

The generalized Maxwell model, can be written as follows (Ozturk & Takhar, 2017), was used to explain the stress relaxation data of carrots.

$$E(t) = E_0 + \sum_{i=1}^{N} E_i e^{-t/\lambda_i}, \tag{3}$$

TABLE 1 Moisture content, color parameters (L^*, a^*, and b^*), and shrinkage data of dried carrots at different temperatures

Drying temperature (°C)	Drying time (hr)	Moisture content (db)	Shrinkage	L^*	a^*	b^*
Raw	–	7.52 ± 0.15^{a}	–	43.95 ± 1.06^{a}	32.80 ± 0.76^{a}	38.33 ± 1.43^{a}
50	1	3.52 ± 0.08^{b}	0.48 ± 0.04^{g}	38.26 ± 0.81^{b}	30.41 ± 1.12^{b}	32.60 ± 1.39^{b}
	2	1.85 ± 0.05^{e}	0.59 ± 0.03^{e}	33.88 ± 1.74^{cd}	25.43 ± 0.98^{de}	24.89 ± 1.04^{d}
	3	1.07 ± 0.03^{fg}	0.66 ± 0.04^{d}	30.80 ± 1.45^{efg}	23.84 ± 1.48^{ef}	24.71 ± 1.01^{d}
	4	0.65 ± 0.03^{h}	0.73 ± 0.03^{bc}	28.07 ± 1.39^{hi}	22.92 ± 1.14^{fg}	23.68 ± 1.16^{d}
60	1	3.03 ± 0.07^{c}	0.52 ± 0.03^{fg}	37.27 ± 1.42^{b}	28.41 ± 1.02^{bc}	28.87 ± 1.54^{c}
	2	1.28 ± 0.04^{f}	0.66 ± 0.02^{d}	33.29 ± 1.23^{de}	23.69 ± 0.76^{ef}	24.74 ± 0.72^{d}
	3	0.55 ± 0.03^{hi}	0.72 ± 0.04^{bc}	29.86 ± 0.99^{fgh}	21.87 ± 0.37^{fg}	21.06 ± 0.69^{e}
	4	0.29 ± 0.02^{ij}	0.76 ± 0.03^{ab}	27.69 ± 1.59^{hi}	19.60 ± 0.62^{hi}	19.73 ± 1.09^{e}
70	1	2.22 ± 0.05^{d}	0.56 ± 0.04^{ef}	36.47 ± 1.12^{bc}	26.43 ± 0.96^{cd}	27.46 ± 1.59^{c}
	2	0.82 ± 0.03^{gh}	0.69 ± 0.03^{cd}	32.47 ± 1.59^{def}	23.18 ± 1.50^{f}	24.11 ± 1.93^{d}
	3	0.31 ± 0.02^{ij}	0.75 ± 0.03^{ab}	29.19 ± 1.21^{gh}	21.04 ± 1.61^{gh}	20.61 ± 1.43^{e}
	4	0.13 ± 0.02^{j}	0.80 ± 0.03^{a}	26.42 ± 1.62^{i}	18.42 ± 0.80^{i}	18.56 ± 1.25^{e}

Note: The means and standard errors of seven, eight, and six replicates for moisture content, shrinkage, and color parameters, respectively. Different letters in the same column represent significant difference ($p \le .05$).

where N denotes the number of Maxwell elements, t is the time, E_0 is the equilibrium stress or stress at the infinite time, E_i, and λ_i are the stress coefficient and the relaxation time of the ith element of the generalized Maxwell model, respectively. One-, two-, and three-element Maxwell models were investigated to obtain the best-fitting expression.

2.5.2 | Creep behavior

Similar to the procedure of Ozturk and Takhar (2019), the preload force and load were kept as 0.01 N and 0.003 MPa. However, soak time, creep time, and recovery time were determined as 0.5, 1.5, and 1.5 min, respectively, after preliminary tests since carrots reached to constant creep compliance values at a shorter time. Five replications were carried out for each drying condition. The creep data was expressed using Burger's model, which can be given by the following equation:

$$J(t) = J_0 + J_1\left(1-\exp\left(\frac{-t}{\lambda_{ret}}\right)\right) + \frac{t}{\mu_0}, \quad (4)$$

where $J(t)$ is the creep compliance value at a specific time, J_0 is the instantaneous compliance, J_1 is the compliance of Voight component, λ_{ret} is the retardation time, and μ_0 is the viscosity.

