Electrohydrodynamic Spraying of Chocolate

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***Abstract*— Electrohydrodynamic spray quality of chocolate was studied. The ingredients in chocolate samples were varied to determine their effect on the viscosity, yield value and electrical resistivity, and the effect of these physical properties on the drop size and percentage area covered. Samples were sprayed at 35 and 50C and 0 and 35kV. The apparent viscosity, apparent and Casson yield value increased with a decrease in the fat content and with the addition of 1.5% lecithin. The electrical resistivity increased with a decrease in fat content and with the addition of 1.5% lecithin. During electrohydrodynamic atomization, increasing electrical resistivity increased the drop size and decreased the percentage area covered. At both 0 and 35 kV, increasing viscosity and yield value of the samples increased the drop size. Increasing viscosity and yield value decreased the percentage area covered at 35 kV but not at 0 kV.**

***Index Terms*— Electrohydrodynamic spraying, chocolate, viscosity, drop size, percentage area covered**

I. Introduction

Chocolate coating has a wide variety of applications in the snack food and confectionary industry. The two most common ways of coating confectionary with chocolate are moulding and enrobing [1]. During moulding, an outer chocolate shell is created which is filled with the center. During enrobing, the center filling is made which is passed through liquid chocolate. Since chocolate is a relatively expensive food, in terms of both ingredients and processing, accurate weight control of products is very important [1].

The rheological properties of chocolate masses have a large influence on processing and the quality of manufactured products [2]. Viscosity of chocolate is important in determining the coating thickness and the yield value is important in determining how easily the chocolate flows [1]. Molten chocolate is a suspension of particles of sugar, cocoa and/or milk solids in a continuous fat phase [3]. The flow properties of chocolate depend on the proportions of its components [2]. Fat content, lecithin and temperature have a significant effect on both viscosity and yield value. A 1% increase in fat up to 28% decreases plastic viscosity by almost 50% [1]. The yield value of commercial plain chocolate decreases when the fat content increases from 32 to 48% by the addition of cocoa butter [2]. The addition of 0.1-0.3% lecithin has the same viscosity reducing effect as over ten times this amount of cocoa butter [3]. However, above 0.3-0.5% lecithin, thickening of chocolate occurs. For dark chocolate, the Casson yield value decreases with an increase in lecithin concentration up to 0.5%. Above 0.5%, the yield value increases [1], [3]. The viscosity of chocolate decreases by 1.2 to 3.8% per 1 C increase in temperature from 38-42 C [4]. The Casson yield value of cocoa powder and corn oil dispersion decreases with an increase in temperature from 30-90 C [5].

Electrohydrodynamic spraying (EHD), also known as electrospraying, is a phenomenon where an electrified liquid is dispersed into fine droplets owing to an electrostatic force working on the charged surface of a liquid [6]. Its main advantage over other atomization techniques is the ability to form fine droplets with a relatively narrow size distribution [7]. The average droplet sizes produced may range from 0.1 to 1000 μm. Also there is no coalescence of droplets due to electric charge of the same polarity on the droplets [6]. The ability to produce fine droplets increases the weight control and thereby reduces the costs. The advantages of coating operations that utilize electrostatics are control, better quality and cost reduction [8].

The atomization during electrohydrodynamic spraying is affected by voltage, viscosity and electrical resistivity of the liquid [9]. The droplet size decreases with increasing voltage up to a critical voltage [6], [8]. The droplet size increases with increasing viscosity [9], [10] and with increasing electrical resistivity [9], [10]. Few studies have examined the effect of various ingredients of chocolate on its electrical resistivity.

Application of electrohydrodynamic spraying to chocolate is a novel method through which a thin and uniform coating of chocolate can be obtained. EHD helps in reducing the losses and thereby lowering the costs. The objective of this study was to determine the effect of various ingredients of chocolate on the viscosity, yield value, electrical resistivity and in turn, determine the effect of these parameters on the electrohydrodynamic spray quality of chocolate which was studied by measuring the drop size and percentage area covered.

