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Sucrose substitution by polyols in sponge cake and their effects on the foaming and thermal properties of egg protein

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ABSTRACT

Three polyols (maltitol, xylitol, and erythritol) were used to replace sucrose in sponge cake formulation and their effects on the foaming and thermal properties of egg protein in liquid whole egg (LWE) and the qualities of resulted sponge cake were investigated. It turned out that, the presence of maltitol acted closest to sucrose in sponge cake system. LWE with both sucrose and maltitol had relatively higher apparent viscosity and temperature of protein denaturation, while the substitution by xylitol and erythritol increased these parameters to a smaller extent. Surface tension and pH values of LWE solution with different sweeteners presented no significant difference. The replacement of sucrose by polyols increased %overrun and air phase fraction of LWE foam, indicating an increase in foaming ability, while the replacement by xylitol and erythritol reduced the foaming stability significantly ($P < 0.05$). The observation of microstructure of LWE foam also confirmed the effects of sucrose and polyols on the foaming properties of LWE. When compared to sucrose, the treatment with maltitol resulted in similar specific volume of sponge cake, while xylitol and erythritol significantly ($P < 0.05$) decreased this parameter. Positive linear relationship was observed between foam stability and specific volume of resulted sponge cake in this study.

1. Introduction

As a principal ingredient in sponge cakes, sucrose exerts its effect not only by providing energy and sweetness, but also by: (1) retarding and restricting gluten network formation during mixing; (2) increasing the viscosity of cake batter and improving its air holding capacity; (3) increasing the temperatures of egg protein denaturation and starch gelatinization; (4) causing Maillard reaction and Caramel reaction, which contributes to both color and flavor of the cake (Wilderjans, Luyts, Brijs, & Delcour, 2013). So the utilization of sucrose in sponge cake is of importance, which can affect the color, texture and flavor of the final baked products. However, foods being rich in added sucrose are a known risk factor for obesity, diabetes, and cardiovascular disease (Horton & Jeanrenaud, 1990; Liu et al., 2002; Quatromoni et al., 2002). Hence, it is necessary to explore possible substitutes for traditional sweeteners to produce healthier foods with reduced sugar or sugar free. Several studies have been done along this line (Attia, Shehata, & Askar, 1993; Baeva, Terzieva, & Panchev, 2003; Hicsasmaz, Yazgan, Bozoglu, & Katnas, 2003). Polyols are typical sucrose replacers low in calories and low in glycemic index, that when consumed may lower the risk of obesity and diabetes (Kroger, Meister, & Kava, 2006). The applications of polyols in bakery products have been studied for decades (Baeva et al., 2003; Kamel & Rasper, 1988; Kroger et al., 2006). Lin, Hwang, and Yeh (2003) studied the replacement of sucrose with erythritol in chiffon cake. Ronda, Gómez, Blanco, and Caballero (2005) evaluated the application of maltitol, mannitol, xylitol, sorbitol, isomaltose, polydextrose and oligofructose in sucrose free sponge cakes. Akesowan (2009) used a mixture of erythritol and sucralose to produce fat-reduced chiffon cakes. Recently, Psimouli and Oreopoulou (2012) researched the possibility of replacing sugar in cake formulations by an equal amount of mannitol, maltitol,

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sorbitol, and lactitol. It's observed that, most of these studies were focused on the effects of substitution by polyols on the thermal and rheological properties of cake batter or/and sensory and texture properties of bakery products. Also, the effects of polyols as sucrose substitutes on starch gelatinization have sometimes been investigated (Akesowan, 2009; Psimouli & Oreopoulou, 2012). However, the difference between the effects of sucrose and polyols on the functional properties of egg proteins has not been conclusively elucidated, as well as the correlations between the properties of egg proteins and the end-use quality of sponge cake.

As foam type cake, sponge cake depends on the air trapped in the beaten egg for most of their leavening (Conforti, 2006; Wilderjans et al., 2013). Its batter is made in two basic steps. After egg and sugar are whipped into a thick, pale foam, the other ingredients such as flour and oil/melted butter are folded in (Wilderjans et al., 2013). Considering the importance of egg protein in sponge cake making, it is necessary to study its functional properties after being treated with sucrose/polyols. In this study, three kinds of polyol (maltitol, xylitol, and erythritol) were used to replace sucrose in sponge cake formulation. The object of this study was to evaluate the different effects of sucrose and polyols on the foaming and thermal properties of liquid whole egg, and to explore possibility of polyols used as sucrose substitution in sponge cake producing, which will provide useful information in developing foods with reduced sugar or sugar free.