2.5.3 | Frequency sweep tests

The procedure of Ozturk and Takhar (2019) was followed for this analysis. Storage (G') and loss (G'') modulus values were reported as a function of frequency and temperature. The values reported represent averages of the six replications.

2.6 | Statistical analysis

Analysis of variance (ANOVA) was performed using MINITAB (Version 16, Minitab Inc.) to determine the significant differences between samples. In case of significant difference, Tukey single range test was applied for comparison.

3 | RESULTS AND DISCUSSION

3.1 | Drying profiles

Figure 1 presents the drying profiles of carrots at different temperatures. The initial moisture content of carrots was found to be 7.52 ± 0.15 kg water/kg solids. Owing to the facilitated heat absorption as a result of greater vapor pressure difference, the drying at higher

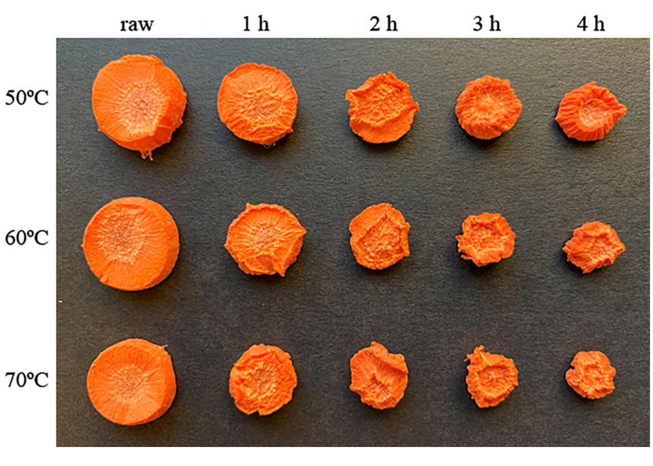

FIGURE 2 Images of carrots before and during the drying process at different conditions

