Factors influencing rheological and textural qualities in chocolate — a review

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Chocolate, a complex emulsion, is a luxury food that during consumption evokes a range of stimuli that activate pleasure centres of the human brain. Central to chocolate quality is an appropriate melting behaviour so that products are solid at ambient temperature and on ingestion melt to undergo dissolution in oral saliva, with a final assessment of texture after phase inversion. Particle size distribution and ingredient composition play important roles in shaping its rheological behaviour and sensory perception but are poorly understood. With opportunities for improvements in quality possible through improved and more transparent supply chain management, plant breeding strategies and new product development, there is a need for greater understanding of variables.

Introduction

Chocolates are semi-solid suspensions of fine solid particles from sugar and cocoa, about 70\% total, in a continuous fat phase. Cocoa solids are derived from beans obtained from the fruit of \textit{Theobroma cacao}, with world production dominated by Forastero types, made up of small, flattish and purple beans. Another type, Criollo, is presently rare in production; Trinitario, a disease-resistant hybrid of Criollo and Forastero, regarded as a flavour bean (Awua, 2002), is about 3\% of world production. Growth of Forastero, in the trade name basic or bulk cocoa, occurs mainly in West Africa and Brazil. Criollo (flavour cocoa) is largely grown in Central and South America. West Africa now produces over 70\% of world cocoa (Amoye, 2006). New demand for fair trade and premium products has stimulated improvements in quality assurance that make possible single variety and origin chocolates (Table 1).

Primary chocolate categories are dark, milk and white that differ in content of cocoa solid, milk fat and cocoa butter. The outcome is varying proportions of carbohydrate, fat and protein (Table 2). Chocolate manufacturing processes (Awua, 2002; Beckett, 2000; Whitefield, 2005) differ due to variation in national consumer preferences and company practices.

Central to sensory character is continuous phase lipid composition, which influences mouthfeel and melting properties. Chocolate triglycerides are dominated by saturated stearic (34\%) and palmitic (27\%) fatty acids and monounsaturated oleic acid (34\%). Chocolates are solid at ambient (20−25 °C) and melt at oral temperature (37 °C) during consumption giving a smooth suspension of particulate solids in cocoa butter and milk fat (Beckett, 1999; Whitefield, 2005). This constrains lipid composition. The oral epithelia are also sensitive to gradations of smoothness which selects for desirable lipid crystal forms.

Despite high lipid and sugar contents, chocolate consumption makes a positive contribution to human nutrition through provision of antioxidants, principally polyphenols including flavonoids such as epicatechin, catechin and notably the procyanidins. White chocolates differ from milk and dark through the absence of cocoa nibs containing antioxidants, reducing product shelf-life (Beckett, 2000; Whitefield, 2005). Chocolates also contain minerals, specifically potassium, magnesium, copper and iron (Holland, Welch, Unwin, Buss, & Paul, 1991). Differences in the sensory characters of chocolate can be attributed to use of different cocoa types, variations in ingredient proportions, use of milk crumb instead of milk powder, blending techniques and processing methods. Specifications depend on type of chocolate and its intended use (Jackson, 1999).
Table 1. Definition of some technical words used

<table>
<thead>
<tr>
<th>Technical word used</th>
<th>Definition</th>
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<tr>
<td>Bloom</td>
<td>Fat or sugar on the surface of chocolate giving it white sheen or sometimes individual white blobs.</td>
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<tr>
<td>Cocoa butter equivalent (CBE)</td>
<td>Vegetable fats totally compatible with cocoa butter and can be mixed with it in proportions stipulated by regulation.</td>
</tr>
<tr>
<td>Cocoa butter replacer (CBR)</td>
<td>Vegetable fats that may be mixed with cocoa butter but only in a limited proportion by regulation.</td>
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<tr>
<td>Cocoa nib</td>
<td>Cocoa cotyledon, bean with shells removed.</td>
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<tr>
<td>Cocoa liquor, cocoa mass</td>
<td>Roasted, ground cocoa nibs.</td>
</tr>
<tr>
<td>Origin liquor</td>
<td>Cocoa mass manufactured in country of bean origin.</td>
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<tr>
<td>Non-Newtonian liquid</td>
<td>A liquid such as molten chocolate whose viscosity varies according to rate of stirring (shear).</td>
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<td>Plastic viscosity</td>
<td>Amount of energy required to keep a non-Newtonian liquid moving once motion has been initiated.</td>
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<tr>
<td>Yield value</td>
<td>Amount of energy required to initiate motion in a non-Newtonian liquid, e.g. molten chocolate.</td>
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<tr>
<td>Casson equation</td>
<td>[ \tau = \sqrt{\frac{\rho}{\mu}} + \sqrt{\frac{\mu_s}{\rho \mu}} \sqrt{\gamma} ] Variable definitions: ( \tau ): yield stress; ( \mu_s ): Casson yield stress; ( \mu ): Casson viscosity; and ( \gamma ): shear rate.</td>
</tr>
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As chocolates melt in the mouth the continuous fat phase inverts into the oral continuous aqueous phase mixing with saliva that dissolves the sugar particles. Lipids and cocoa solids coat oral epithelial surfaces. Oral particle dissolution influences perception of coarseness and solvation at rates corresponding to size and work input such as mastication, tongue compression and swallowing (Lee & Pangborn, 1986). Particle size distribution and ingredient composition therefore influence perception of primary taste (gustation) and oral volatiles release with retronasal flavour characters in magnitude and temporal profile.