2. Materials and methods

2.1. Materials

Commercial wheat flour with 13.9% moisture content, 8.5% crude protein content and 0.8% ash content measured according to methods 44-15A, 46-12, 08-01 (AACCI 2000), respectively, was purchased from Nanshun Flour Co., Ltd (Jingyuan, Shenzhen, China). Maltitol, xylitol, erythritol and sucrose were obtained from Lvjian Biotech Co., Ltd (Shandong, China), Shandong Longlive Biotech Co., Ltd (Shandong, China), Shandong Sanyuan Bio-tech Co., Ltd (Shandong, China), and Guangzhou Huaqiao Sugar factory (Guangzhou, China), respectively. Soybean oil and fresh eggs were purchased from local market in Wuxi, China. Liquid whole egg (LWE) with protein content of 13.96% (method 984.13, AOAC, 2006) was prepared by breaking fresh egg manually and mixing egg white and yolk evenly. All other reagents used in this study were purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China) and were of analytical grade.

2.2. pH, surface tension and apparent viscosity measurement of LWE solution and differential scanning calorimetry (DSC) measurement

To evaluate the effects of sucrose replacement by polyols on pH value, surface tension and apparent viscosity of LWE, LWE solutions were prepared. According to the formulation of sponge cake, 180 g LWE and 100 g sweeteners were poured into a mixer bowl (5K5SS Kitchen Aid Mixer, St. Joseph's, MI, USA) and mixed by a wire whip at room temperature (25 °C), until the sweeteners were completely dissolved. To avoid bubble formation, low mixing speed was adopted (speed 1 for about 2 min). The apparent viscosity of LWE solution was directly analyzed using a NDJ-1 rotational viscometer (Shanghai Precision Instrument Co., Ltd., China) with a #3 spindle revolved at a speed of 30 rpm at room temperature. After LWE solution was diluted with distilled water at the ratio of 1:10 (v/v), the surface tension was measured by a DCAT21 automatic surface tension meter (Dataphysics, German) and the pH value was measured with MP225 pH meter (Mettler-Toledo, Switzerland).

The denaturation temperature was also tested using the LWE solution by DSC. A portion (10 mg) of LWE-sucrose/polyols solution was placed into an aluminum DSC pan. The pan was hermetically sealed and scanned from 20 °C to 130 °C at a heating rate of 10 °C/min. An empty sealed pan was used as a reference. The denaturation temperature of egg proteins was evaluated from the thermograms using a Pyris 1 DSC (PerkinElmer, Ltd., Waltham, MA, USA).

2.3. Gelling characteristic

For gel hardness test, 50 g LWE-sucrose/polyols solution was poured into a cylindrical aluminum tube with inner diameter 40 mm, height 70 mm, and then the tube was sealed with plastic wrap. Samples were pretreated according to the method reported by Raikos, Campbell, and Euston (2007): Tubes were heated in a water bath at 90 °C for 30 min and then cooled down in ice water for 30 min. Texture profile analysis (TPA) was performed using Brookfield CT3 Texture Analyzer (Brookfield Engineering Laboratories, Inc., MA, USA) according to Raikos et al. (2007) with slight modification: A cylindrical plunger (TA11/1000, diameter 25.4 mm) was used to penetrate the gel in tube to 50% of its original height at a test speed of 1.0 mm/s. The hardness defined as the maximum peak force measured during the first penetration was recorded.

2.4. Foam preparation and foam characteristics

According to the exact manipulation of sponge cake preparation, egg foams with sucrose/polyol (maltitol, xylitol, erythritol) were generated using a 5K5SS Kitchen Aid Mixer (St. Joseph's, MI, USA) at room temperature (25 °C). Sucrose/polyols (100 g) and LWE (180 g) were whipped with wire whip at speed 4 for 4 min, followed by mixing at speed 6 for 20 min, and then the egg foam was obtained.

