อิทธิพลขององค์ประกอบที่มีต่อสมบัติเชิงความร้อนและโอกาสของปรากฏการณ์การเกาะตัวกันเป็นก้อนของผลิตภัณฑ์นมผง

Compositional Effect on Thermal Properties and Opportunities of Milk Powder Stickiness Phenomena

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ABSTRACT

Stickiness in the production of food powders can cause low yield, operational problems of equipment, powder-handling problems and fire hazards. It may result from the appearance of attractive forces between particles including static electricity. Stickiness in food systems often appears when the surface viscosity of amorphous particle components decreases and particles adhere. Increasing adhesion forces between particles causing stickiness and caking depends on the material properties, storage and processing conditions. Stickiness is a serious problem in spray drying of sugar-rich and fat-rich products, such as milk and juice. Solids composition affects structure formation and changes of foods during processing and storage. Powders containing high sugar contents show high adhesion of powder particles with increasing temperatures and water contents as a result of surface plasticization and the formation of liquid bridges. The stickiness of milk powders resulted from liquid flow of amorphous non-fat solids components, such as lactose and other hydrophilic components. They are plasticized by water, which is one of the dominant factors that control glass transition of amorphous solids. Glass transition is relation to stickiness and the SPT at 20 °C above the T_g. Increasing molecular mobility of molecules occurs above glass transition with concomitant appearance of viscous liquid-like characteristics, which are relative to the development of stickiness in amorphous particles. Although several researchers have indicated the relationships of stickiness and glass transition, the relaxation times and molecular mobility still remain as challenging areas in the glass transition research. Increased molecular mobility is related to decreased relaxation times and a lower viscosity above the glass transition. Changes in solid structure around the glass transition of amorphous systems can be measured from molecular motions using various techniques, such as dielectric analysis (DEA) and dynamic-mechanical analysis (DMA). The primary α-relaxation appears in measurements of dielectric and mechanical properties since the molecules gain translational mobility and long-range molecular motions around the glass transition. However, the stickiness behavior and molecular mobility of milk solids systems with different solids compositions (carbohydrate-carbohydrate and carbohydrate-protein) has not been either well addressed. Therefore, the present review emphasized the solids compositional effect on relaxations and molecular mobility around the glass transition in relation to stickiness behavior.

Key words: glass transition, relaxation, stickiness, molecular mobility, solid composition

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1. Stickiness and Caking of Powders

Stickiness and caking are phenomena that often occur during production and storage of dried powders. Stickiness and caking phenomena occur in amorphous foods, which are heated or exposed to high humidities. The difference between stickiness and caking is not always clearly defined, but it may be assumed that stickiness refers to the tendency of a material to adhere on a surface. Such adhesion may occur temporarily and it does not necessarily involve caking. Caking may be considered as a collapse phenomenon, which occurs when particles form permanent aggregates and harden into a mass, resulting in loss of free-flowing properties. Caking occurs over time and stickiness appears as an instantaneous process [1].

Stickiness appears as adhesion or cohesion of two similar or different surfaces. An example is a hygroscopic material such as a sugar-rich product, which sorbs water rapidly resulting in a decrease in surface viscosity and may be called a sticky material. The mechanism of stickiness and caking of powders can be explained by surface properties [2-5]. Surface property is directly related to interfacial surface energy of contacting materials, viscosity and surface tension of components [2-3]. Surface tension is an important parameter for characterizing adhesive behavior of materials. The driving force for the flow is surface tension, and resistance to flow is measured through the viscosity [3-5]. Greater surface tension-driving force or longer contact times allow the liquid flow to build a bridge between particles, while higher viscosity decreases tendency toward sticking (Figure 1).

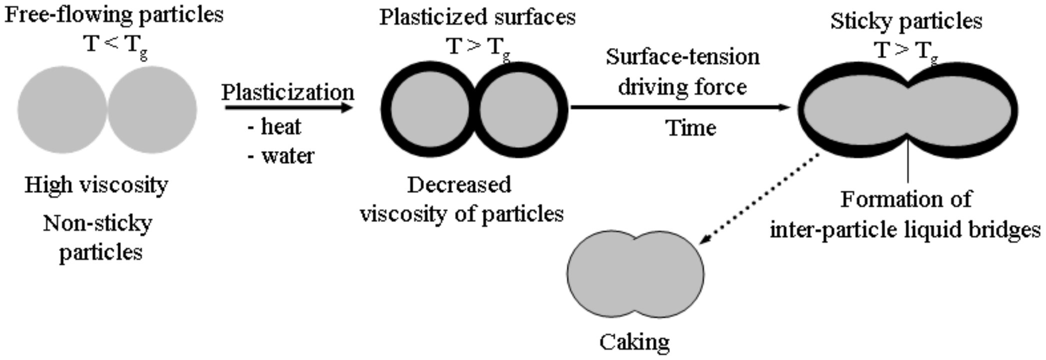

Figure 1 Schematic diagram explaining mechanism for occurrence of stickiness and caking in powders [6].