Rheological properties of chocolate are important in manufacturing process for obtaining high-quality products with well-defined texture (Servais, Ranc, & Roberts, 2004). Chocolates with high viscosity have a pasty mouth-feel, persisting in the mouth (Beckett, 2000). Viscosity relates to composition, processing strategy and particle size distribution. Apparent viscosity in aqueous solutions influences flavour “by-mouth” and taste intensity during consumption (Denker et al., 2006), thus rheological measurements often give information related to sensory character of chocolate.

This article assesses current information relating processing strategy, particle size distribution and ingredient composition to rheological and sensory qualities in chocolates.

The initial stages of the chocolate manufacturing processes

In cocoa pods, 30–50 white pulp-covered seeds reach maturity after 4–6 months and contain two cotyledons (nibs) that yield cocoa mass for chocolate manufacture or when pressed, cocoa butter and cocoa powder (Fowler, 1999; Whitefield, 2005). Chemical reactions during processing for cocoa solids are complex contributing to final flavour and textural properties and have been reviewed (Awua, 2002; Beckett, 2000; Minifie, 1989).

Enzymic and microbial fermentations after harvest induce physical and chemical changes in beans over 5 to 7 days (Fowler, 1999) with key browning reactions of polyphenol with proteins (ca. 12–15% total) and peptides giving colours characteristic of cocoa. Fermentation reactions have been reviewed by Fowler (1999) and Beckett (2000). Drying limits mould growth during transportation and storage, reducing bean moisture content from 60 to 8%. Sun drying is favoured for flavour development and can be carried out above or on hard surfaces, with differences in air flow (Amoye, 2006) and final moisture content (Fowler, 1999).

Beans are transported under controlled storage conditions to chocolate manufacturing sites, or processed in the origin country to add value with requirements for traceability in quality assurance (Whitefield, 2005).

Beans are roasted before or after winnowing with shells broken by high-speed impact against metal plates. Heat transfer in nib roasting is facilitated by grinding of cotyledons. Liquor roasting (Awua, 2002) uses a prior liquefaction. In roasting moisture contents fall to <3% and Maillard reactions of amino acids, from fermentation protease activities, yield flavour-active aldehydes with chocolate notes. Fermentation-derived volatile acids are also removed influencing astringency and taste. Roasting temperature (90–170 °C) and time influence nib composition, as does rate of moisture loss and whether moist or dry roasted (Awua, 2002; Whitefield, 2005). Grinding of nib cells releases cocoa butter into a liquor with particle size up to 30 μm and for production of cocoa powder, fine grinding is particularly important. Typically ca. 78–90% cocoa butter is collected by pressing; residual lipids may be removed by supercritical fluid extraction (Beckett, 2000).

Chocolate manufacturing processes generally share common features (Fig. 1) such as mixing, refining and conching of chocolate paste. The outcome sought is smooth textures of products considered desirable in modern confectionery and elimination of oral perceptions of grittiness.