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II. Procedure

Chocolate ingredients and making:

The ingredients used in the preparation of chocolate were cocoa beans (Dominican Republic, Chocolate Alchemy, Yoncalla, OR), cocoa butter, whole milk powder (Dana foods, Hillsboro, WI) with 28.5% fat , sucrose (Kroger Company, Cincinnati, OH) lecithin (American Lecithin Company, Oxford, CT) and vanilla powder (Beanilla Trading Company, Grand Rapids, MI). Cocoa liquor was made by roasting the cocoa beans at 149 C for 10 min in a convection oven. This was followed by cracking the beans in a Crankandstein Cocoa mill (Chocolate Alchemy, Yoncalla OR) and winnowing them to separate the hulls from the cocoa nibs. They were then ground in a Champion Juicer (Plastaket Manufacturing Corp., Lodi CA) to produce cocoa liquor.

Sugar was ground to < 30 µm by passing it 10 times through a centrifugal pin mill (Glenmills Inc., Clifton, NJ) operating at 18000 RPM. The particle size of sugar was measured using a Malvern Mastersizer (X standard bench, Worchestershire, UK) parameter [D (4,3)]. In order to understand the effect of each ingredient on viscosity, resistivity and electrohydrodynamic spray quality, different combinations of ingredients were used.

Sample preparation:

All samples containing sugar, milk powder or lecithin were conched before using. Cocoa liquor or cocoa butter were melted in a hot air oven, weighed and added to an 'Alchemist's Stone' Chocolate Melanger (Chocolate Alchemy, Yoncalla, OR). Required amounts of sugar and milk powder were weighed out and mixed. The mixture was then added to the cocoa liquor and cocoa butter in the concher. Lecithin was added immediately after the addition of dry ingredients. The sample was conched for 24 hours.

Electrohydrodynamic Coating:

All the samples were coated using a TDC Liquid Electrostatic Coater (Terronics Development Corporation, Elmwood, IL). The spray quality was studied at two different outlet temperatures, 35 and 50 C. At each temperature, the samples were sprayed at 0 kV and 35 kV. The spray nozzle was covered with a plastic box and was heated using a space heater. The temperature of the nozzle was changed by adjusting the temperature of the space heater. The sample was put in an oil bath set at 65 C. It was pumped to the nozzle using a peristaltic pump (Cole-Parmer Instrument Company, Vernon Hills, IL). The outlet temperature was measured using a thermocouple as the sample was being sprayed. The inlet and outlet tubes of the pump were insulated. The samples were sprayed onto a 17.9 cm× 15.9 cm glass slide, maintained at room temperature, placed on a conveyer belt moving at a speed of 1.7 cm /sec. The sprayed sample was photographed and analyzed using Photoshop 6.0 (Adobe Systems Incorporated, San Jose, CA). The pictures were converted to black and white images and the number of total pixels and black pixels were read. The number of drops on the glass slide was counted manually. For some samples, a number of drops merged into one single drop. If the number of drops merging was visually evident, the drops were counted as individual drops. Otherwise, it was counted as a single drop. The procedure was repeated for each of the three replicates for each sample at different temperatures and voltages.

The following values were calculated:

Area covered by the drops = Black pixels in the picture / Pixels per cm^2

Droplet size = Area covered by the drops / Number of drops

Percentage area covered = (Black pixels in the picture / Total pixels in the picture) × 100

Measurement of Viscosity:

Viscosity was measured using a Brookfield HB DV Π + Digital Viscometer (Brookfield Engineering Laboratories Inc., Middleboro, MA) using a small sample adapter and spindle 27. The sample cell was enclosed in a jacket connected to a water bath. The sample was filled before the spindle was put in and was pre-sheared for 3 min at 50 RPM before recording the shear stress values. The spindle was rotated at 5, 10, 20, 50 and 100 RPM. The shear stress values were recorded by decreasing the spindle speeds followed by an increase. The average shear stress values were used to calculate the viscosity and yield value. The viscosity was measured at 35, 40, 45 and 50 C. The temperature of the sample was changed by changing the temperature of the water bath.

The viscosity of cocoa butter was lower than the range of viscosities that could be measured using the Brookfield HB DV Π+ viscometer. Therefore it was measured using a Brookfield LV DV Π+ Digital viscometer (Brookfield Engineering Laboratories Inc., Middleboro, MA) using spindle 1 and a guard leg. The viscosity was noted at speeds of 20, 50 and 100 RPM and at temperatures of 35, 40, 45 and 50 C.

The Casson plastic viscosity, yield value and apparent viscosity, yield value of all the samples were determined. However, for cocoa butter, the viscosity displayed by the viscometer was noted.

