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Impact of cocoa fibers on the stability and rheological properties of chocolate ganaches

Fadi Merachli^a, Julia Devienne^a, Romain Delmas^b, Laurent Plawinski^b, Fernando Leal-Calderon^b, Mathieu Delample^{a,*}

extent of partial coalescence.

^a CRT AGIR, 37 Avenue Albert Schweitzer, BP 100, Talence Cedex, France

^b Université de Bordeaux, CNRS, Bordeaux INP, CBMN UMR 5248, 33600, Pessac, France

| ARTICLE INFO | A B S T R A C T |
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| Keywords: Chocolate ganaches Partial coalescence Cocoa fibers Jamming transition Rheological behavior | This work investigates the structure and behavior of model oil-in-water chocolate ganaches by comparing two systems differing in the nature of the dispersed (fat) phase: cocoa butter and cocoa mass (mix of cocoa butter and fibers). Significant differences regarding the textural properties and stability were evidenced. Concentrated liquid emulsions made with cocoa butter had a thick and homogeneous macroscopic aspect. Upon cooling, fat crystallization produced partial coalescence and the emulsions became solid. With molten cocoa mass, a homogeneous aspect was observed until 50 g/100 g of dispersed phase and a grainy texture was obtained at larger fractions. This textural transition was interpreted as being due to a jamming transition. Both conventional and fluorescence microscopy revealed that cocoa fibers were transferred from the fat phase to the aqueous phase and were partially anchored to the interfaces. Upon cooling, cocoa fibers acted as a physical barrier that limited the |

1. Introduction

A chocolate ganache is generally obtained by mixing a dense cream and chocolate or cocoa butter. In industrial conditions, a hot cream is poured into molten chocolate. Depending on the chocolate type (dark, milk or white) and on the respective quantities of the two main ingredients, various textures can be obtained from fluids to pastes (Saglio, Bourgeay, Socrate, Canette, & Cuvelier, 2018). Ganaches can be consumed as end products or can be further used for many applications such as fillings in bakery, pastry or confectionary food products.

A ganache comprises an aqueous and a fat phase, which are intrinsically immiscible. The fat phase is generally composed of triglycerides that are partially crystallized depending of the proportion of saturated and unsaturated fatty acids. According to Saglio et al. (2018), the total proportion of fat in ganaches is generally between 20 and 40 g/100 g. However, the fat content may fall out of this range depending on the chocolate/heavy cream ratio and on the chocolate composition. For instance, the fat content in a 2:1 chocolate/heavy cream mixture may reach 55–60 g/100 g of emulsion. Ganaches are referred to as emulsions, since they are made of droplets of one phase finely dispersed into the other phase. Emulsions are metastable materials whose kinetic stability is generally ensured by amphiphilic molecules (emulsifiers) adsorbed at the oil/water interface, like surfactants or proteins, (Leal-Calderon, Schmitt, & Bibette, 2007,). Depending on several parameters such as the manufacturing process, the emulsifiers used and the proportion of the two immiscible phases, the emulsion can be of the Oil-in-Water (O/W) or of the Water-in-Oil type (W/O). Following the well-known Bancroft rule (Bancroft, 1912), the most influencing parameter with respect to the emulsion type is the preferential solubility of the emulsifier: the continuous phase of the preferred emulsion is the one that solubilizes the emulsifier. Proteins like casein naturally present in the aqueous phase of heavy creams favor the formation of O/W ganaches. Conversely, oil-soluble emulsifiers like lecithin or PolyRicinoleate of PolyGlycerol (PGPR) tend to form W/O ganaches (Norton & Fryer, 2012; Norton, Fryer, Parkinson, & Cox, 2009; Schantz & Rohm, 2005).

Once fabricated, emulsions may undergo several types of instabilities such as flocculation, creaming, coalescence and Ostwald ripening (McClements & Jafari, 2018). In the case of emulsions whose dispersed phase is partially crystallized, a specific instability named partial coalescence may happen (Fredrick, Walstra, & Dewettnick, 2010; Munk & Andersen, 2015; Petrut, Danthine, & Blecker, 2016). Emulsions based on crystallizable oils (fats) are fabricated at a temperature such that oil in

* Corresponding author. *E-mail address*: m.delample@agir-crt.com (M. Delample).