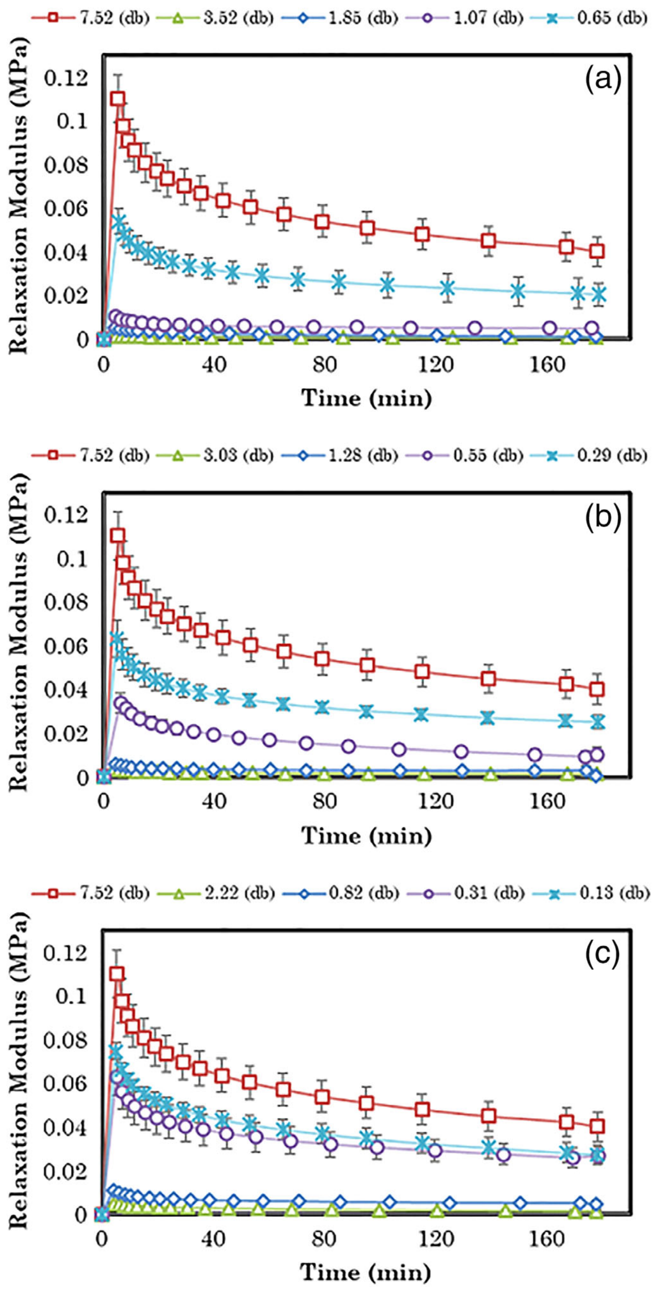

FIGURE 3 Stress relaxation data for raw and dried carrots: (a)—50°C, (b)—60°C, (c)—70°C. db represents moisture content on dry basis (kg water/kg solids)

temperature led to quicker decrease in moisture content (Figure 1a). Therefore, the required time to reduce the moisture content to 0.1 on dry basis decreased from 8 to 5 hr as the temperature increased from 50 to 70°C. As will be discussed in the next sections, the change in drying temperature and duration led to different viscoelastic characteristics in samples. The facilitated absorption effect of higher drying temperature can also be observed from the drying rate data presented in Figure 1b, which shows the drying rate increased as the drying temperature increased. This means heat and mass transfer was favored and the water removal was sped up. Except for a very short heat-up period at 50°C drying, drying happened in falling rate period for all drying temperatures. The sample was usually at a colder temperature than its ultimate temperature in the beginning of drying process. Therefore, this heat-up period was the one where first the product and water inside the structure were heated up, then free water at the surface of the sample was vaporized. Since the heat and mass transfer quickly happened at higher temperature, this heat-up period was not observed at 60 and 70°C contrary to 50°C. Also, similar to many other studies on carrots (Doymaz, 2004; Xiao et al., 2010; Zielinska & Markowski, 2007), the drying rate started to decrease quickly and constant rate drying period was not observed. The decrease in drying rate might be attributed to the rapid decrease of water content on the surface and the lack of enough moisture supply from inside to surface due to high internal resistance against moisture transfer, which can be a consequence of shrinkage and the decrease in porosity during drying process (Doymaz, 2015). Also, the layer formation on the surface of the samples due to case hardening might be a reason behind slower drying rate, which also affects the mechanical properties.

3.2 | Shrinkage

Shrinkage during drying is another valuable physical property, which can be linked to textural and quality attributes since it affects the structure and consequently water transport as discussed in previous section. Table 1 presents the shrinkage data of carrots at different drying temperatures and durations. A significant decrease was observed in the volume of samples at all conditions as can also be observed in Figure 2. The results showed that there were significant differences, in most cases, between samples considering both drying temperature and duration ($p < .05$). The high correlation coefficient ($R = .988$) confirmed that there was a strong linear relationship between the volume loss and the amount of water removed during the process, which is also in agreement with the findings of Aversa, Curcio, Calabro, and Iorio (2012) and Krokida and Maroulis (2001) on drying of carrots. Besides the volume change, shrinkage resulted in distortion in the shape (Figure 2) and increased the hardness of the sample (Goncalves, Pereira, Almeida, Freitas, & Waldman, 2017) as will be discussed in viscoelastic properties.

3.3 | Color parameters

Drying affects color parameters since this process leads to chemical changes such as browning reactions and the degradation of carotenoids (Zielinska & Markowski, 2012). Table 1 shows the changes in color parameters with moisture content at different drying temperatures. All color parameters decreased with the increase in drying time and consequent decrease in moisture content. The first 2 hr of drying had a significant impact on the decline in color parameters, around 25% for parameters L^* and a^*, and 35% for parameter b^*. However, this decreasing trend was slighter for drying after 2 hr, approximately 17–19% for parameter L^*, 10–20% for parameter a^*, and 5–25% for parameter b^*. On the other hand, the increase in drying temperature caused a further decrease in color parameters. The decreasing trends in lightness (L^*), greenness-redness (a^*), and blueness-yellowness (b^*) could be due to rapid decomposition of α- and β-carotenoids and the formation of brown pigments due to thermal destruction of these critical components (Doymaz, 2015). Aversa et al. (2012) and Rajkumar et al. (2017) indicated that water evaporation, shrinkage, oxidation of