Downton et al. [3] estimated the critical viscosity was 10^6-10^8 Pa.s, which indicated sticky-point temperature as measured by method of Lazar et al. [7]. Roos and Karel [8] found that the critical viscosity was related to temperature 10-20°C above T_g. The viscosity of amorphous foods is extremely high in the glassy state (10^{12}-10^{16} Pa.s), but it decreases dramatically with increasing temperature or water content. Under the influences of water and thermal plasticization, a glassy material transforms into supercooled liquid, of which

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surface viscosity may reduce to below the critical viscosity [3] inducing adhesion and stickiness of particles within a short time [5, 9]. Above T_g, the reduced viscosity is related to increased molecular mobility of the systems, which has been determined by several techniques such as dielectric and dynamic-mechanical analysis [10-17].

2. Powder Characterization

Free-flowing properties are crucial in powder production and handling. Stickiness properties in dairy powders have been studied extensively as they may significantly affect changes in flow characteristics during spray drying and storage of powders [18]. The changes in moduli and flow properties of synthetic polymers occurring above the glass transition have been investigated by Bengoechea et al. [14]. Glass transition reflects the molecular mobility of amorphous components, and it can be measured from changes in material characteristics [15, 19-20]. Above the T_g, the increased molecular motions result in softening of amorphous components [10, 13, 16-17, 21-23]. Thus, the techniques often used in the characterization of powder stickiness are based on the detection of their structural properties associated with glass transition.

2.1. Torque Measurement

Retarded flow at some temperature and water content indicates a ‘sticky point’ for the powder, which can be measured by various techniques [7, 24-25]. Sticky-point tester is one of the oldest techniques used for characterizing stickiness behaviour of powders. It was used by Lazar et al. [7] to measure the sticky-point of tomato powders. In this technique, a test tube is packed with a powder sample of known water content and sealed using rotating mercury seal. Subsequently, the tube is immersed in a water bath. The temperature of the bath is slowly increased while the powder is stirred by the small stirrer embedded in the powder samples. A certain temperature, at which the force required to turn the stirrer increases sharply, is recorded as a function of water content of powder. The temperature at this point is referred to as the sticky-point temperature (SPT) of the powder [3, 26]. However, this technique cannot provide quantitative information about the strength of materials and they are clear to monitor the changes that occur in the powder at the early stages of stickiness. Therefore, this technique has been developed by Özkan et al. [24] determining stickiness of milk powders based on the measurement of the torque during stirring of a powder sample and it is suitable for the determination of flow properties of powders as affected by their stickiness behavior.

Many studies have been carried out to relate stickiness and glass transition [8, 16, 18, 27-29]. Flow characteristics of amorphous food solids are affected by the glass transition due to changes in molecular mobility which is coupled with dielectric and mechanical α-relaxations [10-11, 13, 15-16, 21-23, 30]. Impaired flow of amorphous solids may be observed at a specific temperature at which the surface viscosity of particles falls to below a critical value referred to as sticky-point [3, 7]

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Roos and Karel [8] showed that sticky-point temperatures as reported by Downton et al. [3] for an amorphous sucrose/fructose (7:1) mixture followed its glass transition temperature, T_g, measured using differential scanning calorimetry (DSC). Glass transition of an amorphous solid results in increasing translational mobility of molecules with concomitant appearance of liquid-like characteristics (Figure 2), which are associated with the development of stickiness in amorphous particles [8, 15-16, 18, 25, 27, 29]. Glass transitions are reported as results of measurements of thermodynamic changes during heating of a glassy solid to above its glass transition. A differential scanning calorimetric (DSC) measurement shows a change in heat capacity over the material specific glass transition.