Table 2. Dark, milk and white chocolate: major constituents

<table>
<thead>
<tr>
<th>Product</th>
<th>Carbohydrate (%)</th>
<th>Fat (%)</th>
<th>Protein (%)</th>
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<tbody>
<tr>
<td>Dark chocolate</td>
<td>63.5</td>
<td>28.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Milk chocolate</td>
<td>56.9</td>
<td>30.7</td>
<td>7.7</td>
</tr>
<tr>
<td>White chocolate</td>
<td>58.3</td>
<td>30.9</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Source: Chan, Brown, and Buss (1994).
Chocolates contain cocoa liquor, sugar, cocoa butter, milk fat and milk powder (depending on product category). A mix of sugar, milk solids and cocoa liquor at an overall fat content of 8–24% is refined to particle size <30 µm normally using a combination of two- and five-roll refiners (Beckett, 1999, 2000). Final particle size critically influences the rheological and sensory properties. A five-roll refiner consists of a vertical array of four hollow cylinders, temperature controlled by internal water flow, held together by hydraulic pressure. A thin film of chocolate is attracted to increasingly faster rollers, travelling up the refiner until removed by a knife blade. Roller shearing fragments solid particles, coating new surfaces with lipid so that these become active, absorbing volatile flavour compounds from cocoa components.

Texture in milk chocolate appears improved by a bimodal distribution of particles with a small proportion having sizes up to 65 µm. Optimum particle size for dark chocolate is lower at <35 µm although values are influenced by product and composition (Awua, 2002). Refiners, in summary, not only effect particle size reduction and agglomerate breakdown but also distribute particles through the continuous phase coating each with lipid. Refined mixtures then move into conching, a process that contributes to development of viscosity and final texture and flavour. This is the endpoint for manufacture of

![Fig. 1. Processing steps for chocolate manufacture: (a) Skimmed milk powder is only used in milk chocolate manufacture; (b) panning means that the chocolate is used as coating for hard centres such as nuts (Babin, 2005) with some modification.](image-url)
bulk chocolate. Conching is normally carried out by agitating chocolate at >50 °C for few hours (Beckett, 2000). In the early stages moisture is reduced with removal of certain undesirable flavour-active volatiles and subsequently interactions between disperse and continuous phase are promoted. Conching times and temperatures vary (Awua, 2002) typically: for milk crumb, −10 to 16 h at 49–52 °C; with milk powder products, 16–24 h at up to 60 °C; and with dark chocolates at 70 °C and continue up to 82 °C. Replacing full-fat milk powder with skim milk powder and butter fat, temperatures up to 70 °C may be used (Awua, 2002). To give chocolate a suitable viscosity, additional cocoa butter and lecithin can be added towards the end of conching to thin chocolate prior to tempering (Beckett, 2000; Whitefield, 2005).

**Lipid crystallization and continuous phase character during chocolate manufacture**

Cocoa butter can crystallize in a number of polymorphic forms as a function of triglyceride composition, with fatty acid composition influencing how liquid fat solidifies (Awua, 2002). Cocoa butter has six polymorphic forms (I–VI), the principal being α, β and β′ (Table 3). Form V a β, is the most desirable form (in general) in well-tempered chocolate, giving a glossy appearance, good snap, contraction and resistance to bloom (Beckett, 2000).

If chocolate is poorly tempered, the outcome is the β form IV which rapidly transforms into form V. This influences colour as reflected light is disoriented by unstable, disorganised crystal growth. Untempered chocolate is soft and not effectively demoulded. In cocoa, butter forms V and VI are the most stable forms. Form VI is difficult to generate although formed on lengthy storage of tempered chocolate accompanied by fat bloom. In addition form VI has a high melting temperature (36 °C), and crystals that are large and gritty on the tongue. The unstable form I has a melting point of 17 °C and is rapidly converted into form II that transforms more slowly into III and IV. Polymorphic triglyceride forms differ in distance between fatty acid chains, angle of tilt relative to plane of chain end methyl group and manner in which triglycerides pack in crystallization (Talbot, 1999).

