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Determination of sponge cake volume with a mathematical method

H. Dizlek[1*] and A. Altan[2†]

[1]Osmaniye Korkut Ata University, Faculty of Engineering, Department of Food Engineering, 80000 Osmaniye, Turkey; [2]Çukurova University, Faculty of Agriculture, Department of Food Engineering, 01330 Adana, Turkey; hdizlek@osmaniye.edu.tr

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RESEARCH ARTICLE

Abstract

The volumes of the sponge cakes prepared by using different baking powder formulas and rates were determined with a reasonable mathematical method constituted by us. The volume index and the total volume index values were calculated according to American Association of Cereal Chemists (AACC) method 10-91 and the methods presented in literature. Then, these values were compared with volume calculated by mathematical method under consideration. In the study, the lower and upper part of the cake were taken as the shape of a cylinder and a sphere, respectively, and then volume of these two parts were calculated separately. A high correlation is observed between the index values presented in literature, and the volume values determined with the mathematical method carried out in this study. Therefore, the mathematical method performed in this study can easily be applied to calculate the volumes of the cakes which are prepared by using baking pans, described in AACC method 10-90 or the pans similar to ones in AACC method 10-90.

Keywords: sponge cake, cake volume, volume index, baking powder, mathematical method

1. Introduction

The cake, which can be produced with several methods, is very important in bakery product industry since the production and the consumption of it increase continuously as a result of the increase in population, and urbanisation, easement of access and application of new technologies. Cake products can be produced in wide variety of formulations all over the world. The differences in the formulation of the cakes make them attractive not only for their pleasing flavours but also for their appearance. Although they contain high levels of calorie, they are preferred because of their sweet taste and easy consumption (Matsakidou *et al.*, 2010; Pyler, 1988; Schutz and Judge, 1986; Walker *et al.*, 1987; Wijnans and Baal, 1997; Zhang *et al.*, 2012).

The volume is one of the most important factors for most of the baking products, especially for the cakes in terms of external view. Measurement of the volume is important in evaluating cake quality because the volume is an indicative parameter about the quality and the structural development of the cake alone (Cloke *et al.*, 1984).

Many researchers have measured the volumes of the cakes using the seed displacement method with the help of small seeds such as mustard, rapeseed or amaranth (Baeva *et al.*, 2000; Guy and Vettel, 1973; Lee *et al.*, 1982; Myhara and Kruger, 1998; Raeker and Johnson, 1995; Tan *et al.*, 2011). Alternatively in some other studies, it has been determined by calculating volume index and total volume index values which do not measure the cake volume directly but give an idea about it (Bath *et al.*, 1992; Chittrakorn *et al.*, 2014; Doğan and Walker, 1999; Ebeler and Walker, 1984; Karaoğlu *et al.*, 2001; Kim and Walker, 1992; Stinson, 1986; Şümnü, 2001; Thomasson *et al.*, 1995; Walker and Walker, 1996).

As well known, there are many parameters which affect the volumes of the cakes prepared with different methods and ingredients (Garcia *et al.*, 2014; Jia *et al.*, 2014; Zhang *et al.*, 2012). Therefore, one or more parameters can be investigated in the determination of the volumes of the cakes. That is, the calculations of the volumes of the cakes can be extended by changing the types and amounts of the materials constituting the ingredient of the cake, such as flour, baking powder, sugar, etc. However in this study, it is focused on to constituting a mathematical method for the determination of the volumes of the sponge cakes prepared with different formulas and rates of baking powder.

In the first attempts of the study, the seed displacement method was used to measure the volume of the cake. The cake was replaced in a volume measuring device including approximately 12 kg of mustard seed according to the method. However, the seeds which are dropped rapidly on the cake were observed to destroy the surface of the cake having a weight of about 380 g and a volume of 1,300-1,900 cm^3. This deformation also led to adverse effects on the other cake analyses such as texture and porosity. In addition, Cloke *et al.* (1984) reported that cake volumes determined by using seed displacement method were smaller than those calculated from cross-sectional tracings and they found compact structural deformations caused by the rapeseeds. Hence, they preferred to freeze the cakes to prevent these undesirable effects. Therefore, we had to use seed displacement method to measure the volume of the cakes accurately.