The foam ability of egg protein affected by sucrose/polyols was measured as overrun and air phase fraction according to the method reported by Yang and Foegeding (2010) with slight modification:

$$\%\text{Overrun} = (\text{wt.100 mL solution} - \text{wt.100 mL foam}) \times /\text{wt.100 mL foam} \times 100. \quad (1)$$

$$\text{Air phase fraction } (\Phi) = \%\ \text{overrum}/(\%\ \text{overrun} + 100) \quad (2)$$

At the same time, liquid drainage of the egg foam was measured to assess the foam stability following the method reported by Wang, Huang, Rayas-Duarte, Wang, and Zou (2013) with slight modification: Liquid drainage was calculated as the volume of liquid separated from 250 g of egg foam in a 3 h holding period at room temperature.

2.5. Foam microstructure observation

The egg foam bubble distribution was determined using microscopy methods and a digital camera (Motic, Motic China Group Co., Ltd, China). The egg foam was spread on a slide and covered with a cover glass, then mounted onto the microscope. A magnification of x 4 was used. Microstructure of egg foam with different sweeteners was evaluated using software Image J by the method of Li et al. (2011). The scanned color image was first cropped to a field of view of known size and converted to grayscale. Pixel values were then converted into distance units based on a given bar of known length. The grayscale image was thresholded with the Otsu algorithm through the Image J software. The contrast between the two phases (pores and solids) was compared by the software. Pore area

as a fraction of total area (area fraction [AF]) and the number of pores per square centimeter (cell density [CD]) were analyzed.

2.6. Sponge cake preparation

The formulation of polyol sponge cakes, based on the weight of wheat flour was: 180% liquid whole egg (LWE), 100% polyol (Maltitol, Xyltitol, and Erythritol), 100% flour; 15% soybean oil. A cake prepared with sucrose was used as control cake.

To prepare the sponge cake, flour was gently added to a previously prepared egg foam containing sucrose or polyols, and a plastic scraper was used to ensure full incorporation. Soybean oil was then slowly added and mixed with a plastic scraper until a smooth batter was obtained. A portion of cake batter (230 g) was immediately poured into a 6″ round cake pan before baking at 170 °C for about 40 min in a preheated deck oven (SM-503, Sing Mine International Co., Wuxi, China). Cake was taken out of the oven after baking and bottomed up at room temperature (≈25 °C) for 1 h. After that, they were removed from the pan and placed at room temperature for another 30 min followed by packaging in polypropylene bags for quality analyses. Cakes for each formulation were prepared for three times and the analyses for them were carried out in triplicate.

2.7. Physical properties of sponge cakes

Rapeseed displacement method (AACC Method 10-05, 2000) was used to measure cake volume. Specific volume of the cake was calculated from cake volume divided by cake weight. Texture profile analysis (TPA) of cake samples (4 × 4 × 2 cm) with crust removed was performed under the same conditions as LWE gelling characteristic measurement.

2.8. Statistical analyses

Measurements for each experimental treatment from three different batches were conducted. The data obtained were presented as mean and standard deviation of the mean and were statistically treated by the variance analysis procedure of the Statistical Analysis System (SAS Institute, Inc., version 8.0). A significance level of 5% was adopted for all comparisons.

3. Results and discussion

3.1. Apparent viscosity, surface tension and pH of LWE solution

Sucrose addition was found to increase the viscosity of protein solution (Yang & Foegeding, 2010). This may be explained by the preferential hydration/exclusion mechanism that mediate the interactions between sugar and protein molecules (He et al., 2011). When sugars are present in protein solutions, the preferential exclusion effect drives sugar molecules away from proteins and causes the local sugar concentration in the bulk solution to rise. In this study, LWE solution with sucrose had the highest apparent viscosity (324.6 mPa s). Similar viscosity value was also observed in LWE solution with maltitol (Table 1). The addition of xylitol slightly reduced the apparent viscosity of LWE solution which was not statistic significant ($P < 0.05$), while the substitution by erythritol decreased this parameter by 11.89% when compared to that with sucrose. Molecular weight of the sugar is a main factor in determining solution viscosity. It has been reported that disaccharides have a greater effect on viscosity of protein solutions than monosaccharides with the same number of monosaccharide units (He et al., 2011). The viscosity variation by polyols addition in this study may be also explained based on their molecular differences. Maltitol, a disaccharide alcohol, gave LWE solution similar viscosity with sucrose did, while both xylitol and erythritol, monosaccharide alcohol, produced LWE solution with lower viscosity.