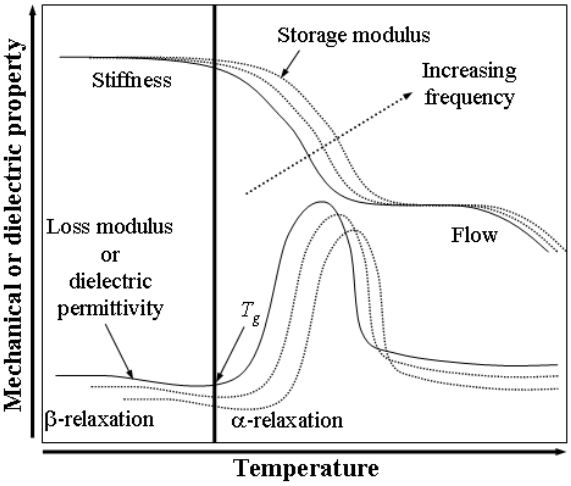

Figure 2 Changes in dielectric and mechanical properties of materials around and above glass transition. In dielectric measurements, dielectric permittivity increases rapidly and shows a dielectric peak above glass transition temperature, while mechanical properties show a drop in storage modulus and a peak of loss modulus at temperature above T_g. The α-relaxation as measured by dielectric (DEA) and dynamic-mechanical (DMA) analysis can be identified from changes in dielectric and mechanical properties around and above glass transition. Appearance of α-relaxation suggests some changes in molecular mobility in the materials [6, 52].

Above the glass transition, enhanced molecular mobility is associated with decreasing relaxation times and a lower viscosity. The α-relaxations indicating molecular mobility around the glass transition can be observed from changes in dielectric and mechanical properties as reported by several studies [10-11, 13, 16, 21-23, 30-32. Changes in dielectric and mechanical properties above the glass transition are also shown in Figure 2. The α-relaxations are frequency-dependent, indicating the non-equilibrium and time-dependent nature of the system.

2.2. Dielectric Analysis

Dielectric Thermal Analysis (DEA/DETA): This technique provides the various dielectric relaxations of the amorphous systems, which have been measured from changes in

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dielectric properties including the dielectric constant or permittivity (ε'), dielectric loss (ε''), and their ratio tan δ = ($\varepsilon''/\varepsilon'$) as a function of temperature. The ε' describes an alignment of dipoles (permittivity) and the ε'' describes an energy that is required to align dipoles, i.e., dielectric loss [13, 15, 33]. The method has been used in characterization of liquid and solid systems including low molecular weight sugars and high molecular weight components, such as wheat and powder samples, over a wide temperature range [13, 22, 33-37]. Many authors used the DEA measurement to observe glass transitions in food materials such as frozen wheat dough systems [33] and amorphous polyols [13]. However, some authors attempted to correlate dielectric relaxation with the textural properties of food materials such as crispness using the dielectric spectroscopy. This technique provides the information of molecular mobility of material components due to the rotation of the dipoles expected to couple with the structural relaxation of the matrix [16, 22]. Dielectric relaxation studies on low molecular weight sugars and the mixtures [34-35, 38] showed a primary (α) relaxation associated with molecular orientation in the viscous liquid, while sub-T_g relaxations (below calorimetric T_g) such as γ- and β-relaxations is a result of the motion of pendant hydroxymethyl group.

2.3. Dynamic-Mechanical Analysis

Dynamic-Mechanical Thermal Analysis (DMA/DMTA): DMA series the molecular motions and viscoelastic behavior of a material by applying a stress to the material and monitoring its response. The mechanical α-relaxation as measured by the DMA is analogous to the dielectric α-relaxation and it results in a decrease in storage modulus, *E'*, and a peak in loss modulus, *E”*, and tan δ around the glass transition [11]. Amorphous materials show various relaxations when they are exposed to an external, oscillating stress. The main relaxation associated with the glass transition is known as an α-relaxation. The α-relaxation can be observed from change in modulus at temperature above glass transition. The α-relaxation appears as storage modulus decreases dramatically and loss modulus increases with increasing temperature (Figure 2). These changes are frequency-dependent and followed the nonequilibrim, time-dependent nature of glassy and supercooled liquid forms of the amorphous materials [16, 30, 39]. T_g of carbohydrates is weakly dependent on structure but it is strongly dependent on molecular weight [8, 17, 40], while the DMA data of food and other systems have shown that this technique is more sensitive to changes in material properties around the glass transition than DSC [13, 15, 41-42]. Changes in mechanical behavior and molecular relaxations have been used to explain the textural properties of bread [16, 21-23].