TABLE 2 Estimated parameters of three-element generalized Maxwell model

Drying temperature (°C)	Drying time (hr)	E_1 (MPa)	λ_1 (s)	E_2 (MPa)	λ_2 (s)	E_3 (MPa)	λ_3 (s)	E_0 (MPa)	*RMSE*	R^2
Raw	–	0.04630	150.66	0.02959	16.74	0.14740	2.42	0.02648	2.08×10^{-4}	.9998
50	1	0.00029	93.79	0.00052	17.05	0.00040	2.05	0.00064	5.30×10^{-6}	.9993
	2	0.00543	95.67	0.00187	23.17	0.00279	2.98	0.00263	1.00×10^{-5}	.9999
	3	0.00218	157.60	0.00307	14.21	0.00676	3.09	0.00425	1.16×10^{-5}	.9999
	4	0.02224	194.09	0.01622	18.90	0.06429	2.67	0.01166	8.02×10^{-5}	.9999
60	1	0.00076	110.20	0.00105	25.49	0.00187	4.36	0.00124	2.51×10^{-6}	.9999
	2	0.00119	123.00	0.00170	16.65	0.00605	2.51	0.00253	2.72×10^{-5}	.9991
	3	0.01869	141.10	0.00708	23.88	0.01952	5.51	0.00399	3.96×10^{-5}	.9999
	4	0.02316	95.30	0.01965	11.41	0.11335	1.71	0.02162	6.69×10^{-5}	.9999
70	1	0.00245	130.30	0.00143	14.85	0.00287	2.46	0.00093	6.43×10^{-6}	.9999
	2	0.00292	180.30	0.00278	14.47	0.00905	2.99	0.00399	2.10×10^{-5}	.9998
	3	0.02257	111.71	0.01897	12.95	0.11019	1.99	0.02131	7.71×10^{-5}	.9999
	4	0.03062	97.21	0.02072	11.72	0.14125	1.84	0.02326	5.19×10^{-5}	.9999

ascorbic acid, caramelization, and condensation of hexoses and amino compounds resulted in changes in the composition of carrots, which affect color parameters. Doymaz's (2015) study on the effect of infrared power and Xiao et al.'s (2010) study on the effects of air velocity reported similar decreasing trends even though the values showed differences. However, Zielinska and Markowski (2012) did not observe any decreasing trend in parameter L^* contrary to our results. This might be attributed to the different dryer types used in these studies, as they used a spout-fluidized bed dryer and we used a hot air dryer. Aversa et al. (2012) observed an increase in L^*, a^*, and b^* at drying temperatures below 70°C and claimed that carotenoids were well preserved under the operating conditions they tested.

3.4 | Stress relaxation

The linear viscoelastic region of carrots was found to exist up to a strain level of 3% (R^2 = .873 at 3% strain). Figure 3 shows the stress relaxation modulus, $E(t)$, of carrots at different conditions. The relaxation curves showed a gradual decrease after reaching the desired strain level at all conditions, revealing that carrots showed viscoelastic behavior. The stress relaxation curves, except for the one for raw carrots, shifted upward as moisture content decreased, indicating relaxation modulus was highly dependent on moisture content similar to creep behavior. Fresh carrots exhibited the highest relaxation modulus values since they were hard and compact. However, relaxation modulus decreased to its lowest after 1 hr-drying since samples became soft and flexible at that time. Additional drying led to moisture loss and provided harder samples, and thereby resulted in an increase in relaxation modulus with time, which was also in agreement with the findings of Krokida, Kiranoudis, and Maroulis (1999). This can be attributed to the plasticization effect of moisture in food biopolymers. In addition to the plasticization effect of moisture, the glass transition might be another reason behind the significant jumps between the relaxation modulus values at the same drying temperature (Briffaz, Bohuon, Meot, Dornier, & Mestres, 2014; Singh, Cushman, & Maier, 2003), which also affects the textural properties since the structural conformation changes as a result of transformation of material from rubbery to glassy state. As can be seen in Figure 3a, a big jump or a shift was observed between the relaxation modulus values of the samples with 1.07 and 0.65 kg water/kg solid at 50°C drying. Similar jumps were also detected for 60°C drying from 1.28 to 0.55 kg water/kg solid (Figure 3b), and for 70°C drying from 0.82 to 0.31 kg water/kg solid (Figure 3c). The studies of Karmas, Buera, and Karel (1992), Georget, Smith, and Waldron (1999), and Sablani, Kasapis, and Rahman (2007) showed that the glass transition temperature of carrots increased from −5°C to 55–58°C when the moisture content was decreased from 88–89% to a lower level (around 3.5% on wet basis). Carbohydrates comprise the majority of the dry matter in carrots, and they set the primary characteristics of carrots. Therefore, it is consistent for dried carrots to have a glass transition temperature around 55–58°C, since the reported glass transition temperatures of some carbohydrates such as sucrose, glucose, and trehalose are between 30 and 100°C (Simperler et al., 2006). Since the drying temperatures used in this study were around the glass transition temperature, the transformation of the structure from rubbery to glassy state at low moisture content as a result of drying process might result in larger shifts in relaxation behavior (Ozturk & Takhar, 2018).