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fully melted. Upon cooling, the smooth spherical surface of the droplets becomes rough because of the formation of irregularly shaped and randomly oriented crystals. Such protruding crystals can pierce the thin film in between droplets and bridge their surfaces. The shape relation induced by surface tension that would lead to a single spherical drop is inhibited because the droplets are rigid. The process may lead to the formation of a gel made of strands of semi-solid droplets (Fredrick et al., 2010; Saglio et al., 2018). The kinetics of the gelation process can be modulated by several parameters, including the type of fat crystals, the solid fat content, the crystal microstructure, the processing conditions and the size of the droplets (Fredrick et al., 2010; Moens, Tavernier, & Dewettinck, 2018; Thivilliers, Laurichesse, Saadaoui, Leal-Calderon, & Schmitt, 2008; Thivilliers-Arvis, Laurichesse, Schmitt & Leal-Calderon, 2010).

With liquid oil, proteins are able to stabilize O/W emulsions due to their amphiphilic properties. These hydrocolloids form a viscoelastic, dense and thick layer at the interface that provides an efficient protection against coalescence. Upon cooling, especially when crystallizable oils are used, this kind of protection may be insufficient especially for low protein/fat ratios where a fraction of the interfaces is uncovered resulting in partial coalescence (Frederick et al., 2010).

Amphiphilic particles can also be used to stabilize emulsions (Berton-Carabin & Shroën, 2015; Duffus, Norton, Smith, Norton, & Spyropoulos, 2016; Tavernier, Wijaya, Van der Meeren, Dewettinck, & Patel, 2016). Such systems are referred to as Pickering emulsions (Pickering, 1907; Ramsden, 1903). Numerous food-grade particles can be used including starches, cellulose fibers, waxes, fat crystals, proteins aggregates (Campbell, Holt, Stoyanov, & Paunov, 2008; Destribats, Rouvet, Gehin-Delval, Schmitt & Binks., 2014; Yusoff & Murray, 2011). Their amphiphilic properties are of great interest as they allow replacing synthetic emulsifiers in foods. Solid particles can also be by-products of the agri-food industry like rapeseed press-cakes or cacao powder (Joseph, Savoire, Harscoat-Schiavo, Pintori, Monteil, Faure et al., 2019). Particles are irreversibly anchored at the oil-water interface thus providing an interfacial barrier against coalescence as soon as the interface is covered (Gould, Furse, & Wolf, 2016; Gould, Vieira, & Wolf, 2013; Joseph, Savoire, Harscoat-Schiavo, Pintori, Monteil, Leal-Calderon et al., 2019, 2020).

In this paper, we investigate the stabilization and rheological properties of model ganaches, i.e. O/W emulsions made with (i) cocoa butter and (ii) cocoa mass (*i.e.* cocoa butter + fibers) during emulsification at 45 °C and upon cooling. Despite the absence of milkfat globules, the colloidal structure is the same as in real ganaches, where fat droplets are dispersed in an aqueous phase containing proteins, sugar and potentially cocoa fibers released by chocolate in the aqueous phase. Emulsions at various fat droplet fractions were made with an aqueous phase comprising sodium caseinate and sucrose. By comparing the two fat types, we evidence the role of cocoa fibers. The systems were characterized by droplet sizing, phase contrast microscopy, fluorescence microscopy and oscillatory rheology. Overall, we demonstrate that the presence of cocoa fibers has profound consequences for the stability and texture of dense ganaches.

2. Materials and methods

2.1. Chemicals

Sodium caseinate (SC; Mw = 20,000 g/mol), sodium azide (NaN₃, used as a biocide) and sodium dodecyl sulphate (SDS) were purchased from Sigma Aldrich (Saint-Quentin Fallavier, France). D (+) sucrose (98% of purity) was supplied by Fluka (Illkirch, France). Cocoa butter (CB) and whole cocoa mass (CM) were provided by Barry Callebault (Louvier, France). According to the product specifications, CM is composed of (average values for 100 g): total fat, 54.5 g (saturated fatty acids, 32.8 g); available carbohydrates, 5.4 g; mono and disaccharides, 0.3 g; fibers, 18.6 g; total proteins, 11.6 g; sodium, 0.001 g. The water

used in the experiments was deionized with a resistivity close to 0.15 $M\Omega$ m at 20 $^\circ C.$

2.2. Emulsions fabrication

Emulsions were prepared in 250 mL beakers immersed in a water bath at 50 °C, a temperature allowing full melting of cocoa fat. Typical emulsion batches had a total mass of 100 g. O/W emulsions were prepared by drop-wise addition of either CB or CM to an aqueous phase containing 5 g/100 g SC, 0.08 g/100 g sodium azide and 55 g/100 g sucrose under manual stirring. The oil phase was incorporated up to 70 g/100 g of the O/W emulsions. The incorporation process never exceeded 10 min to limit water evaporation during the emulsification process.