**Table 3. Melting point and chain packing of the polymorphic forms of cocoa butter**

<table>
<thead>
<tr>
<th>Polymorphic forms of cocoa butter</th>
<th>Melting point (°C)</th>
<th>Chain packing</th>
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<tbody>
<tr>
<td>Form I β2</td>
<td>16–18</td>
<td>Double</td>
</tr>
<tr>
<td>Form II α</td>
<td>21–22</td>
<td>Double</td>
</tr>
<tr>
<td>Form III Mixed</td>
<td>25.5</td>
<td>Double</td>
</tr>
<tr>
<td>Form IV β1</td>
<td>27–29</td>
<td>Double</td>
</tr>
<tr>
<td>Form V β2</td>
<td>34–35</td>
<td>Triple</td>
</tr>
<tr>
<td>Form VI β1</td>
<td>36</td>
<td>Triple</td>
</tr>
</tbody>
</table>


Polymorphic form is determined by processing conditions. Fatty acids crystallize in a double- or triple-chain form depending on triglyceride composition and positional distribution. Form IV crystallizes in a double-chain form, form V in a triple-chain system that enables closer packing and greater thermodynamic stability. Unstable lower polymorphic forms (II and III) transform into higher melting, more stable forms, with closer packing and lower volume. These changes can be observed in terms of overall contraction of the chocolate, appearance, or undesirable fat bloom formation at rates dependent on relative stabilities of the polymorphic forms and temperature (Talbot, 1999). For chocolate to be in an appropriate polymorphic form, tempering is crucial, influencing final quality characteristics such as colour, hardness, handling, finish and shelf-life characteristics.

Tempering involves pre-crystallization of a small proportion of triglycerides, with crystals forming nuclei (1–3% total) for remaining lipid to set in the correct form. Tempering has four key steps: melting to completion (at 50 °C), cooling to point of crystallization (at 32 °C), crystallization (at 27 °C), and conversion of any unstable crystals (at 29–31 °C) (Talbot, 1999) (Fig. 2). Tempering sequence is a function of recipe, equipment, and the final purpose. Before the use of tempering machines, chocolate used to be hand-tempered, and this method is still occasionally used by Chocolatiers, who produce relatively small quantities of hand-made confections. Current tempering machines consist of multistage heat exchangers through which chocolate passes at widely differing rates making it difficult to identify optimum conditions. Time—temperature combinations are of paramount importance in process design and in continuous tempering, molten chocolate is usually held at 45 °C then gently cooled to initiate crystal growth.

Working with the Buhler “Masterseeder”, Windhab (ETH Zurich, Switzerland) and Mehrle (Buhler AG, Uzwil, Switzerland) found that high shear seed tempering can be beneficial as the kinetics of fat crystal nucleation and

![Fig. 2. Tempering sequence during lipid crystallization in chocolates.](image-url)
polymorphic transformations ($\alpha \rightarrow \beta_2 \rightarrow \beta_1'$) are strongly accelerated by shear forces acting in high shear flow fields: overall quality of products was better, as fat bloom was reduced (Windhab et al., 2002). During tempering, the temperatures are precisely controlled and agitation provided enhances nucleation rates. As the viscosity increases, the chocolate is reheated again in the third stage to prevent runaway solidification. In the fourth stage, crystals are matured.

Chocolate can also be tempered by the use of high pressure (Yaseda & Mochizuki, 1992) with molten chocolate compressed to 150 bar. This increases chocolate melting point and causes it to solidify into solid crystals of all polymorphic forms. When pressure is released, lower polymorphic forms melt leaving behind tempered chocolate. Subsequent batches can be seeded with stable fat crystals.

A well-tempered chocolate will have the following properties: good shape, colour, gloss, contraction from the mould, better weight control, stable product — harder and more heat resistant (fewer finger marks during packaging) and longer shelf-life. The tempering regime for milk chocolate slightly differs from that for dark due to the influence of milk fat molecules on crystal lattice formation (Haylock & Dodds, 1999). Milk chocolate contains a proportion of butter fat that causes an eutectic effect, which prevents bloom formation, results in a lower melting point, softening of texture and lowering of temperature to obtain crystal seed for the tempering process (around 29.4 °C compared to 34.5 °C for plain chocolate). Cocoa butter equivalents (CBEs) and replacers (CBRs) may also find application in the chocolate industry. While cocoa butter equivalents are compatible with cocoa butter, cocoa butter replacers (CBRs), which do not require tempering, can only be used if almost all the cocoa butter is replaced. These CBRs melt in the same temperature range as cocoa butter, but crystallize only in the $\beta'$ form (Talbot, 1999; Whitefield, 2005).