The one-, two-, and three-element Maxwell model equations were fitted into the stress-relaxation data using nonlinear fitting, and the best fit was determined according to high R^2 and low *RMSE* and BIC values. The results show that the three-element generalized Maxwell model fitted well to describe the viscoelastic behavior of carrots with its high R^2 (.9991–.9999) and low *RMSE* (0.025×10^{-4} to

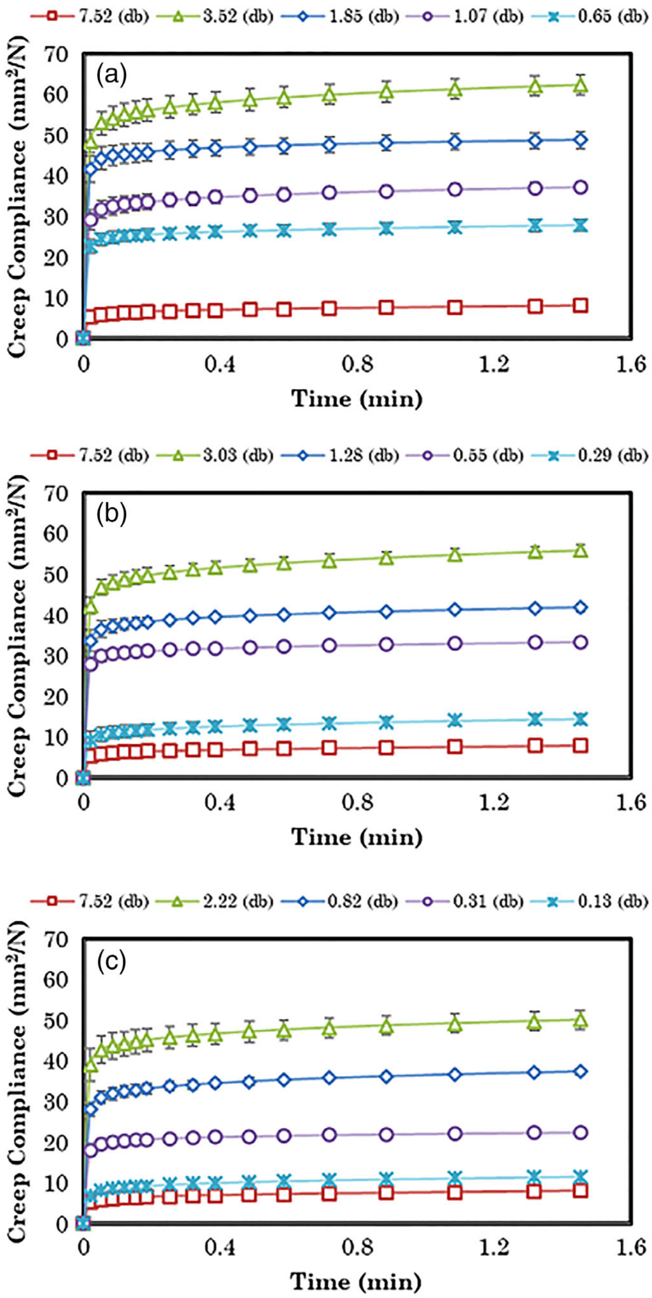

FIGURE 4 Creep data for raw and dried carrots: (a)—50°C, (b)—60°C, (c)—70°C. db represents moisture content on dry basis (kg water/kg solids)