The surface tension of aqueous sugar solution varied as different sweetener additions (Bensouissi, Roge, & Mathlouthi, 2010; Kaushik & Bhat, 1998). But no significant difference ($P < 0.05$) was observed among the surface tensions of LWE solutions with sucrose or polyols analyzed in present study (Table 1). It has also been observed that the differences between the surface tension of LWE solutions in the absence and presence of sugar/polyols were not significant (data not shown). They all showed surface tension value of about 41 mN/m. It seemed that in the presence of protein, the surface tension was independent of sugar or polyol types. Similar research results were reported earlier (Chanasattru, Decker, & McClements, 2008). It's supposed that the protein molecules are more surface active than the sugar/polyols molecules we used and tend to adsorb to the air–water interface and displace the sugar/polyols molecules. Therefore, the free energy associated with increasing the surface area was mainly governed by the presence of the adsorbed proteins molecules, rather than the sugar/polyols molecules (Chanasattru et al., 2008).

The pH values of LWE solution could also affect their foaming property besides factors mentioned above. However, in this study, there was no significant difference ($P < 0.05$) between the pH of LWE treated with sucrose and polyols. All of these samples showed similar pH value in a range of 8.51–8.63.

3.2. Protein denaturation temperature of LWE

A crucial role of sucrose in cake making during heating is to increase the thermal stability of proteins (Raikos et al., 2007). In combination with the increased temperature of starch gelatinization, it allows CO_2 and water vapor, and consequently the air cells to expand sufficiently before the batter sets (Ronda et al., 2005). In this study, the addition of sucrose and polyols resulted broad range for denaturation temperatures of egg proteins from 77.5 to 87.5 °C (Table 1). An earlier research reported that a presence of 50% (w/w) sucrose increased the temperature of maximum rate of denaturation of ovalbumin from 77 °C to 88 °C, while glucose and sorbitol increased this parameter by 15.5 °C and 14 °C, respectively (Back, Oakenfull, & Smith, 1979). The addition level of sucrose can also bring out different influence on the heat denaturation of whey proteins (Kulmyrzaev, Bryant, & McClements, 2000). Therefore, it

Table 1
The effects of sucrose/polyols on the physicochemical properties of liquid whole egg solution.

Egg solutions	Apparent viscosity (mPa s)	Surface tension (mN/m)	Temperature of protein denaturation (°C)
Sucrose	324.6 ± 14.6^{a}	41.09 ± 0.68^{a}	87.5 ± 1.2^{a}
Maltitol	320.0 ± 11.5^{a}	40.76 ± 1.74^{a}	84.4 ± 2.8^{ab}
Xylitol	305.7 ± 8.1^{ab}	41.01 ± 0.25^{a}	82.2 ± 1.4^{b}
Erythritol	286.0 ± 8.9^{b}	40.92 ± 0.74^{a}	77.5 ± 0.8^{c}

Each value is expressed as mean ± standard deviation ($n = 3$).
Means in the same column with different superscript letter indicate significant difference ($P < 0.05$).

suggests that the presence of sweeteners could increase thermal stability of proteins and the magnitude of the stabilizing effect depended on both nature of the proteins and sugars (Kaushik & Bhat, 1998; Raikos et al., 2007).

When compared with LWE solution with sucrose, substitution by maltitol resulted in no significant difference ($P < 0.05$) between the temperatures of egg protein denaturation (87.5 °C for the former and 84.4 °C for the later), while the substitution with xylitol and erythritol decreased the protein denaturation temperature by 6.06% and 11.43%, respectively (Table 1). Sugars and polyols stabilize proteins against heat denaturation, not by directly interacting with them but by altering the structure of water, and hence strengthen the hydrophobic interactions of proteins (Campbell, Raikos, & Euston, 2003). Steric exclusion is reported as the dominant mechanism of the preferential interactions between the protein surface and the cosolvent–solvent molecules (Timasheff, 2002). Sucrose and maltitol have relatively larger molecular size, so their preferential exclusion from the nonpolar surface of proteins increased. The resultant increase in chemical potential of proteins would minimize the protein-solvent interface, to prevent the protein from thermal unfolding (Liu, Ji, Zhang, Dong, & Sun, 2010). As for linear polyols, xylitol and erythritol, their chain length acts as the main factor that affecting their stabilizing ability.