Because of the unexpected results obtained in the first attempts of the study, we focused alternatively on a mathematical method which can be used to calculate the volume of the cake. After calculating the volumes of the cakes by using our proper mathematical method they are compared with the ones obtained from AACC method 10-91 (AACC, 2000) by determining the volume, symmetry and uniformity indexes and shrinkage value using cake measuring template. Meanwhile among the indexes used in AACC method 10-91, volume index is preferred since it gives more definite results than the others.

2. Materials and methods

Materials

Wheat flour was purchased from Ova Flour Mills (Konya, Turkey). The flour had 14.0% moisture, 0.59% ash content, 0.03% total acidity, pH=5.9, 10.27% dry gluten content, gluten index = 77%, sedimentation = 34 ml, falling number value = 343 s, farinograph water absorption = 62.2%, development time = 3.8 min, stability = 6.3 min, degree of softening = 170 BU; extensograph maximum resistance to extension = 570 BU, extensibility = 105 mm, and energy = 85 cm^2 (AACC, 2000). Surfactant (Ovalette) which has gel structure containing 'mono and diglycerides of fatty acids (E471)' and 'polyglicerol esters of fatty acids (E475)' was obtained from the Katsan (İstanbul, Turkey). Powdered sugar, fresh egg, vanilla and salt were purchased from an ordinary supermarket in Adana, Turkey. Sodium bicarbonate (Mersin Soda Industry, Mersin, Turkey), potassium bitartarate, monocalcium phosphate anhydrate (AMCP) and sodium acid pyrophosphate (SAPP) were obtained from the Mühlenchemie (Ahrensburg, Germany) and corn starch (Sadıkoğlu, Adana, Turkey) was used to prepare baking powder (BP). The stainless steel baking pans with an inside diameter of 203 mm and a depth of 38 mm described in AACC method 10-90 were used (AACC, 2000). Kitchen Aid type KSM 45 model electric mixer (KitchenAid Inc., St. Joseph, MI, USA) was used to mix the batter and Arçelik MF6 model oven (Arçelik Company, İstanbul, Turkey) that is fired electrically and capable of maintaining temperature range of ±3 °C was used.

Table 1. Formulation of baking powders.

Formulation code	Components				
	Sodium bicarbonate (g)	Potassium bitartarate (g)	Monocalcium phosphate anhydrate (g)	Sodium acid pyrophosphate (g)	Corn starch (g)
Baking powder 1 (BP_1)	30.0	–	–	–	0.0
Baking powder 2 (BP_2)	30.0	66.7 (100%)[1]	–	–	3.3
Baking powder 3 (BP_3)	30.0	–	36.1 (100%)	–	33.9
Baking powder 4 (BP_4)	30.0	–	–	41.7 (100%)	28.3
Baking powder 5 (BP_5)	30.0	33.3 (50%)	18.1 (50%)	–	18.6
Baking powder 6 (BP_6)	30.0	33.3 (50%)	–	20.8 (50%)	15.9
Baking powder 7 (BP_7)	30.0	–	18.1 (50%)	20.8 (50%)	31.1
Baking powder 8 (BP_8)	30.0	22.2 (33.3%)	12.0 (33.3%)	13.9 (33.3%)	21.9

[1] Values in the brackets are declared the percentage of acids (potassium bitartarate, monocalcium phosphate anhydrate and sodium acid pyrophosphate) which were used to neutralise sodium bicarbonate at neutralisation reaction.