TABLE 3 Estimated parameters of Burger's model

Drying temperature (°C)	Drying time (hr)	J_1 (µPa^{-1})	λ_{ret} (s)	μ_0 (Pa·s)	J_0 (µPa^{-1})	*RMSE*	R^2
Raw	–	6.267	0.693	45.125	0.00616	0.141	.993
50	1	54.808	0.571	10.026	0.01348	0.841	.996
	2	45.239	0.482	17.354	0.00247	0.428	.998
	3	32.868	0.570	21.469	0.00789	0.498	.996
	4	25.059	0.573	27.410	0.00281	0.284	.998
60	1	48.555	0.603	10.507	0.01690	0.768	.996
	2	37.655	0.545	18.176	0.00607	0.484	.997
	3	30.689	0.505	24.834	0.00247	0.310	.998
	4	11.362	0.750	27.888	0.01899	0.320	.990
70	1	44.137	0.570	12.915	0.01036	0.649	.997
	2	32.349	0.599	19.099	0.01191	0.568	.995
	3	20.324	0.553	28.068	0.00389	0.276	.997
	4	8.858	0.918	35.927	0.04030	0.309	.986

2.08×10^{-4}). In addition to these values, three-element model presented the lowest BIC values, showing that it was not overfitted to data. The coefficients of the three-element Maxwell model are shown in Table 2. The residual component of the model, E_0, presented an increasing trend as the moisture content decreased during drying. The components of the Maxwell model (E_1, E_2, and E_3 for three-element model) could be used to express either of elastic, viscous or viscoelastic properties of a sample. These values with relaxation time components represent the elasticity and resistability of samples to deformation due to mechanical forces. This is specifically important for food processors aiming at producing viscoelastic products. The results showed that these components exhibited similar decreasing trends with an exception, which was observed in the E_1 component of 2 and 3 hr dried samples at 50°C. Nevertheless, it could be concluded that the resistance of carrots against applied load increased during drying as the consequence of water removal. On the other hand, the relaxation time components (λ_1, λ_2, and λ_3) at the same drying temperature showed fluctuations as moisture content changed, and no trend was observed. However, since moisture loss results in higher viscosity, the samples with lower moisture content were expected to absorb the energy within their structure, causing longer relaxation time (Yildiz et al., 2013). Three relaxation mechanisms were observed from the relaxation time data: one at a longer period (λ_1 = 93.79–194.09 s), one at a medium period (λ_2=11.72–25.49 s), and one at a shorter period (λ_3 = 1.84–5.51 s). The calculation of Deborah number ($D_b = \lambda/t_0$, t_0 is the experiment duration) showed that the first relaxation time (λ_1) presented a viscoelastic response since it was close to one ($D_b \approx 1$) while the second (λ_2) and the third (λ_3) reflected viscous behavior since they were far from one ($D_b \ll 1$).

3.5 | Creep behavior

Figure 4 shows the creep compliance curves of carrots at different drying temperatures and durations. The beginning part of all creep curves presented an instantaneous increase, representing elastic and retarded elastic deformation. Afterwards, the creep compliance values increased in a time-dependent behavior at the region just before the curves reached a plateau due to the effect of retardation time. This part of the curves was responsible for the viscoelastic behavior of carrots (Ditudompo, Takhar, Ganjyal, & Hanna, 2013). Then, a constant region (the plateau) was observed for all drying time and temperature combinations, indicating viscous deformation of carrots. The compression in this region resulted in permanent damage by destructing the internal structure of the samples (Sandhu & Takhar, 2015). The creep compliance of raw carrots was the lowest since the samples were hard, firm, and compact before drying. However, although the dried samples had lower moisture content than the raw samples, they became soft, spongy, and flexible after 1 hr-drying as a result of the destruction of the structure. Thus, creep compliance of 1 hr-dried samples was the highest. Additional drying made samples hard and compact again due to the high loss of moisture from the structure, and creep compliance decreased with time. These results show that creep behavior of carrots was highly dependent on the moisture content. Drying temperature also affected the creep compliance values of carrots. At the same drying time, the samples dried at a higher drying temperature presented lower compliance values since the higher temperature caused higher moisture evaporation.

