Investigation of the structural changes of cocoa bean (with and without seed coat) during convective drying

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Abstract: The influence of seed coat on the behaviour of heterogeneous structure of cocoa bean (frosteros sp.) during convective drying with tempering period was investigated in an isothermal condition. It was found that the removal rate of moisture and air diffusion between the cocoa kernel and seed coat is not the same especially at the temperature of 55℃ and initial drying time for all temperatures used. When the drying temperature increased to 70℃ and 81℃, the cocoa kernel and the seed coat shrinks simultaneously, indicating that the rate of moisture and air removal from the kernel through the seed coat are the same. Change in sphericity of the bean was more pronounced at the temperature of 55℃ for the seeds with seed coat while for all other drying conditions it remains fairly constant after one-hour drying.

Keywords: cocoa bean, shrinkage, tempering, moisture ratio, diffusion, isothermal, convective drying

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1 Introduction

Cocoa beans are the seeds, contained in a cucumber-like fruit, of the cacao tree, a member of the Sterculiaceae family. The flowers/fruit are borne directly on the trunk (cauliflory) and on thick branches (ramiflory). The yellowish, reddish to brownish fruits (botanically speaking, berries), which are of similar appearance to cucumbers, are divided into five longitudinal compartments, each containing up to 10 seeds (cocoa beans). The cocoa bean consists of the seed coat which encloses the cocoa kernel and almost solely consists of the two folded cotyledons, and the radicle. The cocoa kernel is the principal component for the production of cocoa products. Cocoa is widely grown in West Africa and some parts of South America. The predominant specie of cocoa grown in Nigeria and most West Africa countries is the frosteros species. In the most cocoa producing countries, cocoa is harvested throughout the year and the beans are usually dried immediately after fermentation for safe storage.

World production of cocoa beans was about four million metric tons in 2006-2007 with West Africa having the bulk production share of about 70% of this quantity[1]. In many families around the world, chocolate and beverages is among their basic foods which are derived from cocoa. However, the quality of these products depends on how cocoa is initially processed. In West Africa, after harvesting and breaking of the pod, the bean is fermented mostly by heap or basket fermentation method, after which it is dried to safe storage moisture content, and then it is exported or processed into other forms.

Many researchers have reported that changes in shape and size of the products would affect their physical properties, which often modify final texture, load and transport properties of the dried foods[2,3]. During drying of bio-products, the visco-elastic matrix shrinks into the space previously occupied by the evaporated moisture from the pores in the cell[4]. However, some

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seeds dried swell because of either the nature of the seed covering or large presence of air inside the pore spaces. This behaviour affects the drying kinetics of these seeds especially in deep bed drying for the seed. Yadollahinia and Jahangiri[3] reported that shrinkage was studied by direct measurement with a caliper or micrometer or by change of parameters such as porosity and density. Recently, many linear correlation equations presented that the shrinkage of material correlates with physical parameters involving moisture content, volume changes and axial contraction[3,5-10]. It has been noted that change in physical dimension of product is specific and varies depending on drying conditions[3]. Volume shrinkage of some bio material has been investigated by some researchers[3,6-10]. However, scarce research was published on drying measurement of dimensional shrinkage of cocoa bean. The falling rate drying period dominates the cocoa bean drying process[11-16]. Similar to the other bio-material, some drying models were introduced to simulate the drying behavior of bio-material. The aim of this work was to determine the influence of drying temperatures on the shrinkage of cocoa bean kernel during drying, especially on the physical characteristics and also investigate the influence of the seed coat on shaping the dimensions of the overall bean during drying.

2 Materials and methods

2.1 Physical characteristics

The 180 seeds of cocoa bean (frosteros sp.) at moisture contents of 69.7% (w.b.) and at mass of 710.67 g were used for each experimental run. The principal axis (DA, DB and DC) of the cocoa bean (as shown in Figure 1), the minor, major and intermediate diameters with and without seed coat was determined by using a digital dial caliper (mitutoyo, JIS.B.7502.). The descriptions of the parameters used in this study were presented in Table 1.