More recently, the effect of shear on chocolate or cocoa butter tempering has been studied in a number of different flow geometries, for example, scraped surface heat exchanger with cocoa butter and chocolate (Bolliger, Zeng, & Windhab, 1999), Couette geometry with milk chocolate (Stapley, Tewkesbury, & Fryer, 1999) and cocoa butter (Mazzanti, Guthrie, Sirota, Marangoni, & Idziak, 2003), cone and plate system with cocoa butter (Dhonsi & Stapley, 2006; MacMillan et al., 2002), parallel plate viscometer with milk chocolate (Briggs & Wang, 2004), and a helical ribbon device with cocoa butter (Toro-Vazquez, Perez-Martinez, Dibildox-Alvarado, Charo-Alonso, & Reyes-Hernandez, 2004).

**Particle size distribution in chocolate**

Particle size distribution is a key determinant of the flow (rheological) properties in chocolates with a direct influence on sensory perception. Beckett (2000) concluded that the largest particles are important for mouthfeel with respect to grittiness, but the smaller ones are more important with respect to chocolate flow properties. Traditionally, continental European chocolate has been described as having a fineness of 15–22 µm particle diameter, and that in North America 20–30 µm (Jackson, 1999). However, with increased globalization of the industry, traditional differences have begun to blur with specifications becoming much more product specific.

Particle size distribution has been used as a tool to control consistency of solid—liquid mixtures to aid pumping and mixing of molten milk chocolate (Mongia & Ziegler, 2000), transportation, atomization, and grinding of foods of high solid content in milk suspensions (Saeseaw, Shiwatana, & Siripinyanond, 2005), and α-limonene (Sootitantawat et al., 2005). Malvern Instrument identified applicability of their laser diffraction instrument for near-line chocolate process control, indicating the importance of particle size distribution for fluidity control. Understanding and control of factors influencing fluid performance during high solid content processing is necessary with increasing competitiveness in modern chocolate manufacturing processing (Servais, Jones, & Roberts, 2002).

Optimization of particle size distribution in chocolate requires consideration of palate sensitivity. For example, there is a maximum particle size of 30 µm, or a product is perceived as ‘gritty or coarse’ in the mouth. Particle size affects viscosity as well as texture, and a chocolate milled to a maximum particle size of 20 µm will have a creamier taste and texture than that with 30 µm. Particle size distribution plays clear roles in process fluidity, but is generally restricted to experienced-based empirical knowledge (Beckett, 2000). Several clear examples of particle size distribution optimization show improvement in process efficiency and/or yield in food manufacture. In apple juices (Missaire, Qiu, & Rao, 1990) and in mustard (Aguilar, Rizvi, Ramirez, & Inida, 1991) bimodal particle size distribution promoted viscosity reduction and better mixing yielding improvements in final product shear, time and temperature stability. Villagran, McCabe, and Wong (1996) patented a process for reduced fat nut spreads. The process results in bimodal particle size distribution and reduction of spread viscosity, allowing the low fat spread to display the “desirable fluidity, texture and flavour”.

A widely appreciated example of a solid suspension is chocolate, a polydisperse suspension of sugar, cocoa and/or milk solids in a Newtonian fluid (fat phase), hence the applicability of Casson’s equation (Table 1) can model chocolate flow behaviour (Beckett, 2000) where solid content varies from 65 to 75%. Many chocolate products have bimodal and trimodal particle size distribution. A typical particle size distribution of commercial enrobing mass is given in Fig. 3. In bimodal distributions, minima are generally located around 15–25 µm.

Particle size distribution influences chocolate rheology (Chevalley, 1999), with specific surface area and mean particle size influencing yield stress (Beckett, 2000). Bouzas and Brown (1995) noted that “a chocolate with particles
sized according to the infinite modal distribution may give the lowest plastic viscosity”. Aguilar and Ziegler (1995) employed a bimodal particle size distribution for a controlled reduction in viscosity. Servais et al. (2002) reported that in blends of chocolates of fine \((d_{a,3} = 8.5 \mu m)\) and coarse \((d_{a,3} = 17.0 \mu m)\) particles, varying the blend ratio, influenced relationship between packing fraction and the shear viscosity with yield value closely related to mean particle diameter and particle specific surface area but not packing fraction. A ratio of 60% coarse particles to 40% fine particles gave lowest viscosity. Generally, chocolate viscosity is controlled by addition of cocoa butter and expensive viscosity modifiers (surface-active ingredients, such as soybean lecithin). Smaller particle sizes in chocolate are known to improve sensory properties (Ziegler, Mongia, & Hollender, 2001) but plastic viscosity and yield stress increase due to increased surface area of particles in contact with cocoa butter (Mongia & Ziegler, 2000). Clear benefits of particle size distribution optimization are reductions in viscosity modifiers and predictive process control.