3. Stickiness in Food Processing and Handling

3.1. Composition and Particle

Stickiness of milk powders is affected by solids composition and water content, which can control glass transition temperature

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of systems [18, 27, 43-45]. Solids of dehydrated dairy products include lactose, lipids, proteins and minerals. Lactose, proteins and minerals are miscible with water or water-soluble while lipids have fairly little interactions with water [20, 43-44, 46]. The physical state of the non-fat solids (SNF) is highly dependent on water content [1, 43-44, 47-48]; thus, it is important in drying process and stability of dehydrated dairy foods [46, 49]. Lactose in liquid dairy products is dissolved in a continuous water phases, which contains dispersed fat and proteins. Milk powders containing high lactose contents exhibit high adhesive behavior of powder particles when temperature and water content is increased due to surface plasticization [15, 20]. A rapid removal of water in subsequent spray drying allows glass forming of solutes, such as lactose, because lactose is transformed directly from a viscous liquid-like material to a solid-like, amorphous, glass [50-52]. Surface plasticization results in the formation of inter-particle liquid bridges and stickiness as shown in Figure 1. However, the formation of liquid bridges may either result from partial melting of milk fat at surfaces of particles [53-56] or the liquid flow of amorphous surface components [27, 45, 53, 56]. Amorphous carbohydrates, such as lactose, and other hydrophilic compounds are plasticized (softened) by water, which controls the glass transition (transformation of amorphous solid structures to viscous liquid-like materials) of drying dairy solids and also powder stickiness [18, 20, 27, 53].

The tendency of stickiness is also relative to particle size distribution of powders resulting in adhesive and cohesive behavior of powders. Powders containing small particles have high contact area of particles for coalescence [53]. A small contact area of particles is sufficient to form strong bridges between particles, such as liquid and/or solid bridges [57]. Liquid bridges between particle surfaces represent the adhesion and stickiness in agreement with Downton et al. [3], exhibiting that stickiness occurs when sufficient liquid flow can build the inter-particle liquid bridges. Solid bridges may be formed by sintering, by chemical bonds or by crystallization [45, 57-58].

3.2. Stickiness of Powders: Problems and Opportunities

Stickiness is a major problem in various drying operations and handling of low-moisture food materials or dried powders. Dehydration of food materials is often carried out by spray drying allowing free water removal and decreasing changes in food structure. In a drying process, stickiness occurs when insufficiently-dried particles collide with other particles or drier walls due to water plasticization [2-3, 59] and the formation of liquid bridges between particles [4, 9, 53, 57]. Major problems of stickiness are associated with the presence of high concentrations of sugar in the products [1, 29]. Low molecular weight sugars have glass transition at low temperatures and sticky behavior is typical of dehydrated sugar-rich foods at low humidities [60]. Spray drying of solids with low T_g is quite

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difficult since they cannot be dehydrated well during drying (Figure 3). Thus, the products may remain as syrup which can block and stick on the drier wall. This causes low product recovery and operating problems. The solution of these problems is often achieved by a rapid glass forming of solutes [49, 61] and the addition of high molecular weight compounds, such as maltodextrins and proteins [17, 20, 28-29, 62-65]. High molecular weight compounds, often used as drying aids, increase T_g and viscosity of solids resulting in the formation of the solid structures (Figure 3) and extension of contact times required for stickiness and adhesion [3, 5, 17, 66-68]. The amorphous structures of carbohydrates and other hydrophilic components form during rapid dehydration of food solids by spray drying [9, 28].

Various types of impacts of stickiness properties have been reported in many studies [4, 26, 58]. Most important technology for powder particles is agglomeration, which is inter-particle adhesion process to increase particle size of powders [57]. In food manufacturing and pharmaceutical industries, several agglomeration technologies have been applied in spray drying either as an integrated or external process. Agglomerated food powders have gained attention in recent years due to their convenience in applications during transportation, handling, processing and for product formulations [6]. Agglomeration is a common technique to increase the particle size of fine food powders [52]. Agglomeration of food powders is often referred to as "*instantizing*" due to the improved rewetting characteristics of the agglomerated powders prior to drying [69]. Agglomeration uses the control of surface plasticization allowing particles to adhere to, form inter-particle liquid bridges and agglomerate [2, 58-59]. The advantage of agglomerated powders is an increasing water uptake in rehydration and formation of reconstituted liquid foods as the agglomerates have channels between adhered particles [57, 69]. However, processing conditions of agglomeration was reported to be critical because overwetting resulted in unacceptable agglomerates such as stickiness and caking of powders.