The experimental data from creep curves were fitted into Burger's model using the nonlinear fitting. The result shows that Burger's model provided a good representation of creep compliance data of dried carrots with its high R^2 (.986–.998) and low *RMSE* (0.141–0.841). The estimated parameters of the model, representing the effects of moisture content and temperature, are presented in Table 3. J_1 decreased as temperature or drying time was increased, indicating lesser deformation and stiffer samples. Although there were fluctuations in retardation time (λ_{ret}) of other samples, the samples dried for 4 hr and the raw samples presented higher retardation time, which shows that the viscoelastic behavior of these samples was

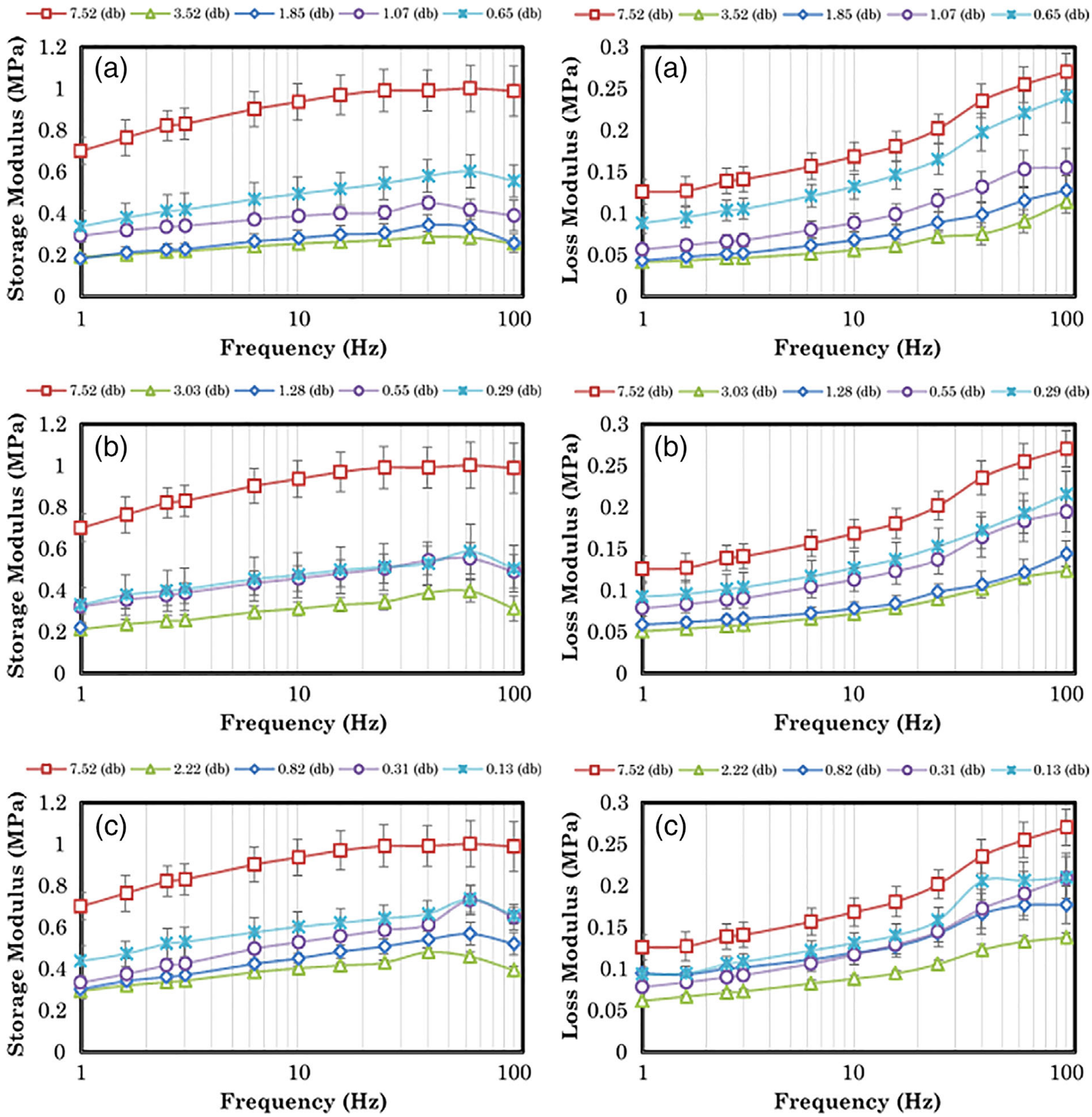

FIGURE 5 Storage and loss moduli of raw and dried carrots: (a)—50°C, (b)—60°C, (c)—70°C. db represents moisture content on dry basis (kg water/kg solids)