Despite the application of particle size distribution in determining suspension flow properties, Awua (2002) and Whitefield (2005) explained that it is not the only factor influencing rheological characteristics. Thus, the general principles of modification of suspension viscosity by changing the particle size require review of a system’s properties and compositional factors that contribute to the changes in physical properties, flow behaviour and sensory character of chocolate.

**Compositional effects on rheological and textural qualities in chocolate**

The role of fats

Cocoa nibs consist of about 55% butter which constitutes around 30% of the final chocolate. Cocoa butter triglycerides have saturated fatty acids at the 1,3-positions and oleic acid at the 2-position. Fatty acid contents are around oleic (35%), stearic (34%) and palmitic acid (26%) in addition with polar lipids, sterols, and tocopherols (Talbot, 1999) each depending on factors such as growing conditions and origin. The simple glyceride composition makes chocolate melt over the temperature range of 23–37 °C. The lipid crystal form V (\(\beta'_v\)) is the desirable form in chocolate production and dominant in well-tempered chocolate (Beckett, 2000; Whitefield, 2005).

Some vegetable fats are similar to cocoa butter in triglyceride composition and such cocoa butter equivalents (CBEs) can be added in any proportion to chocolate without causing a significant effect on texture. Legally such vegetable fats are permitted up to 5% in the EU for a product to be sold as chocolate (Cocoa and Chocolate Products Regulations, 2003). Cocoa butter replacers (CBRs) such as the lauric fats, palm kernel or coconut oils, crystallize only in one crystal form, \(\beta'_v\), in a very different way and are used to totally replace cocoa butter (Talbot, 1999). Low-caloric fats such as caprenin, which contain fatty acids different from cocoa butter, and are poorly absorbed by the gut, also find application as CBRs. With non-lauric fats, some cocoa butter can be used (Babin, 2005) and the mix can be tempered normally.

Most chocolates contain between 25 and 35% fat, although ice-cream coatings are much higher and some special products like cooking chocolate and vermicelli pieces are lower in fat. The actual level present will depend on the process being used and this affects the texture of the finished chocolate, so a high-quality tablet of chocolate is likely to have a higher fat content and a lower particle size than a chocolate that is used to coat a biscuit (Beckett, 2000). The effect of an extra 1% of fat upon the viscosity depends upon the amount already present and the viscosity parameters being considered. Above fat content of 32% there is very little change in viscosity with any further additions. A 1% increase to a 28% fat content has a really dramatic effect especially on the plastic viscosity, which is almost halved. The change becomes more dramatic at even lower fat contents as ‘chocolates’ below 23% fat are normally a paste rather than a liquid (Beckett, 2000).

The effect of fat is proportionately much higher for the plastic viscosity than the yield value. Beckett (2000) explained that this phenomenon is not surprising as the extra fat only adds to the free moving fat that aids particles when they flow past each other. The majority of the fat is ‘wetting’ fat, which is partially tied to the particle surfaces. This free fat has a large effect on lubricating the flow when it takes place and so the plastic viscosity decreases dramatically. The yield value is more pronounced with the forces between the solid particles, which in turn are connected with the absolute distance between them, hence their less effect with fat additions.

The role of sugar

Sugar is considered an inert ingredient in chocolate with regard to subtleties of flavour, contributing “only” to sweetness. A change of 1–2% in sugar content has a great

**Fig. 3.** Particle size distribution of commercial enrobing mass during chocolate manufacture.
effect on costs and other economic factors, and at 5% change large flavour changes become apparent (Beckett, 1999). Fine crystalline sucrose is utilized at up to 50% in chocolate confectionery (Krüger, 1999). Lactose, in milk solids, is present at lower levels in an amorphous form and in its glassy state holds a proportion of milk fat (Beckett, 2000), influencing chocolate flavour and flow properties. Lactose enhances the browning by participating in Maillard reactions (Bolenz, Amtsberg, & Schape, 2006; Krüger, 1999). Monosaccharides, glucose and fructose, are rarely used in chocolate as they are difficult to dry. Consequently, the additional moisture present in chocolate would increase interactions between sugar particles, and increase viscosity. Dextrose and lactose can successfully replace sucrose in milk chocolate (Bolenz et al., 2006; Müller, 2003).