Cake making method

Eight different BPs were prepared by using components which were described in material section according to neutralisation value (LaBaw, 1982) and they are given in Table 1. The batter formula used in making of sponge cake was as follows: 36% wheat flour, 26% powdered sugar, 22% egg, 11% water, 3.5% surfactant, 0.2% vanilla, 0.1% salt and BP which were used at five different percentage as 0.25, 0.75, 1.25, 1.75 and 2.25% of batter weight. As can be seen from the percentage of the BPs, it ruins the total percentage of the sponge cake batter from 100%. This difficulty has been overcome easily by increasing or decreasing ratios of the other ingredients regularly.

In order to make the cake the forthcoming steps are followed: firstly, eggs were beaten through 1 min with 190 rpm, then surfactant and water were added through ½ min with 95 rpm and this mixture were mixed additionally through ½ min with 190 rpm. Then powdered sugar was added through ½ min with 95 rpm and mixed additionally through ½ min with 190 rpm. Lastly, dry ingredients (wheat flour, BP, vanilla and salt) were added through 1 min with 95 rpm and mixed again through 1 min with 190 rpm. At the end of these mixing procedure, batters were put into baking pans when they reached 425±0.1 g. Cake batters were baked at 190±3 °C for 27 min and after being baked they were left in their own baking pans for 20 min. Then, the cakes were taken out of their pans and they were cooled in the room temperature for 40 min on a wire racks. Finally, cakes were kept in wooden cabinets on wire racks until they are analysed. After the batter had been mixed in the mixer it was dropped in the baking pans and it was baked in the oven.

Analyses

Sponge cake analysing methods

In order to analyse the cake, first the volume index is determined using the AACC 10-91 method in terms of millimetres as given in Equation 1 (AACC, 2000). Then, the total volume index is determined using the method described by Bath *et al.* (1992) in terms of millimetres as given in Equation 2. Both measurements are done 6 h after baking and using the cake measurement template given in Figure 1. In the cake measurement template, the length of template is 20 cm and point C shows the centre. B and D points are placed 6 cm away from both the left and right sides of the centre. A and E points are also placed 10 cm distances from both the left and right sides of the centre. The points with prime sings appeared in Figure 1 and thus in Equations 1 and 2 show the intersection points of the cake on the template when it was cut vertically and dropped on its cut surface on the cake measurement template. Finally, the heights |AA'|, |BB'|, |CC'|, |DD'|, |EE'|, |AE| and |A'E'| were measured from the template and those were used for the calculation of the volume index and the total volume index, respectively:

$$\text{Volume index (mm)} = |BB'| + |CC'| + |DD'| \quad (1)$$

$$\text{Total volume index (mm)} = |AA'| + |BB'| + |CC'| + |DD'| + |EE'| + |AE| + |A'E'| \quad (2)$$

In the mathematical model described in this study, the parameters used in Equations 3-13 are measured 6 h after baking as in the previous methods and they were used to calculate the volume of the cake in terms of cm^3.

The lower part of the cake ($cake_{bottom}$) was taken as a cylinder defined as the part from bottom to the inward or outward curvature of the cake and the upper part of the cake ($cake_{upper}$) was taken as a piece of a sphere as shown in Figure 2 and then the volumes of these two parts were calculated separately.

Diameter of the cylindrical part ($cake_{bottom}$) of the cake was taken as 2r and the base line of the template had been taken as (|AE|). The height and the volume of the cylinder were determined as:

$$h = \frac{h_1 + h_5}{2} \quad (3)$$

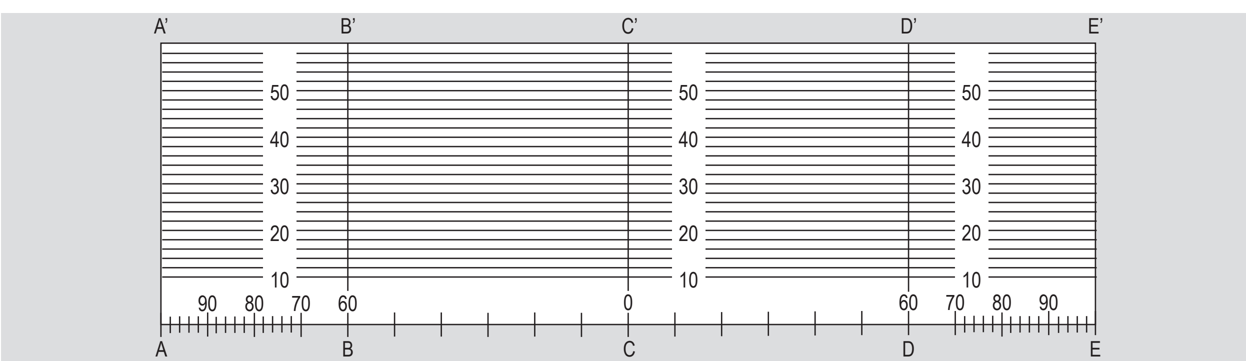

Figure 1. Cake measurement template (AACC, 2000).

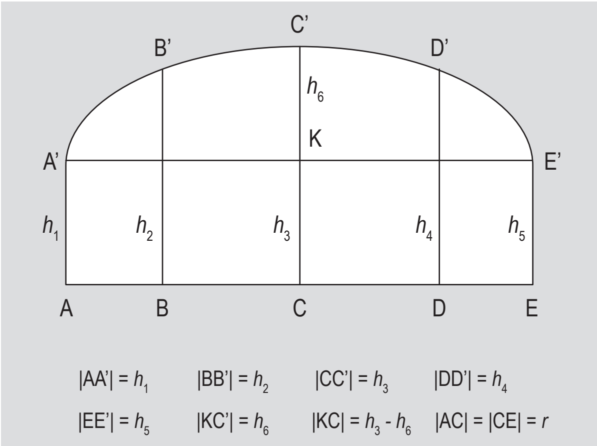

Figure 2. Diagrammatic illustration of the vertically cross-sectional view of the cake.

$$V_{bottom} = \pi r^2 h \tag{4}$$

The volume of the upper part of the cake regarded as the piece of a sphere was calculated as follows: first the radii of three circles which are considered to pass through A'B'E', A'C'E' and A'D'E' points were stated as r_1, r_2 and r_3 and these were calculated from Equations 5-7. Then the radius R of the upper (spherical) part of the cake was calculated by using three different radii in Equation 8:

$$r_1 = \frac{\sqrt{|BA|^2 + (h_2 - h)^2}\sqrt{|BE|^2 + (h_2 - h)^2}}{2(h_2 - h)} \tag{5}$$

$$r_2 = \frac{|CA|^2 + (h_3 - h)^2 / 2(h_3 - h) = |CE|^2 + (h_3 - h)^2}{2(h_3 - h)} \tag{6}$$

$$r_3 = \frac{\sqrt{|DE|^2 + (h_4 - h)^2}\sqrt{|DA|^2 + (h_4 - h)^2}}{2(h_4 - h)} \tag{7}$$

$$R = \frac{r_1 + 2r_2 + r_3}{4} \tag{8}$$

The volume of the upper part of the cake which takes place between the |A'KE'| straight line and A'B'C'D'E' curve as illustrated in Figure 3 was calculated as:

$$V_{upper} = \pi \int_{R-h6}^{R} (R^2 - x^2)dx \tag{9}$$

As a result of the mathematical model treated so far, while the volume of the convex cakes as shown in Figure 2 was calculated as:

$$V_{cake} = V_{bottom} + V_{upper} \tag{10}$$

$$V_{cake} = \pi r^2 h + \pi \int_{R-h6}^{R} (R^2 - x^2)dx \tag{11}$$

and the volume of the concave cakes was calculated as:

$$V_{cake} = V_{bottom} - V_{upper} \tag{12}$$

$$V_{cake} = \pi r^2 h - \pi \int_{R-h6}^{R} (R^2 - x^2)dx \tag{13}$$

Data analysis

All experiments were carried out in three replicates. Analyses of variance (ANOVA) were conducted by using the Statistical Analysis System (SAS) procedures (SAS Institute, 1982). When a significant difference was found among treatments, Duncan's multiple range tests were performed to determine the differences among the mean values.