In order to emulsify fat at relatively low shear rates, a relatively large viscosity is needed (Mabille et al., 2000). In our experiments, this was achieved by increasing the droplet fraction and by dissolving a large amount of proteins and sugar in the continuous phase. Although very simple, this method produced emulsions with reproducible droplet size distributions.

2.3. Droplet size measurements

The size distribution of the oil droplets was measured using a light scattering apparatus Mastersizer 2000 (Malvern, Malvern Hills, UK). Prior to the measurement, 1 g of emulsion was diluted in 10 mL of a 0.5 g/100 g sodium dodecyl sulphate (SDS) solution at 40 °C. This solution helped to deflocculate the aggregates of sodium caseinate and to remove fibers potentially adsorbed at the oil-water interface (Mackie, Gunning, Wilde, & Morris, 2000). Otherwise, size measurements would not be reliable since water-dispersed fibers scatter light. The emulsion was centrifuged at 220 g for 5 min (Rotanta 460 R F Centrifuge, Hettich Lab Technology, Nussloch, Germany) resulting in a phase separation between the oil droplets forming a white cream, a clear aqueous phase, and a brownish fibers sediment. The centrifugation rate was high enough to ensure rapid separation of the droplets and of the aqueous phase but low enough to avoid droplet recombination (Joseph, Savoire, Harscoat-Schiavo, Pintori, Monteil, Leal-Calderon et al., 2019).

A small volume of the dense cream phase was introduced in the inlet recipient connected to the measuring cell. The recipient was filled with water and agitated by means of a helix (1200 rpm). After homogenization (1 min), the static scattering pattern was measured and transformed into size distribution using Mie theory.

The droplet distributions were described in terms of their volumeaveraged diameter ($d_{[4,3]}$) and polydispersity (P), defined as

$$d_{[4,3]} = \frac{\sum N_i D_i^4}{\sum N_i D_i^3}; \quad P = \frac{1}{\overline{D}} \frac{\sum N_i D_i^3 (\overline{D} - D_i)}{\sum N_i D_i^3}$$

where \overline{D} is the median diameter and N_i is the total number of particles with diameter D_i .

2.4. Phase contrast microscopy

An Olympus BX51 (Zeiss, Munich, Germany) phase contrast microscope equipped with a digital camera was used to observe and take photomicrographs of the emulsions. To facilitate the observations, emulsions were diluted 10 times with deionized water. Then, a small amount of sample was spread on a glass slide mounted by a cover slip. The emulsions were viewed through the microscope to observe the shape and size of the suspended droplets.

2.5. Fluorescence microscopy

Emulsions based on CM were submitted to a ten-fold dilution with a hot aqueous phase prior to observations. After confining the sample between a glass slide and the cover slip, images were obtained using a Leica DM5500B microscope with a motorized and programmable stage and a CoolSnap HQ camera controlled by Metamorph 7.6.2. A filter cube N3 (Leica, Wetzlar, Germany) with an excitation wavelength around 546 nm and an emission wavelength around 600 nm was used. All images were acquired at the same exposure time (50 ms), using a 40x objective. Then, the images were processed using Image J freeware version (NIH, https://rsb.info.nih.gov/ij).

2.6. Rheological measurements

Oscillatory experiments were performed at 40 °C with an ARG2 rheometer (TA instruments, New Castle, Delaware, USA) on O/W emulsions based on either CB or CM. Oscillatory experiments were conducted in the linear regime, at a deformation amplitude of 0.1%, and at a frequency of 1 Hz. We adopted a parallel-plate geometry with a gap of 500 μ m and rough surfaces in order to avoid wall slipping. The emulsions were loaded in the cell of the rheometer very carefully and covered by a protection cap to avoid water evaporation; the sample compression during loading was the minimal possible and was always done at the smallest rate. Temperature within the sample was controlled with a precision of 0.1 °C via a thermoelectric Peltier module. All rheological measurements were conducted in triplicate and the deviation between experiments never exceeded 20%.