The Casson plastic viscosity and yield value were determined using [11]:

Viscosity = $(\text{Slope})^2$ = $[(\text{Change in Shear Stress/ Change in Shear Rate})]^2$

Yield Value = $(\text{Y-Intercept}/2)^2$

The apparent viscosity and yield value were determined using [12]:

Viscosity = (Shear stress / Shear rate) at a shear rate of 30 s^{-1}

Yield value = Shear stress at a shear rate of 5 s^{-1}

The viscosity measurements were repeated three times for every sample.

Measurement of Electrical Resistivity:

The electrical resistivity was measured using a resistivity cell (Electrostatic Solutions Ltd., Southampton, UK), electrometer (Keithley Instruments, Cleveland, OH) and a voltmeter (Kepco Inc., Flushing, NY). The resistivity was measured at 4 different temperatures 35, 40, 45, 50 C. The sample was heated in a hot air oven to achieve the desired temperature. The sample cell was also warmed up in a hot air oven. 5 ml of the sample was put in the resistivity cell using a syringe to avoid any air gaps and the current was measured with the electrometer and the voltage was read using the multimeter (Radio Shack, Fort Worth, TX).

The resistivity of the sample was calculated using:

Resistivity = (k*I)/V

where k is 0.014, the cell constant of the cell. The resistivity measurement was repeated three times for every sample.

Statistical Analysis:

Statistical analysis was done using SPSS (SPSS Inc., Chicago IL). ANOVA One and two factor tests with post hoc analysis using HSD were done and $p< 0.05$ was used to indicate significantly different results. Correlations between physical properties and spray quality were done. Pearson correlation coefficients were calculated and correlations significant at $p< 0.01$ and $p< 0.05$ (two-tailed) were determined.

III. RESULTS AND DISCUSSION

The viscosity, yield value and electrical resistivity of the samples are affected by the amount of cocoa liquor, fat content, lecithin and temperature. These properties were varied to produce samples with different viscosities, yield values and electrical resistivities to study their effects on spray quality. The electrohydrodynamic spray quality was studied by measuring the drop size and percentage area covered.

Viscosity:

The Casson plastic viscosity of cocoa liquor was 2.9 Pa.s at 35 C which is similar to the value of 2.2 Pa.s reported by Aeschlimann and Beckett [4]. Until 2000, the Casson equation was the official model to be used for calculating the viscosity and yield stress of chocolate by the International Office of Cocoa, Chocolate and Confectionery (IOCCC). However, the use of the Casson model does not provide good reproducibility and therefore measurement of shear stresses at several shear rates was recommended [4]. Servais *et al.* [13] proposed the calculation of apparent viscosity and yield value at shear rates of 40 and 5 s^{-1} as they were more reproducible.

In this study, both Casson plastic viscosity and apparent viscosity have been measured and reported. From 35 to 50 C, cocoa liquor had significantly higher apparent and Casson viscosities than the samples which contained added cocoa butter, sucrose, milk powder or lecithin (Figure 1). The fat content of all the samples, except for CL+CB and CB, is in the range of 50-53%. Therefore the difference in viscosity is not due to a difference in fat content of the samples. Cocoa liquor has 13% protein and 16% dietetic fiber [14]. After roasting and conching the cocoa beans, most of the extractable protein is insoluble and complexed [15]. The viscosity of a suspension increases with a decrease in the average particle size [16]. Therefore when cocoa solids are replaced with smaller sucrose molecules and protein micelles, the average particle size decreases and the viscosity should increase. In contrast, the viscosity of cocoa liquor was significantly higher than the rest of the samples.

The apparent viscosity significantly increased with a decrease in the fat content, as expected (Figure 1). However, the Casson plastic viscosities of samples were significantly different only from cocoa liquor but not from each other.When the fat content decreased from 100 to 76% with the addition of cocoa liquor (CB vs. CL+CB), the apparent viscosity increased significantly from 0.01 to 0.1 Pa.s at 35 C (Figure 1). When the fat content decreased from 76 to 53% with the addition of sucrose (CL+CB vs. CL+CB+S) the apparent viscosity increased from 0.12 to 0.48 Pa.s at 35 C. The rest of the samples had a fat content in the range of 50-53% and were not significantly different from each other. A decrease in the amount of liquid that forms the continuous phase of a particulate suspension (in the case of chocolate: cocoa butter with or without milk fat) increases its viscosity [3].The viscosity of suspensions increases markedly with an increase in solid content [17].