3.3. Gelling properties of LWE

Heat-induced gelling of egg proteins is important to cake producing since it plays a key role in determining the rheological and textural properties of end product (Raikos et al., 2007). During heating, the proteins unfold firstly. Then the denatured molecules interact with other similarly unfolded neighboring molecules to form high-molecular weight aggregates, which can further interact to form a continuous network (gel) (Kulmyrzaev et al., 2000; Raikos et al., 2007). The addition of sugar could cause significant increase in the rigidity of protein gels due to strengthening of protein–-protein interactions once the protein had been heated at temperature above the denaturation temperature of protein for a period of time that enables to reach more complete irreversible protein denaturation and thereafter cooled, however, opposite results might be brought out when proteins were heated at temperature below denaturation temperature or during short holding time (Baier & McClements, 2001; Kulmyrzaev et al. 2000; Semenova, Antipova, & Belyakova, 2002). In this study, LWE gel with sucrose, maltitol and xylitol present similar hardness, while the addition of erythritol dramatically increased the hardness of the LWE gel to 2244 g (Fig. 1). When compared to that with erythritol, LWE solutions with sucrose, maltitol and xylitol had relatively high protein denaturation temperature. Therefore, high temperature had to be reached before the protein molecules unfolded and their gelling temperature increased. For LWE solutions with sucrose, maltitol and xylitol heated at 90 °C for 30 min, the fractions of irreversibly denatured protein decreased (Baier & McClements, 2001). However, the presence of sucrose/polyols may have more complicated influence on the hardness of protein gel. They may also influence the strength of protein–protein interactions and gel structure formed as protein denatured. To obtain a more fundamental understanding of this, further studies such as comparing scanning electron microscope (SEM) images for gel structure would be needed.

3.4. Foaming properties

Foamed sugar-whole liquid egg mixtures are considered to be the basis for sponge cake producing (Wilderjans et al., 2013). The additions of sucrose could decrease foaming ability of proteins (egg white protein and whey protein isolate) and two main factors were proposed to be responsible for it: the bulk phase viscosity of the protein solution and the interfacial properties of proteins (Lau & Dickinson, 2005; Raikos et al., 2007; Yang & Foegeding, 2010). The presence of sucrose in protein solution increased solution viscosity, which allows less air to be incorporated into the interfacial liquid lamellae. Since high solution viscosity may slow down diffusion rate of the protein molecules toward the interface, the amount of foam formed in a given period of time reduced (Raikos et al., 2007). In addition, the addition of sucrose is known to effect the preferential hydration of protein in the solution and create a less favorable thermodynamic environment for protein unfolding (Lau & Dickinson, 2005; Raikos et al., 2007). Therefore, it limits protein unfolding and the development of protein–protein interactions at the water–air interface.

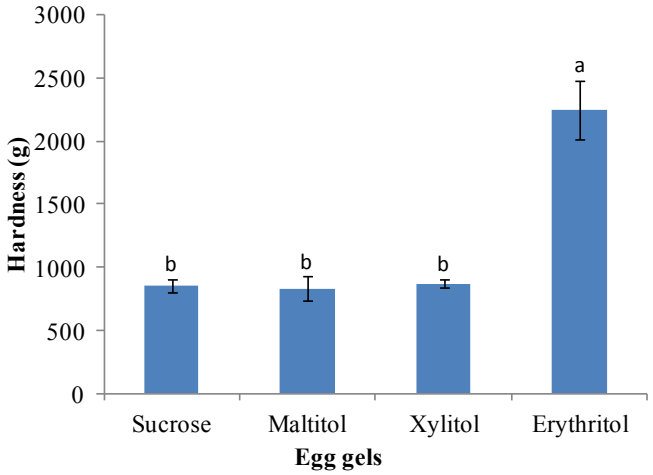

Fig. 1. The effects of sucrose/polyols on the hardness of liquid whole egg gel. Means ($n = 3$) with different letters are significant different ($P < 0.05$).

In this study, the foaming ability of LWE with different sugars is indicated by % overrun and air phase fraction. LWE with sucrose had lowest % overrun and air phase fraction values of 484.7 and 0.829, respectively, among all four samples. When compared with the presence of sucrose, the addition of polyols increased the foaming ability of LWE, which might be due to their different effects on apparent viscosity. As LWE solution with erythritol had lowest viscosity, it showed highest foaming ability, followed by xylitol and maltitol. The forming of hydrogen bonds between sugar and proteins (ovalbumin) might decrease the adsorption of proteins was reported (Antipova, Semenova, & Belyakova, 1999). Therefore, the addition of sugars with more hydroxyl groups in their molecules being available for hydrogen bonding was expected to result in protein solutions with lower foaming ability. However, maltitol with more hydroxyl group in the molecular formula than sucrose gave LWE solution higher foaming ability. It suggested that the effect of maltitol and sucrose on the foaming ability of protein may not depend on their inherent hydrogen bonding capabilities but on their molecular structures.