3. Results and discussion

3.1. Textural evolution during emulsification

We first describe the fabrication of emulsions based on CB. The oil phase was incorporated gradually up to 70 g/100 g of the total O/W emulsion mass. The micrographs of Fig. 1 show the macroscopic aspect of the sample at different stages of oil incorporation. As oil was added, the system became increasingly viscous, especially above 60 g/100 g (Fig. 1 a-c). In dispersions made of randomly distributed spheres, neighboring droplets are in permanent contact above a critical volume fraction generally close to 64%, named Random Close Packing Fraction (Radin, 2008; Scott, 1960; Van Acken, Vingerhoeds, & De Wijk, 2011). The dissipative behavior is then dominated by the friction at the level of the droplets contacts and the average viscosity increases dramatically.

Once fabricated, emulsions were observed under the microscope and characterized in terms of droplets size distribution. Fig. 1-d is a micrograph obtained immediately after fabrication, before fat crystallization took place. The liquid droplets had a regular spherical shape and a smooth surface. Their volume-averaged diameter was $d_{[4,3]} = 8.91 \mu m$ and their polydispersity P = 0.91 (Fig. 1e).

An emulsion based on CM was fabricated following the same procedure. The emulsion had a viscous and smooth texture as long as the cocoa fraction remained below ~ 50 g/100 g (Fig. 2-a). Above this fraction, the texture became rough and grainy, as observed in Fig. 2-b and c. Concomitantly, further oil incorporation required longer agitation time and more intense manual stirring. To facilitate microscope observations, the final emulsion was diluted with hot water (T = 45 $^{\circ}$ C). Fig. 2d reveals the presence of dark (i.e. light absorbing) particles fragments in the aqueous phase, attributed to cocoa fibers. Interestingly, they are located around transparent oil droplets. Such observations reveal that cocoa fibers are transferred from the oil phase to the aqueous phase during the emulsification process. The volume averaged size distribution of the oil droplets measured by light scattering was $d_{[4,3]} =$ 9.10 μ m and the polydispersity was P = 0.85 (Fig. 2e). We would like to emphasize that the pre-dilution of the emulsion in a SDS solution, as indicated in section 2.3, allowed the fibers to desorb from the interfaces so that the size distribution is that of the oils droplets alone.

The transition from a macroscopically smooth to a grainy texture is probably due to a jamming transition induced by interfacial roughness. Jamming was first observed in suspensions of solid spherical particles



Fig. 1. Dependence of the cocoa butter (CB) fraction on emulsions texture: (a) 40 g/100 g CB; (b) 60 g/100 g CB; (c) 70 g/100 g CB; (d) phase contrast microscopy image of CB droplets at the end of emulsification (the scale bar represents 100 μ m) and (e) corresponding particle size distribution for the higher proportion of droplet (70 g/100 g of CB).

submitted to an intense shear for which lubrication between spheres was inoperative (Cates, Wittmer, Bouchaud, & Claudin, 1998; Farr, Melrose, & Ball, 1997; Holmes, Fuchs, & Cates, 2003; Liu & Nagel, 1998; Melrose & Ball, 1995). This phenomenon was extended to colloidal systems where attractive interactions hinder the exploration of the accessible configurations (Bertrand, Bibette, & Schmitt, 2002; Holmes et al., 2003). In our case, cocoa fibers form a rigid and thick layer around the oil droplets, creating steric hindrance. It is likely that surface roughness of the drops provokes a restriction of the internal dynamics' characteristic of a jammed state.

3.2. Transfer of cocoa particles from the fat phase to the aqueous phase

In Fig. 3-a obtained under conventional light microscopy, we observe oil droplets as well cocoa particles. The same system was observed under florescent configuration. Cocoa fibers exhibit self-fluorescent properties owing to the presence of molecules in which π – π electronic delocalization takes place (*e.g.* polyphenols, tocopherols or theobromine) (Campos-Vega, Nieto-Figueroa, & Oomah, 2018). Consequently, cocoa particles can be observed by fluorescence microscopy without a fluorescent probe. Prior to the observations, other emulsions ingredients were analyzed independently. Neither SC, sucrose nor CB were fluorescent under these experimental conditions. The micrograph of Fig. 3-b reveals that the equatorial plane of the oil droplets is surrounded by bright fluorescent cocoa fibers. Particles attached to the interface are



Fig. 2. Dependence of the cocoa mass (CM) fraction on emulsions texture: (a) 40 g/100 g CM; (b) 60 g/100 g CM; (c) 70 g/100 g CM, (d) phase contrast microscopy image of CM droplets at the end of emulsification (the scale bar represents 50 μ m) and (e) corresponding particle size distribution for the higher proportion of droplet (70 g/100 g of CM).