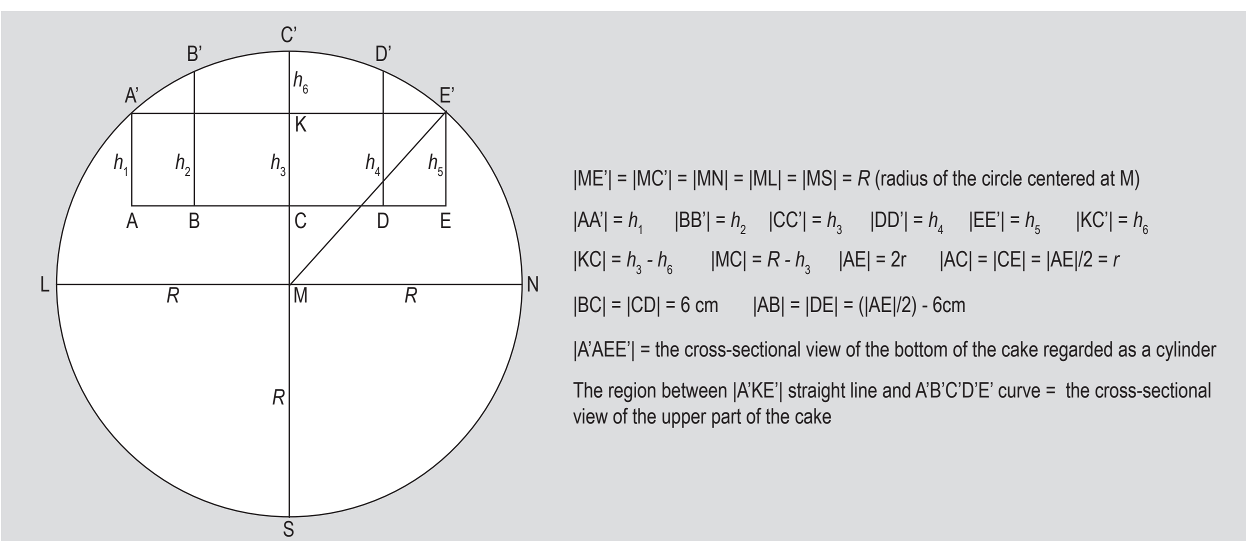

Figure 3. Diagrammatic illustration of the circle formed as the upper part of the cake.

3. Results and discussion

The volumes of the sponge cakes produced by using various composition and utilisation rate of BPs given in Table 1 were calculated from the mathematical model and they were given together with the volume and total volume indexes in Table 2 for comparison.

As can be seen from Table 2, while the highest cake volume (1,820 cm^3) was obtained at BP_4 with a utilisation rate of 1.25%, the lowest cake volume (1,332 cm^3) was obtained at BP_2 with a utilisation rate of 2.25% which is the highest BP rate among the all utilisation rates during experiment. Using different rates of BP (0.25% at BP_2; 0.75% at BP_1, BP_5, BP_6 and BP_7; 1.25% at BP_3 and BP_4; 1.25-1.75% at BP_8) were observed to increase the volumes of the cakes ($P<0.01$). However, while using more BP than a rate of 1.25% was observed not to increase the volume of the cakes significantly, using BP more than a rate of 1.75% was observed to decrease the volume of the cakes up to 16%. In contrast, the increase in the amount of BP in BP_1 formula did not affect the volume of the cake adversely ($P>0.01$). Although the volume of the cake decreased with a utilisation rate of more than 1.25% BP in BP_2 formula, the volumes of the cakes prepared with utilisation rates of 0.25% and 0.75% in BP_2 formula was observed to have similar or greater volumes than the cakes prepared with other seven BP formulas. Meanwhile, the minimum cake volumes were obtained in the rates of 1.75 and 2.25% of BP_2. This shows that using much fast acting leavening agent (BP_2) in the production of the cake damaged the volumes of the cakes ($P<0.01$). In addition, the highest volumes of the