The effect of sucrose and polyols on the foam stability of LWE proteins is shown as liquid drainage (Table 2). The increment in foam stability of protein due to sucrose addition was attributed to the effect of sugars on the viscosity of the bulk phase, since the viscosity is important in preventing the gas bubbles from coalescing together to create large bubbles (Berry, Yang, & Foegeding, 2009; Yang & Foegeding, 2010). The liquid drainage of foam with sucrose during a period of 30 min was 35.7 mL, while the replacement of sucrose by xylitol and erythritol significantly

Table 2
The effects of sucrose/polyols on the foaming properties of liquid whole egg.

Egg foams	% Overrun	Air phase fraction	Liquid drainage (mL)
Sucrose	484.7 ± 20.8^{c}	0.829 ± 0.006^{c}	35.7 ± 2.1^{c}
Maltitol	582.7 ± 15.9^{b}	0.853 ± 0.003^{b}	38.3 ± 1.5^{c}
Xylitol	573.7 ± 14.3^{b}	0.851 ± 0.003^{b}	46.3 ± 1.2^{b}
Erythritol	772.0 ± 38.0^{a}	0.885 ± 0.005^{a}	51.7 ± 1.5^{a}

Each value is expressed as mean ± standard deviation ($n = 3$).
Means in the same column with different superscript letter indicate significant difference ($P < 0.05$).

increased this parameter to 46.3 mL and 51.7 mL. No significant difference was observed between egg foam with sucrose and maltitol. The addition of sucrose and polyols increased the apparent viscosity of LWE solution following the order of sucrose ~ maltitol > xylitol > erythritol. The foaming stability of LWE with different sweeteners might therefore be related to the solution viscosity.

3.5. Microstructure of egg foam

Liquid foams are two phase systems which consist of a discontinuous air phase dispersed in a continuous liquid lamellar phase. The addition of sucrose and polyols in LWE resulted in variation of foam microstructures (Table 3& Fig. 3). LWE with sucrose generated foam with cell density (CD) of 7541 cells/cm^2 and pore area as a fraction of total area (AF) of 62.1%. The substitution of sucrose by polyols (maltitol, xylitol and erythritol) reduced the CD values of LWE foams significantly ($P < 0.05$) while increased their AF values. From these data, it could be told that LWE foam with sucrose had smaller size bubbles than those with polyols, and individual air bubbles of it were surrounded by thicker liquid lamella film, which would form stiffer foam, contributing to better foam stability. The influence of sweeteners on the apparent viscosity of LWE solution could be responsible for these differences. The variation of AF value was in agreement with that of foaming ability (air phase fraction) of LWE foam (Lau & Dickinson, 2005; Yang & Foegeding, 2010). When storing the foams at ambient temperature, the increase in bubble size and the decrease in bubble uniformity in LWE foams, especially which with erythritol, were observed (Table 3). Coalescence of air bubbles and liquid drainage from foam microstructure was occurred, resulted in bigger air bubbles and thinner lamellar wall surrounding the bubble airs. The AF values of LWE foam with sucrose and maltitol decreased by a small margin after storing for 10 min, indicating that these two kinds of foam were more stable in the earlier period of storage, while the AF values of foam with xylitol and erythritol significantly increased from 63.4% to71.4% and

Table 3
Microstructures of foam from liquid whole egg with sucrose/polyols after holding at ambient temperature for 0, 10, and 30 min.