In recent years, sucrose-free chocolates have become popular among consumers and manufacturers because of reduced calorific values, and the fact that these are both noncariogenic and suitable for diabetics (Olinger, 1994; Olinger & Pepper, 2001; Sokmen & Gunes, 2006; Zumbe & Grosso, 1993). Sugar alcohols, including xylitol, sorbitol, mannitol and lactitol are used for the manufacture of lower-calorie or sugar-free products. Replacement of sucrose with sugar alcohols however affects rheological properties and thus the processing conditions and quality of chocolates (Sokmen & Gunes, 2006; Wijers & Sträter, 2001; Zumbe & Grosso, 1993). Sokmen and Gunes (2006) noted that maltitol results in similar rheological properties of chocolate to sucrose, and thus may be recommended as a good alternative to sucrose in chocolate formulations. These authors also observed that chocolate with isomalt resulted in higher plastic viscosity while xyitol causes higher flow behaviour index. Polydextrose may be added as an edible carbohydrate and intense sweeteners used. The EU limits consumption of sugar alcohols to 20 g per day due to laxative effects (Krüger, 1999).

The role of milk and other dairy components

As water binds sugar particles, milk solids rather than liquid milk is added to chocolate contributing about 12–25%. Milk contains about 5% lactose, 5% milk fat, 3.5% protein and 0.7% minerals. Milk fat triglycerides, dominated by saturated fatty acids, exhibit a different crystalline structure although present are adequate amounts of palmitic, stearic and oleic acid, the main fatty acids found in cocoa butter (Haylock & Dodds, 1999). Milk fat is mainly liquid (15–20% solid) at ambient, and softens chocolate texture, slows setting, and is used at up to 30% of the total fat content (German & Dillard, 1998), inhibiting fat bloom. Milk fat is prone to oxidation and influences shelf-life (Haylock & Dodds, 1999).

Milk proteins add to the perceived creaminess of milk chocolate and at 80% caseins and 20% whey proteins, the casein fraction act as surfactants and reduces viscosity of chocolate, whey proteins in contrast increase viscosity (Haylock & Dodds, 1999). Milk solids added as spray-dried skimmed milk powder or full cream milk powder contribute to flavour, texture and liquid flow properties dependent on heat treatment and drying conditions. Milk fat is free to react with the cocoa butter when mixed with skim milk powder but strongly bound in full cream milk powder. Skim milk powder softens cocoa butter to an extent (Haylock & Dodds, 1999) and addition of milk solids in the form of chocolate crumb is preferred in certain European countries. Chocolate crumb, developed when cocoa liquor is mixed with sugar—milk mass and vacuum dried, is characterized by a brown colour and slightly cooked flavour. Crumb has a longer shelf-life than milk powder as the chocolate liquor provides natural antioxidants—flavonoids (Holland et al., 1991), stabilizing it against rancidity (Beckett, 2000; Haylock & Dodds, 1999). Chocolate flavours vary depending on the crumb processing conditions. Whey and lactose powders can be used to reduce sweetness in some chocolate confectionery. Demineralized whey powder is preferred to avoid off-flavour generation (Haylock & Dodds, 1999).

The role of surfactants in modern chocolate confectionery

Chocolate has a continuous fat phase in which sugar, being hydrophilic and lipophobic will not dissolve, so surfaces have to be coated with fat. This does not occur readily and a surface-active agent is beneficial and allows the fat content of the chocolate to be reduced while maintaining desirable flow properties. Choice of natural surfactant—gums, lecithin, soluble polysaccharides or synthetic (carboxymethyl cellulose) — depends upon function in the end-product (Schantz & Rohm, 2005).

Lecithin, a by-product of soya-oil production, is a mixture of natural phosphoglycerides (Minifie, 1989). In chocolate the most surface-active component of crude lecithin (mainly oleic C18:1 and palmitic acid C16:0), is believed to be phosphatidylcholine (Vernier, 1998). Lecithin addition dramatically changes yield value and plastic viscosity and when added at between 0.1 and 0.3% reduces chocolate viscosity and enhances toleration of higher moisture levels. At more than 0.5%, yield value increases while plastic viscosity continues to fall (Chevalley, 1999; Rector, 2000; Schantz & Rohm, 2005). Increase in yield value is linked to micelle formation in the continuous phase possibly as multi-layers around sugar, which hinders flow. Alternatively, reverse micelles may form in the continuous phase and interact with fully covered sugar particles, consequently increasing yield value (Vernier, 1998). Thickening depends on the particle size distribution as smaller particles require more lecithin to coat sugar surfaces. Lecithin can only be added up to 1% but will always be present in chocolate as traces from both cocoa and milk.