4. Stickiness of Carbohydrate-Protein Systems

4.1. Glass Formation of Milk Solids

In dairy systems, lactose is often responsible for stickiness of milk powders. Lactose vitrifies in spray drying if the water content is sufficiently decreased. Dehydration is an efficient food preservation method, which reduce water content and water activity to levels that do not allow the growth of microorganisms. Dehydration of food materials is often carried out by air drying, allowing free evaporation of water with decreasing volume and changes in food structure. A spray-drying process involves atomization of liquid and rapid dehydration of particles. This process requires solidification of particle surfaces at the initial conditions in the drying to retain free-flowing properties of particles and avoid stickiness of particles in the equipment. Dehydration of the atomized liquid particles proceeds from the particle surface to inner core. A layer of concentrated solutes is formed

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on the particle surface. The extremely rapid water removal increases viscosity of remaining solids and the particle surface approaches the glassy state prior to colliding with other particles or drier walls [52]. A high surface viscosity of drying particle surfaces allows the formation of solids (Figure 3). In order to achieve a high viscosity, the water content must decrease since temperature increases [3]. The formation of solid structures requires a rapid increase in viscosity at the particle surfaces to extend contact time for stickiness and adhesion [3]. This can be achieved by glass-forming solutes or drying aids, such as high-molecular-weight compounds [28, 62-65, 67].

The quality of dehydrated foods could be improved by keeping the material temperature close to or below the glass transition to avoid structural and other quality changes during dehydration and storage [5, 27]. Above T_g, powder particles are plasticized by thermal or water plasticization causing decreased viscosity (Figure 1) contributing to a liquid flow and formation of inter-particle liquid bridges and stickiness behavior [3, 5, 20, 59].

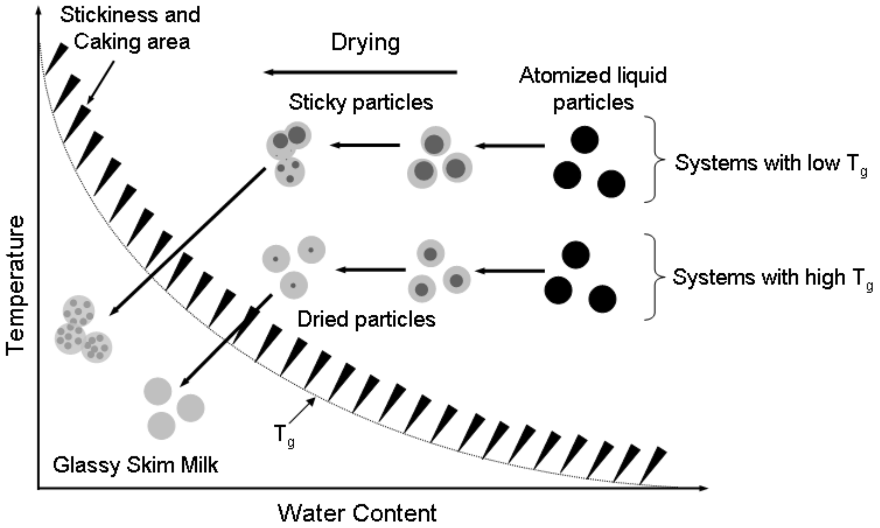

Figure 3 A schematic representation of dehydration of solid systems with low molecular weight sugars and with high molecular weight compounds during water removal in spray drying. The temperature-water content corresponding to viscous flow of plasticized solids at particle surfaces can cause stickiness, agglomeration and caking. Solid systems containing low molecular weight sugars show sticky particles due to the residual of some water contents on the particle surfaces (dark areas). Solid systems containing high molecular weight compounds give dried particles as a dried surface of particle solids is rapidly formed (grey areas) [52].