Fig. 3. Microscopy observations of oil droplets surrounded by cocoa particles: (a) phase contrast microscopy; (b): same droplets observed under fluorescent mode; (c) equatorial section of a droplet and (d) the same droplet as (c) observed at the level of its apex (the scale bar represents 50 μ m).

clearly discernible. The same colloidal structure was observed by (Joseph, Savoire, Harscoat-Schiavo, Pintori, Monteil, Leal-Calderon et al., 2019) in Pickering O/W emulsion stabilized by cocoa powder. These authors showed that the particles were dispersed in the aqueous phase and were not present at all in the fat phase. The focal plane of the objective was displaced along the z (vertical) axis. The micrograph of Fig. 3-c obtained at the equatorial plane of a single oil droplet confirms the absence of particles in the droplets volume as well as their preferential location at the interface, on the water side. Fig. 3-d shows particles randomly distributed at the apex of the oil droplets.

In addition, when emulsions were diluted with water and submitted to gentle centrifugation, a brownish sediment was readily formed at the bottom of the sample, providing further evidence for the transfer of fibers into the aqueous phase (fibers are denser than water).

3.3. Cocoa fibers protection against partial coalescence

In order to assess the impact of cocoa fibers located around the oil droplets on stability, concentrated emulsions made with CB and CM ($\varphi_{oil} = 70 \text{ g}/100 \text{ g}$) were diluted at 50 g/100 g with a hot aqueous phase (T = 45 °C). Then, both systems were stored at 4 °C. At this temperature, the emulsions remained macroscopically homogeneous. Coalescence, if any, was necessarily partial (no shape relaxation) because of the



Fig. 4. Emulsions stored at 4 $^{\circ}$ C and warmed at 45 $^{\circ}$ C: (a) left: emulsion based on cocoa butter (top: cocoa butter; down: aqueous phase) and right: emulsion based on cocoa mass; (b): Droplets size distribution of the emulsion based on cocoa mass (70 g/100 g of CM). Red solid line: fresh emulsion; Red dashed line: emulsion stored for 24 h at 4 $^{\circ}$ C and warmed to 45 $^{\circ}$ C without agitation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

intrinsic firmness of the fat phase (Thivilliers et al., 2008). After 24 h et 4 °C, the emulsions were warmed up to 45 °C without any agitation. As shown in Fig. 4a (left), the system made with CB underwent rapid full phase separation with the oil phase residing at the top of the recipient, after a few minutes only. As the sample was warmed, the oil drops were fully molten, and shape relaxation occurred (Thivilliers et al., 2008). The macroscopic phase separation observed at 45 °C reflects the fact massive partial coalescence of the droplets occurred at 4 °C and that network of partially coalesced droplets was almost continuous.

Instead, the system made with CM remained macroscopically homogeneous at 45 °C, although the observation had to be considered with care because of the intrinsic darkness of the emulsion (Fig. 4a, right). The sample was redispersable in hot water, thus confirming that the emulsified structure was preserved. In Fig. 4b, we compare the size distributions before cooling (freshly prepared emulsion; red solid line) and in the final state after storage at 4 °C and warming at 45 °C (red dashed line). The size distribution shifts towards larger sizes as a result of partial coalescence ($d_{[4,3]} = 30.79 \,\mu$ m and the polydispersity was P = 0.58). However, in this case, the extent of partial coalescence is limited.

These experiments highlight the fact that the emulsion made with CM can withstand the crystallization-melting cycle, whereas the emulsion based on CB do not. The stability gain in the emulsion based on CB can be attributed to the presence of cocoa fibers that provides better interfacial protection -Pickering-type- than SC alone.

3.4. Rheological behavior of emulsions: contribution of cocoa fibers

Mother emulsions containing 70 g/100 g of dispersed phase (whole CM) were prepared and were diluted with hot aqueous phase to obtain daughter emulsions at variable volume fractions. We checked that the size distribution of the droplets remained invariant upon dilution. The freshly prepared emulsions were then analyzed by oscillatory rheology at 40 °C (Fig. 5). G' was always larger than G", reflecting the essentially elastic nature of the emulsions. For low φ values (<45 g/100 g), G' exhibits a weak dependence on ϕ . However, a sharp transition occurs above a threshold fraction, with a 10-fold increment of G' as ϕ varies from 45 to 55 g/100 g. These measurements are consistent with the above-mentioned macroscopic observations revealing a sudden change in the textural properties of the emulsions. Above 55 g/100 g, both the storage and loss moduli display a smoother dependence on volume fraction. Consequently, by gathering visual observations and rheological behavior, it can be stated that a jamming transition occurs in the range between 45 and 55 g/100 g (highlighted by a dedicated zone on the graph). The presence of cocoa fibers onto the droplets' surfaces induces interfacial roughness. By increasing the oil volume fraction, the average



Fig. 5. Rheological moduli as a function of the weight fraction of cocoa mass. The highlighted zone is where the jamming transition occurs. G': black squares; G': white circles.

distance between the interfaces decreases and the interfaces end up overlapping. Surface roughness then provokes a restriction of the droplets motion.