Polylglycerol polyricinoleate (PGPR), obtained by polycondensation of castor oil and glycerol, is a complex mixture with polylglycerol component dominated by
di-, tri- and tetraglycerols (Vernier, 1998). Legally approved within the EU, PGPR can be used in cocoa-based confectionery at up to 0.5% (Rector, 2000). It does not have large effects on plastic viscosity but can reduce yield value by 50% at 0.2% or remove it at about 0.8% (Rector, 2000; Schantz & Rohm, 2005), turning chocolate into a Newtonian liquid so that it flows more readily and settles rapidly. A similar outcome can be achieved by adding more cocoa butter at greater cost as PGPR coats solid particles, displacing cocoa butter to the continuous phase, decreasing yield value. Rector (2000) reported that chocolate with 35% cocoa butter has a similar yield value to that containing 32% cocoa butter and 0.1% PGPR. PGPR coats solid particles and with higher molecular weight, extends further into the lipid continuous phase, producing a better steric stabilization (Vernier, 1998). In contrast to lecithin, PGPR in chocolate does not structure within the suspension, but increases the continuous phase volume fraction and binds residual water in chocolate, making it unavailable to hydrate and swell the solid particles (Rector, 2000; Schantz & Rohm, 2005).

In recent developments, many chocolate manufacturers use PGPR and lecithin in combination for a desirable yield value and plastic viscosity — balancing out viscosity-reducing effects (Schantz & Rohm, 2005; Vernier, 1998). Adding PGPR to chocolate containing 0.5% of lecithin, gives a further decrease in yield value and only slight increase in plastic viscosity (Rector, 2000). Increases in plastic viscosity at lecithin concentrations above 0.5% are uncontrolled, effects on yield value reduction by adding PGPR have greater influence on the flow properties of chocolate (Rector, 2000). PGPR seems less effective in inhibiting bloom formation (Walter & Cornillon, 2001).

Glycerol mono stearates (GMS) widely used in confectionery industries are formed by the incomplete esterification of hydroxyl groups of glycerol using a single fatty acid (Heath, 1982). Vernier (1998) reported glycerol fatty acid esters were inefficient at reducing yield value and increased plastic viscosity through less efficient coverage of sugar particles, thus leading to greater friction. A mixture of sorbitan and glycerol esters of fatty acids give yield values similar to lecithin but higher plastic viscosity (Rousset, Sellappan, & Daoud, 2002; Vernier, 1998).

**Moisture and chocolate flow**

Molten chocolate typically has moisture contents of 0.5—1.5%, mainly in the cocoa solids, that does not affect chocolate flow. Greater moisture aggregates sugar particles to form gritty lumps and moisture at sugar particle surfaces increases friction and apparent viscosity. Beckett (2000) stated that for every 0.3% of extra moisture left within the chocolate at the end of conching, the manufacturer must add an extra 1% fat, and because fat is by far the most expensive major component in chocolate, it is important that as much ‘free’ water is removed as possible. Water at 3—4% increases viscosity and yield value of chocolate markedly (Chevalley, 1999) and viscosity increases up to 20% moisture, after which an aqueous phase is formed (Beckett, 2000).

**Conclusion and further research**

The physical properties, rheological behaviour and sensory perception of chocolate are influenced largely by its processing techniques, particle size distribution and ingredient composition. To enhance chocolate texture, solid particle size distribution and ingredient composition can be manipulated to modify the physical properties, rheological behaviour and sensorial attributes. Several improvements have been made in recent years on chocolate quality using varying processing strategies and ingredient composition. However, the use of particle size distribution and ingredient composition as tools to modify the rheological behaviour and sensory properties of chocolate still require a greater understanding of underlying principles and factors affecting changes in flow behaviour. Thus, factors shaping chocolate character during and after its manufacture require much in-depth investigation.

Further studies require integration of sensory and instrumental analyses of texture and flavour release and characterizations of effects of tempering on melting behaviour of chocolate.

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**References**


Bolliger, S., Zeng, Y., & Windhab, E. J. (1999). In-line measurement of tempered cocoa butter and chocolate by means of near-infrared