Foams	Storage time at ambient temperature (min)		
	0	10	30
Sucrose	CD: 7541 ± 439^{a} AF: 61.1 ± 3.0^{f}	CD: 3691 ± 364^{cd} AF: 62.6 ± 1.7^{ef}	CD: 1542 ± 213^{f} AF: 70.4 ± 3.5^{d}
Maltitol	CD: 6500 ± 375^{b} AF: 62.1 ± 2.5^{ef}	CD: 3092 ± 250^{d} AF: 64.4 ± 3.2^{ef}	CD: 1300 ± 150^{f} AF: 73.7 ± 2.1^{cd}
Xylitol	CD: 6392 ± 339^{b} AF: 63.4 ± 1.5^{ef}	CD: 2433 ± 300^{e} AF: 71.4 ± 1.9^{d}	CD: 1208 ± 88^{fg} AF: 78.6 ± 2.3^{b}
Erythritol	CD: 3817 ± 301^{c} AF: 65.7 ± 2.5^{f}	CD: 1592 ± 153^{f} AF: 76.8 ± 1.6^{bc}	CD: 708 ± 88^{g} AF: 83.6 ± 3.2^{a}

Mean values ($n = 3$) of the same parameters followed by different letters are significantly different ($P < 0.05$).
CD = the number of pores per square centimeter (cell density, cells/cm^2); AF = pore area as a fraction of total area (air fraction, %).

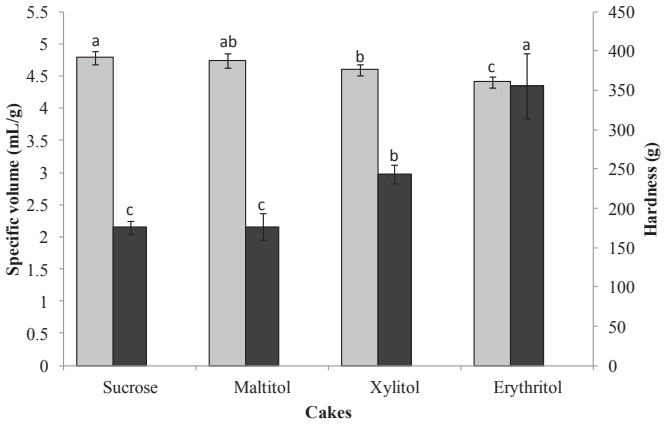

Fig. 2. The effects of sucrose/polyols on the hardness of sponge cake. Means (n = 3) of the same parameters with different letters are significant different ($P < 0.05$) (□ Specific volume; ■ Hardness).

from 65.7% to 76.8%, respectively ($P < 0.05$). After storing for 30 min, the microscopic observation of the aerated systems indicates that the samples containing sucrose and maltitol showed a lower rate of increase of the bubble size compared with that containing xylitol and erythritol (Table 3). The CD and AF values between samples with sucrose and maltitol showed no significant difference. In a storage period of 30 min, the microstructure of foam system with xylitol and erythritol dramatically changed ($P < 0.05$), especially those with erythritol. These results were accordance with the variation of foam stability. To compare to foam with sucrose, the CD value of foam with erythritol decreased by 54.1%, while the AF value increased by 15.8%.

3.6. Specific volume and texture properties of sponge cake

The sweeteners replacement by polyols resulted in different effects on the specific volume of sponge cakes (Fig. 2). When compared to control with sucrose, the treatment with maltitol resulted in similar specific volume of sponge cake, while xylitol and erythritol significantly ($P < 0.05$) decreased this parameter by 3.9% and 14.1%, respectively. It's suggested that foam stability during heating (cake formation) cannot be simply predicted by the foam stability at room temperature, since both intra-droplet and inter-droplet protein–protein interactions at interfaces during heating occurred, the action of which resulted opposite results: the former reinforce the interfacial elasticity, while the latter increase the tendency to flocculation (Rodríguez Patino et al., 2001). This explanation may be fit to aerated systems generated from different proteins, for example, egg white protein and whey protein isolate (Yang & Foegeding, 2010). However, positive linear relationship was observed between foam stability and specific volume of resulted sponge cake in this study. Besides, the influence of sucrose and polyols on temperature of protein denaturation is also in part related to cake volume due to that higher gelling temperature favored enough expansion of cake volume (Ronda et al., 2005).

Hardness of sponge cake with sucrose or polyols has been evaluated after baking (Fig. 2). Sponge cakes with sucrose had lowest hardness, 175 g, while cakes with maltitol had closer hardness to it. The substitution of sucrose by xylitol and erythritol increased the hardness of cakes by 38.9% and 96.8%, respectively. The variation of cake hardness was partially related to the specific volume of the cake. The replacement by xylitol and erythritol significantly decreased the specific volume of sponge cake, resulting in compacter and harder cake. Although the gelling properties