Table 2. The volumes calculated from the mathematical model, volume and total volume indexes of the sponge cakes.[1]

Baking powders (BP)	Utilisation rate of BP (%)					
	0	0.25	0.75	1.25	1.75	2.25
Calculated volume (cm^3)						
Control	1,580^{nop}					
BP_1		1,614^{lmno}	1,680^{hij}	1,692^{fghij}	1,717^{efghi}	1,706^{efghi}
BP_2		1,727^{defgh}	1,739^{cdef}	1,710^{efghi}	1,484^{r}	1,332^{s}
BP_3		1,620^{klmn}	1,644^{jklm}	1,746^{bcde}	1,707^{efghi}	1,666^{ijk}
BP_4		1,684^{ghij}	1,722^{efgh}	1,820^{a}	1,785^{abc}	1,535^{pq}
BP_5		1,567^{op}	1,749^{bcde}	1,779^{abcd}	1,725^{efgh}	1,685^{ghij}
BP_6		1,679^{hij}	1,748^{bcde}	1,758^{bcde}	1,734^{cdefg}	1,588^{no}
BP_7		1,595^{mno}	1,706^{efghi}	1,723^{efgh}	1,752^{bcde}	1,651^{jkl}
BP_8		1,619^{klmn}	1,728^{defgh}	1,748^{bcde}	1,797^{ab}	1,518^{qr}
Volume index (mm)						
Control	170st					
BP_1		172^{rs}	176^{pq}	182^{mn}	187^{hijk}	190^{efghi}
BP_2		179^{nop}	188^{fghijk}	187^{hijk}	160^{u}	152^{v}
BP_3		171^{rst}	178^{p}	186^{jkl}	192^{cdef}	182^{mn}
BP_4		185^{klm}	183^{lm}	201^{b}	193^{cde}	170st
BP_5		168st	191^{efgh}	204^{a}	193^{cde}	193^{cde}
BP_6		179^{nop}	191^{efgh}	195^{cd}	195^{cd}	177^{p}
BP_7		173^{qr}	191^{efgh}	187^{hijk}	195^{cd}	188^{fghijk}
BP_8		176^{pq}	188^{fghijk}	190^{efghi}	191^{efgh}	168st
Total volume index (mm)						
Control	638^{q}					
BP_1		644^{p}	650no	652^{mn}	662^{fghij}	665^{efgh}
BP_2		660^{hijk}	667^{def}	666^{efg}	636^{qr}	631^{r}
BP_3		646^{op}	653^{lmn}	660^{hijk}	665^{efgh}	657^{jklm}
BP_4		659^{ijk}	659^{ijk}	682^{a}	675^{b}	650no
BP_5		634^{qr}	667^{def}	676^{b}	669^{cde}	669^{cde}
BP_6		658^{jklm}	665^{efgh}	675^{b}	675^{b}	660^{hijk}
BP_7		643^{p}	666^{efg}	657^{jklm}	672^{bcd}	655^{klmn}
BP_8		646^{op}	664^{efghi}	669^{cde}	673^{bc}	644^{p}

[1] Mean values in the table for the same properties shown with the same superscript letter are not significantly different ($P<0.01$).

cakes were seen to be almost obtained by using BPs with a utilisation rate of 1.25%. In general, no so much difference was observed between the volumes obtained with utilisation rates in the range of 0.75 and 1.75%. Moreover, the volumes of the cakes were seen to be decreased when using BPs less than 0.75%. The same manner was also observed when using BPs more than 1.75%. It can be summarised that using much BP, i.e. more than a rate of 1.75% in the batter composition, causes a decrease in the volume of the cake.