retained for longer periods. The viscosity (μ_0) of samples got higher as drying temperature and duration was increased, meaning viscous structure as drying progressed.

3.6 | Frequency sweep

The storage (G') and loss (G'') moduli of raw and dried carrots at different drying conditions are exhibited in Figure 5 as a function of oscillation frequency. Both G' and G'' moduli values increased with the increase in frequency. However, their respective frequency dependence curves differed from one another although they presented curves with similar shapes. Similar findings were reported by Ditudompo et al. (2013), Ozturk and Takhar (2019), and Li, Li, Wang, Ozkan, and Mao (2010) on cornstarch, strawberries, and potatoes, respectively. The increase in G' at high frequencies can be attributed to storage of more deformation energy within the structure. Inversely, when frequency decreased, more energy was released from the system due to friction between molecules. Ditudompo et al. (2013) indicated the materials present glass-like properties at high frequencies when the temperature and moisture are low. In comparison, rubber-like behavior is observed for the materials with high moisture and temperature at low frequencies.

The loss tangent values (G''/G'), for all samples, were lower than 1, meaning both raw and dried carrots showed a solid-like behavior.

However, the loss moduli values continuously increased while the storage moduli values reached a stationary phase at high frequencies. This result indicates that the viscous properties of samples became stronger with increasing frequency. However, the increase in viscous properties was never high enough to overcome the elastic properties within the experimental frequency range. The effects of drying temperature and duration were also investigated. The results showed similarities with the findings of creep behavior and stress relaxation. At the same drying temperature, raw carrots had the highest moduli values, followed by the samples dried for 4, 3, 2, and 1 hr, respectively. On the other hand, the change in temperature was not as effective on moduli values and the samples presented similar values at different temperatures.

4 | CONCLUSIONS

This study investigated the effects of various drying conditions on the physical and mechanical properties of carrots. Drying occurred in the falling rate period, showing that internal resistance limited water transport in the carrots' matrix during the process, probably due to shrinkage effect. Color parameters ($L*$, $a*$, and $b*$) showed decreasing trends with increasing drying temperature and duration, especially the first 2 hr of drying were found to be more effective on color. Drying caused a significant shrinkage in carrots and it was found that there was a strong correlation (R = .988) between water evaporation and shrinkage during drying. The structural deformation and the loss of stiffness due to drying led to shifts in creep compliance and relaxation moduli curves, indicating both creep and relaxation behavior were highly dependent on moisture content and shrinkage. The storage moduli (G') values were higher than the loss moduli (G'') values for all samples, indicating solid-like behavior. The findings of this research can be used to improve the textural attributes of carrots and carrot-based products. The results also can be utilized in mathematical models describing drying processes to improve the processing conditions and to obtain better quality attributes.

ACKNOWLEDGMENT

This work was funded by Center for Advanced Research in Drying (CARD) and National Science Foundation (NSF) under the award number 1624812. The authors wish to thank them for providing financial support.

AUTHOR CONTRIBUTIONS

P.S.T. conceived the overall project and provided guidance to O.K.O. in conducting the experiments. Both authors discussed the data analysis. Both authors planned the manuscript layout and collaborated in writing and editing of the manuscript.

ETHICAL STATEMENTS

Conflict of Interest: The authors declare that they do not have any conflict of interest.

Ethical Review: This study did not involve any human or animal testing.

Informed Consent: The study did not involve any other participants, subjects, or sensory panels, and thus written informed consent is not applicable.

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How to cite this article: Ozturk OK, Takhar PS. Physical and viscoelastic properties of carrots during drying. *J Texture Stud*. 2020;51:532–541. https://doi.org/10.1111/jtxs.12496