Amorphous, low molecular weight sugars, such as mono- and disaccharides, are hygroscopic and show glass transitions at low temperatures [70]. Mixing a small-molecular-weight-solvent with a glass-forming polymer leads to depression of the glass transition temperature [71]. The evaluation of compositional effects on physical properties may often be based on the effects of food components on the T_g of their binary or

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tertiary mixtures [72]. Maltodextrins are widely used as food components to increase T_g of food solids [17] as maltodextrins are mixtures of homologous carbohydrate polymers [73], which have high T_g values [8]. Maltodextrins are supplied with different dextrose equivalent (DE) values, which link to the number average molecular weight and their T_g [8]. Low DE maltodextrins are; therefore, often mixed with foods containing low molecular weight sugars to obtain solids with increased T_g and improved dehydration properties [17, 20, 28]. However, many studies indicated that high-molecular-weight proteins did not show a significant effect on T_g of sugar/protein mixtures due to low miscibility of proteins and carbohydrates [10], but they resulted in non-sticky particles due to formation of the solid structures and the covering of particle surfaces with hydrophobic materials [63-65].

4.2. Miscibility of the Solid Components

Polymer interaction is quite complicated leading to the complex formation, miscibility or phase separation. The mixing of biopolymers is dominated by enthalpic effects, which may be given by the relative strength of the interactions of polymers among each other, such as hydrogen bonding or dipole-dipole interactions [74-76]. Miscibility of the systems occurs when different solid components can mix homogenously together, while phase separation of the biopolymer system results from immiscibility of two different solid components (Figure 4).

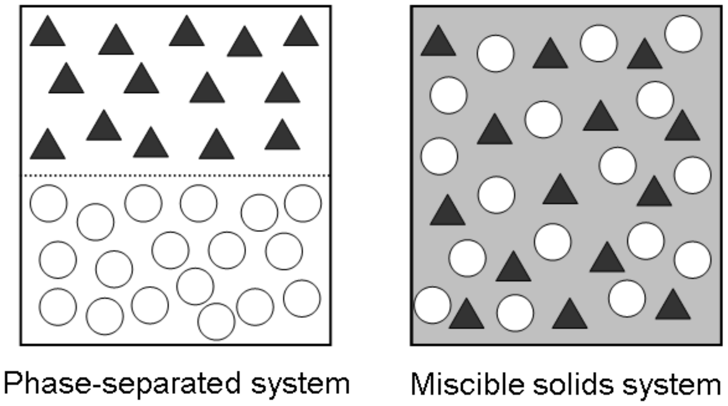

Figure 4 Schematic diagrams for the mixing behavior of two different solid components in the systems. The presence of solvent or water (grey area) can increase miscibility of mixture systems.

Phase separation and miscibility of solid components affect physicochemical properties of polymer blends; for examples, some polymers such as proteins may inhibit molecular mobility and lactose crystallization, and may act as a barrier to water diffusion due to phase separation of the system [1, 10, 47, 77]. Proteins have high hydrophobicity and they are self associated largely by hydrophobic interactions and phosphate group electrostatic interactions leading to phase separation in the mixture systems [10]. However, if self-associations are not too strong, the presence of solvent can enhance miscibility by diluting

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unfavourable polymeric interactions [41, 74, 78] as shown in Figure 4.

There are several techniques used to determine the miscibility of blends. A common method used is a measure of the glass transition temperature, T_g. In general, miscible polymer mixtures have a single T_g between the two T_g values of the two components, and broadening of the transition is observed as the components become more immiscible [41, 74-75, 78]. These observations may be important in the control of physicochemical properties and stability of food materials.

4.3. Molecular Properties of Carbohydrates and Proteins

Various carbohydrates and proteins are widely used as food ingredients to stabilize food products, for example, beverage stabilization, baked products, cheese products, extruded products, powder products and pharmaceutical applications [45, 62]. Caseins are one of the milk proteins and consist of four components (α_{S1}-, α_{S2}-, β- and κ-casein) depending on molecular weight (19,000-23,900) determined by SDS PAGE electrophoresis [79]. Maltodextrins are hydrolysis products of starch, consisting of α-(1-4)-linked D-glucose and α-(1-6)-linked branch points, to large molecular weight distribution [73]. Information of molecular properties of solid components (molecular weight and mobility) is important to understand physicochemical properties and stability of food materials. Molecular properties of food materials are measured by mechanical and dielectric relaxations around glass transition. The glass transition is relevant to the use of carbohydrate and protein polymers as structural materials since substantial translational motion of molecules above T_g are associated with composition of the blends [10-12, 15-17, 20, 30, 42, 77-78]. The addition of low molecular weight substances are expected to decrease T_g of miscible blends by increasing free volume available, which is relative to a considerable mobility above T_g [13, 19, 21-23, 34-35, 38, 80], whereas the presence of high molecular weight compounds in the systems shows small magnitudes of modulus changes indicating a low molecular mobility of the component molecules above glass transition [10]. Thus, high molecular weight substances are commonly used to increase viscosity and T_g of the blends [8, 20, 70] to improve powder characteristics during processing and storage [5, 28, 65, 81].