The same behaviour of the volume of the sponge cakes was observed in measuring volume and total volume indexes. As an example, the index values of the cakes increased continuously with increasing rates of BP at BP_1. It also increased up to a rate of 0.75% at BP_2; 1.25% at BP_4, BP_5, and BP_6; 1.75% at other formulas of the BPs. It started to decrease from a rate of 1.25% at BP_2, BP_4 and BP_5; 1.75% at BP_3, BP_6, BP_7 and BP_8. The volume and total volume indexes of cakes were measured between 152-204 mm (BP_2, 2.25%-BP_5, 1.25%) and 631-682 mm (BP_2, 2.25%-BP_4, 1.25%). The highest volume and total volume indexes of the cakes were almost obtained by using BPs with a utilisation rate of 1.25%. Similarly, they decreased in the cases of both using BPs less than 0.75% and more than 1.75%.

As it can be understood from the discussions mentioned above, the calculated volume, volume index and total volume index values are in good accordance with each other when they are evaluated together. Furthermore according to Table 2, the same compatibility among these three criteria could also be pronounced for other moderate or small volume cakes produced in this study. Gómez *et al.* (2008) and Karaoğlu *et al.* (2001) also reported that there is a direct proportion between volume of cakes and their volume index values.

The correlation coefficients and the regression equations were obtained for calculated volume, volume and total volume indexes of the produced cakes and they were given side by side in Table 3. From the table, it is clear that there is a high positive correlation between these three criteria. This means that the volume of the cake calculated by the mathematical method improved in this study is compatible with index values. Furthermore, it can be said that the volumes of the cakes are calculated more precisely by using the mathematical method since it measures the volume of the cake directly unlike the index values. The index values give only idea about cake volume, as stated before (Bath *et al.*, 1992; Doğan and Walker, 1999; Guy and Vettel, 1973; Kim and Walker, 1992).

Although the volume index and the total volume index, which give only an idea about the volumes of the cakes and do not calculate them accurately, they are traditional methods based on the same basic principles and thus they are preferred to use in many studies about the measurement of the volumes of the cakes (Baker *et al.*, 1990; Bath *et al.*, 1992; Chittrakorn *et al.*, 2014; Doğan and Walker, 1999; Ebeler and Walker, 1984; Kim and Walker, 1992; Lee *et al.*, 2005). While three different points on the cake measurement template are used in the volume index measurements as given in Equation 1, seven different points are used in the case of the total volume index measurements as given in Equation 2 for the calculation of the cake volumes.

As well known, the volume index and the total volume index present only the vertical development of the cake. However, the volumes calculated by the mathematical method improved in this study present both the vertical and the horizontal development of cake. Therefore, this mathematical method can said to give more accurate values than the index values for the calculation of the cake volumes.

4. Conclusions

In conclusion, as indicated in the explanations about Table 3, the mathematical method is in good accordance with the traditional volume index and the total volume

Table 3. Relation between cake volume and volume index values.

Criteria related with volume (Y)	Correlation coefficient (R)	Regression equation (Y = a + bx)
	Calculated volume	Calculated volume (x at equation)
Volume index	0.906	$Y_{Volume\ index}$ = 9.6(±7.4) + 0.1(±0)x
Total volume index	0.869	$Y_{Total\ volume\ index}$ = 467.4(±9.9) + 0.1(±0)x
	Volume index	Volume Index (x at equation)
Calculated volume	0.906	$Y_{Calculated\ volume}$ = 226.2(±61.9) + 7.9(±0.3)x
Total volume index	0.941	$Y_{Total\ volume\ index}$ = 460.9(±6.5) + 1.1(±0)x
	Total volume index	Total Volume Index (x at equation)
Calculated volume	0.869	$Y_{Calculated\ volume}$ = -2681.0(±225.7) + 6.6(±0.3)x
Volume index	0.941	$Y_{Volume\ index}$ = -356.5(±17.7) + 0.8(±0)x

index measurements with a high correlation between them. Therefore, this method is very successful in the calculation of the volumes of the cakes. In addition, this method can also be extended to the baking pans not only described in AACC method 10-90, but also to the pans of other shapes. In near future, we plan to improve alternative mathematical methods to calculate the volumes of the cakes baked in the pans with different geometries.

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