Lecithin is a surface active agent and its hydrophilic fragment attaches to sucrose while the lipophilic part penetrates the lipid phase. It forms a boundary layer between the two, reducing the internal friction and thereby the viscosity [1,18]. The addition of 0.1-0.3% lecithin has the same viscosity reducing effect as over ten times this amount of cocoa butter [3]. However, above 0.3-0.5% lecithin, thickening of chocolate occurs. When 1.5% lecithin replaced the equivalent amount of cocoa butter in CL+CB+S+MP, the apparent viscosity increased from 0.3 to 0.9 Pa.s at 35 C (Figure 1). The apparent viscosity of the sample with 0.35% lecithin was lower than that of the sample with 1.5% lecithin (CL+CB+S+MP+0.35Le+Va vs. CL+CB+S+MP+1.5Le) but was not significantly different from the samples that did not contain lecithin.

The Casson and apparent viscosities of all the samples, except cocoa butter, decreased significantly with an increase in temperature from 35 to 50 C as expected (Figure 1). The Casson plastic viscosity of both milk and dark chocolate decreases with an increase in temperature [3], [4].

Yield value:

The minimum force to start the chocolate moving is called the yield value [1], [3]. The apparent yield value of cocoa liquor was 33 Pa at 35 C which was significantly higher than the samples containing cocoa butter, sucrose, milk powder and lecithin (Figure 2).

The apparent and Casson yield value significantly increased with a decrease in the fat content (Figure 2). However, the apparent yield values of samples were more significantly different from each other than the Casson yield values. When the fat content decreased from 76 to 54% with the addition of sucrose (CL+CB vs. CL+CB+S) the apparent yield value increased from 0.74 to 6.27 Pa at 35 C (Figure 2). The Casson yield value of milk chocolate increases with a decrease in the cocoa butter content [2], [3]. Addition of cocoa butter coats the particles with fat, reducing the energy required to start the chocolate moving thereby reducing the Casson yield value.

For chocolate containing cocoa liquor, cocoa butter, sucrose and lecithin, an increase in the concentration of lecithin decreases the Casson yield value to a critical point followed by an increase [2]. At about 0.5% lecithin, 85% of sugar is already coated [1]. With an increase in lecithin content above 0.5%, the lecithin molecules may be free to attach to each other or form a bi-layer around the sugar. Both of these would hinder the flow resulting in an increase in the apparent yield value. Thus, when 1.5% lecithin replaced the equivalent amount of cocoa butter in CL+CB+S+MP, the apparent yield value increased from 3.29 to 15.05 Pa at 35 C (Figure 2). The sample containing 0.35% lecithin had a lower apparent yield value than the sample containing 1.5% lecithin (CL+CB+S+MP+0.35Le+Va vs. CL+CB+S+MP+1.5Le) and was not significantly different from CL+CB+S+MP.

The Casson yield value of cocoa powder and corn oil dispersions decreases with an increase in temperature from 30-90 C [5]. Thus the yield value was expected to decrease with an increase in temperature. There was no significant effect of temperature on the apparent and Casson yield values for any of the samples except cocoa liquor. The apparent yield value of cocoa liquor decreased significantly with an increase in temperature.

Electrical resistivity:

The electrical resistivity of cocoa liquor was 18×10^9 ohm-meter at 35 C which was significantly higher than the samples containing cocoa butter, sucrose, milk powder and lecithin (Figure 3). Replacing the cocoa solids with sucrose and milk powder significantly reduced the electrical resistivity.

Electrical resistivity significantly decreased with an increase in the fat content. The electrical resistivity decreased significantly when the fat content increased from 53 to 76% (CL+CB+S vs. CL+CB) and from 76 to 100% (CL+CB vs. CB). There was no significant difference in the electrical resistivity between samples with a fat content of 50-53% except for the sample with 1.5% lecithin. The electrical conductivity of cocoa butter, which is 100% fat, is significantly lower than the rest of the samples. As the solid content increases, the electrical resistivity increases due to a disruption in the continuous fat phase. An increase in the solid content decreases the ionic movement thereby increasing the electrical resistivity [19]. As the solids content increases, the drag for ionic movement increases which may be a reason for the increasing electrical resistivity [20].