3.5. Evolution of the texture by addition of cocoa fibers

Cocoa fibers were selectively extracted from CM by successive additions of *n*-hexane. This process was repeated three times in order to remove completely cocoa butter. After four centrifugations ($40 \,^{\circ}$ C; 2000 rpm; 20 min), cocoa fibers were collected and dried during 24 h under vacuum.

Starting from a mother emulsion at 70 g/100 g CB, a series of 45 g/100 g daughter emulsions were made by dilution with a hot aqueous phase containing SC and sucrose. An increasing amount of extracted cocoa fibers was added in all samples between 0 and 25 g/100 g. Each sample was then carefully mixed by hand during 30 s. Rheological analyses were conducted at 40 °C by plotting G' and G'' as a function of the cocoa fibers content (Fig. 6).

From 0 to 10 g/100 g, we observe a strong dependence of the rheological moduli on the amount of fibers in the emulsion, with a 10^4 -fold increment of G' in the explored concentration range. With CB alone (0% cocoa fiber), G''>G' revealing a predominantly viscous behavior. However, the behavior becomes predominantly elastic above 3 g/100 g. As the amount of incorporated fibers increases, the system tends progressively towards a jammed state. This is confirmed by the macroscopic aspect of the emulsion reported on Fig. 6.

Experiments were done with milkfat instead of CB and the same phenomenology was observed. This observation gives a hint that the type of fat is not of any particular significance as long as the system is an emulsion of the oil-in-water type.

To sum up, in Fig. 5, the jamming transition was observed by increasing the amount of CM. In this series of experiments, the ratio between cocoa mass and fibers remained constant. In Fig. 6, the same phenomenon was observed by keeping the fat volume fraction constant and increasing only the amount of cocoa fibers. Consequently, even if Figs. 5 and 6 are not directly comparable (the fat fraction is varying in one series and not the other), they reveal one and the same phenomenon: a jamming transition was obtained in CM emulsions above a critical concentration of cocoa particles in the system.



Fig. 6. Variation of the rheological moduli with the amount of cocoa fibers in an emulsion containing a fixed fraction of cocoa butter ($\phi_{oil} = 45 \text{ g/}100 \text{ g}$). G': black squares; G'': white circles.

4. Conclusion

The main objective of this paper was to reveal the impact of cocoa particles on emulsification and stability of ganaches. Two systems were compared: one made with cocoa butter and other one with cocoa mass (i.e. mix between cocoa butter and endogenous fibers). Both systems were emulsified with sodium caseinate.

At high dispersed volume fractions, the rheological behavior of the emulsions comprising cocoa mass and cocoa butter were significatively different. The emulsions based on cocoa mass exhibited a jamming transition due to the presence of cocoa fibers at the droplets' periphery. Such fibers were transferred from the oil phase to the aqueous phase during the emulsification process and provided a Pickering-type stabilization. Fibers formed a thick and rough layer inducing steric hindrance between the droplets with a strong reduction of their mobility.

After cooling ganaches at 4 $^{\circ}$ C, the emulsified fat phase crystallized and the system tended to evolve under the effect of partial coalescence. This was clearly observed for emulsions based on cocoa butter. However, in emulsions made with cocoa mass, the extent of partial coalescence was limited because the fibers layer provided much better stabilization than sodium caseinate alone.

CRediT authorship contribution statement

Fadi Merachli: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Data curation, Visualization. Julia Devienne: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Data curation, Visualization, Supervision. Romain Delmas: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Data curation, Visualization. Laurent Plawinski: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Methodology, Formal analysis, Validation, Investigation, Methodology, Formal analysis, Validation, Investigation, Data curation, Visualization, Supervision. Fernando Leal-Calderon: Conceptualization, Methodology, Validation, Investigation, Writing original draft, Writing - review & editing, Visualization, Supervision. Mathieu Delample: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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