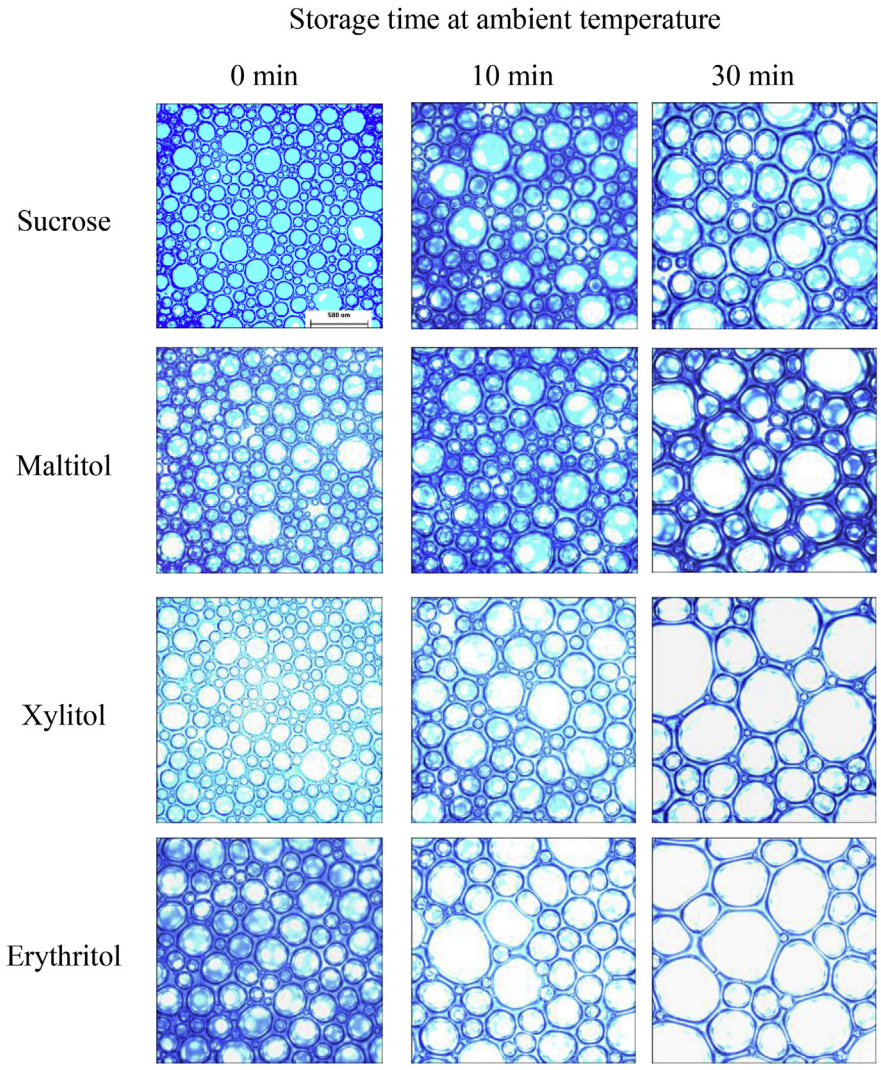

Fig. 3. Microscopic images of foam from liquid whole egg with sucrose/polyols after holding at ambient temperature for 0, 10, and 30 min.

of LWE may partly contribute to the texture of resulted products, hardness of sponge cake is regulated by multiple factors such as starch gel, gluten network and also the air phase fraction in cake. Ronda et al. (2005) reported that the addition of maltitol and xylitol produced softer sponge cake than the addition of sucrose. Psimouli and Oreopoulou (2012) did not find differences in cake hardness when sucrose was replaced by maltitol. These differences may be due to different formulation and process was adopted.

4. Conclusions

The substitution of sucrose by maltitol resulted in similar physicochemical properties in LWE solution, such as apparent viscosity, surface tension, pH value, temperature of protein denaturation. They also had very similar foam stability and evolution actions in foam microstructure, although LWE with maltitol had higher foam ability than that with sucrose. Therefore, the resulted sponge cake with maltitol had closest specific volume and hardness to that with sucrose. As to xylitol, significant difference was observed in foaming and thermal properties between LWE solutions with xylitol and sucrose, which resulting in cakes with smaller volume and harder texture. In contrast, the replacement by erythritol resulted in most obvious difference in all of measurements except surface tension of LWE solution. The study on the influences of sucrose and polyols on the functional properties of LWE will be benefit to achieve optimal formulations for food industrial application such as cake producing.

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