Addition of lecithin decreases the electrical resistivity. Lecithin is an ionic emulsifier. Its structure enables it to dissolve in oil and be charged. Addition of 13% lecithin to soybean oil decreases the electrical resistivity by 1000 times, from 10^{11} to 10^{8} ohm-meter [21].When 1.5% lecithin replaced the equivalent amount of cocoa butter in CL+CB+S+MP, the electrical resistivity decreased significantly from 7.0 to 0.1×10^9 ohm- meter (Figure 3). The sample with 0.35% lecithin (CL+CB+S+MP+0.35Le+Va vs. CL+CB+S+MP+1.5Le) had a higher electrical resistivity than the sample with 1.5% lecithin (Figure 3) and was not significantly different from that CL+CB+S and CL+CB+S+MP.

For all the samples, except cocoa liquor, the electrical resistivity decreased significantly with an increase in temperature from 35 to 50 C (Figure 3). The electrical resistivity of carrot solids in sodium phosphate solution decreases with an increase in temperature from 20 to 100 C [20]. The decrease in electrical resistivity with temperature is due to the reduced drag for the movement of ions. The drag for ionic mobility may depend on size, shape and orientation of particles [20]. Decrease in electrical resistivity of cocoa liquor with increase in temperature might be due to the size, shape and orientation of its protein and fiber.

Spray quality:

Atomization refers to the disintegration of a bulk liquid material via an atomizer into droplets [7]. It is the most widely used process for droplet generation. During atomization, 1 m^3 of liquid can be broken up into approximately 2×10^{12} individual droplets [22]. Atomization of a liquid into discrete droplets can be brought about by aerodynamic, mechanic, ultrasonic or electrostatic means [7]. Electrohydrodynamic spraying is a phenomenon where an electrified liquid is dispersed into fine droplets owing to an electrostatic force working on the charged surface of a liquid [6]. Its main advantage over other atomization techniques is the ability to form fine droplets with a relatively narrow size distribution [7]. The average droplet sizes produced may range from 0.1 to 1000 µm. Also there is no coalescence of droplets due to electric charge of the same polarity on the droplets [6].

Electrohydrodynamic atomization (EHD) of the samples was achieved by using an electrostatic charge. Voltages of 0 and 35 kV were used for nonelectrostatic and electrostatic spraying respectively. Electrohydrodynamic spray quality was studied by measuring the droplet size and percentage area covered. During EHD atomization the small drop sizes obtained are highly desirable as they can form thin coatings and also enhance the coating by reducing the formation of crystals due to thick and uneven coating [23]. Precise layers can be deposited from extremely thin films to relatively thick layers. During EHD, the higher percentage area of the target covered with coating is desirable as it increases evenness of the coating and therefore reduces costs.

Presence of an electrostatic charge had a significant effect on the drop size and percentage area covered. EHD atomization significantly decreased the drop size for all the samples except cocoa liquor. EHD atomization significantly increased the percentage area covered for half of the samples. The drop size decreases with an increase in voltage from 0 to 10 kV for highly viscous polyvinyl alcohol solution [24].

During EHD spraying, the sample atomized as it came out of the spray nozzle. This was visually evident as the sample broke up into a large number of tiny droplets instead of dripping. In the presence of an electric field, the ability of a sample to atomize is dependent on its electrical resistivity. A minimum resistivity must be achieved for electrostatic atomization to occur. Oils containing emulsifiers with resistivity range outside $10^5 – 10^8$ ohm-meter will not atomize [25]. If the electrical resistivity of the liquid is too high, above 1×10^8 ohm - meter then stable atomization at nozzle voltages of 25-35 kV becomes difficult [26]. All the samples, except for cocoa liquor, had an electrical resistivity in the range of 0.01 to 0.7×10^8 ohm-meter and atomized in the presence of an electric field (Figures 4). Cocoa liquor did not atomize because its electrical resistivity at 35 C was 18×10^9 ohm-meter, which was significantly higher than the rest of the samples and was outside the atomizeable range of $10^5 – 10^8$ ohm-meter reported by Abu-Ali and Barringer [25].