The presence of water in biopolymer-based materials is well known to have pronounced influence on their quality and stability [19-21, 51]. Amorphous solids components (carbohydrates and proteins) are plasticized or softened by water [17, 20, 43, 49, 82]. Water content has a marked effect on molecular mobility as observed changes in mechanical and dielectric properties due to water plasticization [10, 15-16, 21-23, 34-35, 38]. In fact, changes in water content of complex materials cause the strength of molecular interactions (hydrogen-bonding) between components. Increasing molecular motions of biopolymer blends in the presence of water or glycerol (plasticizers) shows

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reduced heterogeneity or phase-separated matrix due to decreasing strength of molecular interactions or self-association within the matrix [78, 83-84].

Change in molecular chain flexibility is accompanied by important changes in the rheological behavior of materials (such as deformability, fracture mechanism or flow behavior) with increasing temperature and water content. Processes including collapse of porous matrices or stickiness are consequences of the glass transition [85]. A strong link between the glass transition, α-relaxations and flow characteristics of polymers has been shown by Bengoechea et al. [14] and Silalai and Roos [15]. Stickiness is time-dependent above the T_g and lactose as well as other sugars are the main components affecting the glass transition and stickiness in milk powders [9, 18, 20, 27]. In other amorphous carbohydrate systems, the decrease in viscosity to a relatively constant value of 10^6 to 10^8 Pa.s has been shown to correlate with stickiness of a 7:1 sucrose-fructose mixture [3]. This prediction was based on short contact times of 1 to 10 s typical of the empirical sticky point measurements using the method of Lazar et al. [7]. Such sticky points were located at temperatures of 20°C above the onset temperature of the glass transition, T_g [86]. Thus, this contact time may also be coupled with the dielectric α-relaxation time of 100 s at the calorimetric glass transition temperature, T_g [16, 87-89]. As a glass-forming liquid is supercooled, its relaxation times and viscosity increase dramatically towards the glass transition [87, 90]. Relaxation times are extremely long in the glassy state but a dramatic decrease in relaxation times occurs above the T_g [91-94]. The temperature dependence of relaxation times below the glass transition may follow the Arrhenius relationship, but changes above the glass transition become highly temperature-dependent and deviate from Arrhenius behavior which is used to classify materials to fragile and strong glass formers [95]. A relationship of molecular mobility and viscosity may be used to show the applicability of the William-Landel-Ferry (WLF) relationship to fit viscosity data and relaxation times above the glass transition [90, 96]. The Vogel-Tammann-Fulcher (VTF) relationships can be also used to describe changes in relaxation times above glass transition [88, 97]. The composition and water content of carbohydrate glass-formers has been found to affect their sub-T_g and α-relaxations [15-16, 21-23, 30-31, 34-35, 89, 97]

Conclusions

The present study indicated that water sorption and changes in food powders, such as stickiness and crystallization were affected by solids composition and water content. Stickiness of food powders was related to plasticization of particle surfaces. Dielectric and mechanical α-relaxations were significantly related to flow characteristics and the stickiness behavior above glass transition as a result of enhanced molecular mobility of powder components, particularly mono- and disaccharides. Dielectric and mechanical α-relaxations of carbohydrate-protein solids systems could be governed by properties of

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amorphous sugars and followed sugar mobility in a phase- or partially phase-separated protein matrix. Stickiness can be reduced by mixing high molecular weight substances such as protein and maltodextrin to food powders. Food solids with varying protein contents or low DE maltodextrin contents suggested improved dehydration characteristics as predicted from the effects on the T_g and primary relaxations. As a result, increasing high molecular weight substances content in food powders decreased changes in α-relaxations and increased relaxation times contributing to reduced level of mobility for powder stickiness. Thus, the compositional effects on the relaxation times of food powder solids were related to flow characteristics and powder stickiness around and above the glass transition. This study suggested that the α-relaxations can be used to predict flow characteristics and stickiness of food powders using temperature and water content data. This information is also useful for the control of particle flow and powder stickiness in dairy and food industries.

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