During EHD atomization, the electrical resistivity had a significant effect on both the drop size and percentage area covered. The drop size increased and the percentage area covered decreased with increasing electrical resistivity. With an increase in electrical resistivity, the time required for the charge to transfer to the liquid is too long for good atomization [27]. Increasing resistivity increases droplet size during electrohydrodynamic atomization of soybean oil containing additives, with a resistivity of 10^6 to 10^{10} ohm- meter [9]. With increasing resistivity, the ability of the sample to atomize in the presence of an electric field decreases. Therefore the drop size increases and the percentage area covered decreases.

At 0 and 35 kV, viscosity had a significant effect on the drop size. The drop size increased with increasing apparent and Casson plastic viscosity. The drop size increases with increasing viscosity for soybean oil containing additives [9]. Yield value had a significant effect on drop size at 35 kV but not at 0 kV. At 35 kV, the drop size increased with increasing apparent yield value. There was no correlation between drop size and Casson yield value. Increasing viscosity hinders liquid disintegration into droplets resulting in poor atomization thereby increasing the main droplet size [7], [11]. The effect of viscosity and yield value on the drop size is similar. Since yield value is the minimum energy required by the chocolate to flow a sample with higher yield value would require greater energy to break the liquid into droplets thereby increasing the drop size.

Viscosity and yield value had a significant effect on the percentage area covered at 35 kV but not at 0 kV. At 35 kV, the percentage area covered decreased with an increase in apparent viscosity and Casson and apparent yield value. There was no correlation between percentage area covered and Casson viscosity. Increasing viscosity and yield value hinder liquid disintegration into droplets thereby decreasing the percentage area covered. Increasing viscosity decreases the droplet deformation on a surface [7].

Drop size was more sensitive to changes in physical properties than the percentage area covered. The percentage area covered might also be dependent on the deformation of the drop upon hitting the solid surface. The behavior of droplet deformation is governed by gravitational force, surface tension force, viscous friction force and its interaction with the solid surface [7]. Gravitational and surface tension forces might be significantly affecting the deformation of the drop in the absence of an electric field and therefore at 0 kV, viscosity and yield value might not have a significant effect on the percentage area covered.

IV. Conclusions

Application of electrohydrodynamic spraying to chocolate allows chocolate to be atomized in the presence of an electric field. The ability of a sample to atomize is dependent on its electrical resistivity. All the samples, except for pure cocoa liquor, atomized in the presence of an electric field and had electrical resistivities in the range of 0.01 to 0.7×10^8 ohm-meter. Cocoa liquor did not atomize because its electrical resistivity was outside the atomizeable range.

Electrohydrodynamic spraying improved the spray quality by decreasing the drop size and increasing the percentage area covered. Viscosity, yield value and electrical resistivity of chocolate had a significant effect on the electrohydrodynamic spray quality. Decreasing the viscosity, yield value and electrical resistivity decreased the drop size and increased the percentage covered thereby improving the spray quality. The viscosity, yield value and electrical resistivity of the sample can be varied by varying the fat content, amount of lecithin and temperature. An increase in fat content, temperature and addition of 1.5% lecithin decreased the viscosity, yield value and electrical resistivity. Therefore, chocolate samples with high fat and a lecithin concentration lower than 1.5% produce the best spray quality with electrohydrodynamic atomization. Chocolate is relatively expensive food in terms of both ingredients and processing and therefore good quality and weight control of the products is economically important. Due to decreased drop size and increased percentage area covered, electrohydrodynamic spraying of chocolate can be used to improve spray quality and deposition and reduce costs.

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VI. Tables and Figures

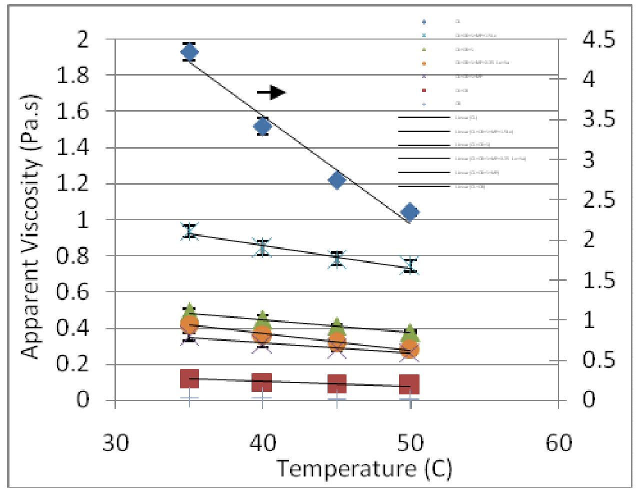


Fig. 1. Effect of temperature on the apparent viscosity of samples. Viscosity of cocoa liquor is plotted on the secondary Y-axis. CL = cocoa liquor, CB = cocoa butter, S = sucrose, MP = milk powder, Le = lecithin, Va = vanilla.

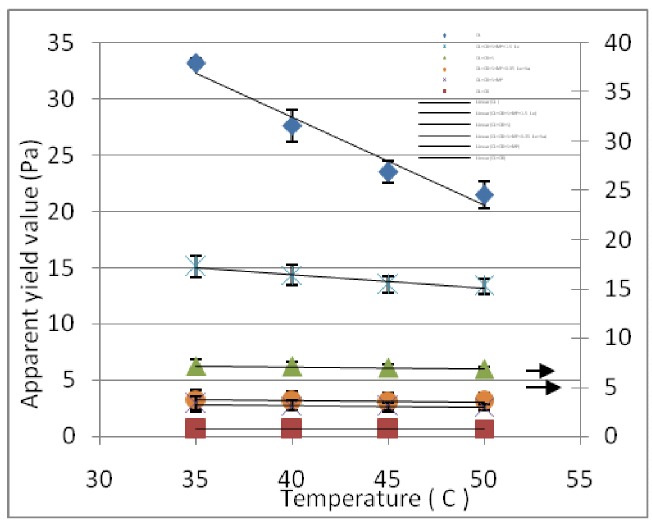


Fig. 2. Effect of temperature on the apparent yield value of samples. The apparent yield values of CL+CB+S+MP and CL+CB are plotted on the secondary Y-axis. CL = cocoa liquor, CB = cocoa butter, S = sucrose, MP = milk powder, Le = lecithin, Va = vanilla

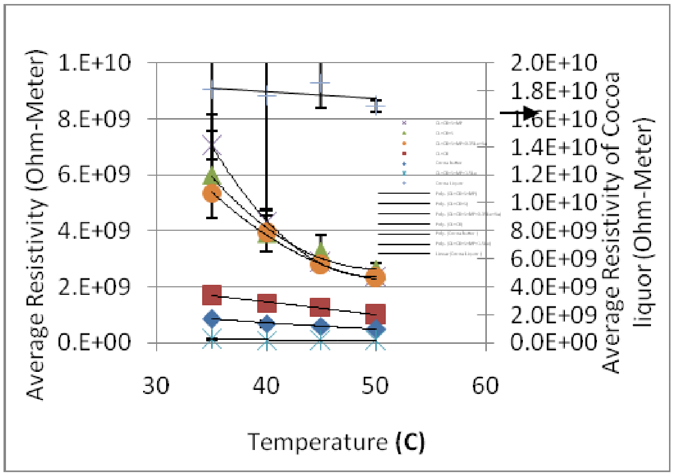
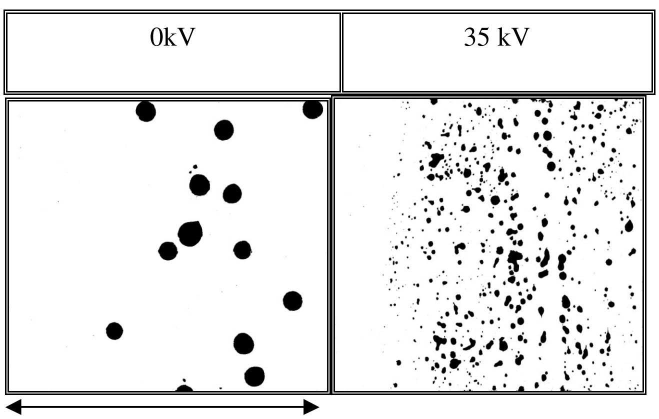


Fig. 3. Effect of temperature on the electrical resistivity of samples (with the electrical resistivity of cocoa liquor on the secondary Y-axis). CL = cocoa liquor, CB = cocoa butter, S = sucrose, MP = milk powder, Le = lecithin, Va = vanilla



18 cm

Fig. 4. Example of droplet formation at 0 and 35 kV

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