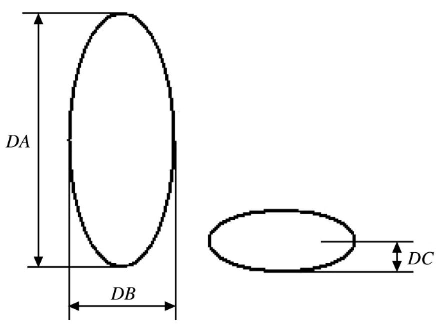

Figure 1 Axial dimensions of cocoa seed

Table 1 Descriptions for the parameters used in this study

Parameters	Description
r	radius of equivalent sphere (m)
t	time (s)
De	effective diffusivity (m^2/s)
MR	moisture ratio
V	volume of an equivalent sphere (mm^3)
d_e	equivalent diameter (mm)
A_m	arithmetic mean diameter (mm)
S_m	square mean diameter (mm)
D_g	geometric mean diameter (mm)
DB	intermediate diameter (mm)
DA	major diameter (mm)
DC	minor diameter (mm)
M	moisture content (%, w.b.) at time t
Me	equilibrium moisture content (%, w.b.)
Mi	initial moisture content (%, w.b.)
A	area of equivalent sphere (mm^2)
S	sphericity

The mass was determined by using a precision weighing balance (Scuot pro SPU 401) made in China with an accuracy of ±0.01 g. The moisture content wet basis was determined with an oven according to ASAE standard S358.2[17]. The above dimensions were also determined in every one hour in the drying progresses to the equilibrium moisture content. The geometric mean diameter was calculated from the relationship described by Asoegwu[18], given as follows:

Geometric mean diameter:

$$D_g = (DA \times DB \times DC)^{\frac{1}{3}} \quad (1)$$

The arithmetic mean diameter is calculated as follows:

$$A_m = \frac{DA + DB + DC}{3} \quad (2)$$

The square mean diameter was calculated as follows:

$$S_m = \left[\left(\frac{DA \times DB) + (DB \times DC) + (DA \times DC)}{3} \right) \right]^{\frac{1}{2}} \quad (3)$$

The equivalent diameter is calculated as follows:

$$d_e = \frac{D_g + A_m + S_m}{3} \quad (4)$$

The method described by Oje et al.[19] was also used to determine the sphericity:

$$S = \frac{d_e}{DA} \quad (5)$$

The elongation including ratio of the longest diameter (D_A) to shortest diameter (D_C) of the cocoa bean was calculated as follows[3]:

$$elongation = \frac{DA}{DB} \quad (6)$$

The cocoa bean shape was assumed to be spherical throughout the drying period. Therefore the volume and area was calculated as volume and area of sphere with equivalent diameter with the following equations.

$$V = \frac{4}{3}\left(\frac{d_e}{2}\right)^3 \quad (7)$$

$$A = 4\pi\left(\frac{D_e}{2}\right)^2 \quad (8)$$

2.2 Drying method

A freshly fermented cocoa bean (frosteros specie) with initial moisture content of 69.7% (w.b.) and mass of 710.67 g was divided into two groups with each of 180 seeds. The first group was artificially dried with the seed coat while the second group was dried with the seed coat removed. The seed coat was carefully removed with hand to avoid tampering with the kernel. For each drying run the beans were dried by spreading (180 seeds for each test run) the cocoa bean in a single layer on a perforated mesh tray inside an air ventilated oven drier (UMB 500 sehutzart, DIN EN 60529-IP 20, memmert, Germany). Prior to the drying, the initial weight and axial dimensions for each seed were taken and recorded. The beans were spread laying on their minor diameter (DC), i.e. the flat side. The drying was carried out at a constant temperature of 55℃, 70℃ and 81℃, respectively[20]. The cocoa beans were turned every half an hour to achieve uniform drying. Measurement of the minor, intermediate and major diameter of each seed samples, originally tagged as DC, DB and DA, respectively, was also conducted at one-hour interval for the 180 seeds and the average value recorded. During the experiments, ambient temperature and relative humidity within the laboratory were recorded as 30.5℃ and 71%, respectively. The drying was carried out continuously for four hours, after which the experiment was stopped and the beans were put in a jute bag at room temperature overnight and placed inside the house before drying commences on the following day[11]. This process is called curing or tempering and is done to redistribute the internal moisture of the seed coat and to allow the fermentation process to be completed. During this process, the highly bitter tannin presented in the bean kernel is oxidized, resulting in the formation of aromatic substances and the development of the typical brown or deep red-brown color of cocoa. Drying operation was continued until there was no change in mass.

2.3 Cut test

Cut test was carried out by cutting through the axial dimensions using a sharp knife. The two halves of the bean were examined in full daylight according to the cross sectional colour of the beans namely fully brown, partly purple-brown and fully purple according to a set of reference pictures of Nigerian cocoa board. According to the standard, beans with more than 60% fully brown colour were considered as premium flavour beans[15]. The test was performed in triplicates and the average was recorded.

2.4 Moisture ratio

The moisture ratio (MR) is calculated as follows[20]:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (9)$$

3 Results and discussion

3.1 Drying kinetics of the cocoa bean

The plots of dimensionless moisture ratio versus drying time for the samples dried at different air temperatures with and without seed coat are shown in Figures 2 and 3. The drying curves are similar to other bio material, i.e. moisture content of cocoa bean decreased exponentially with increasing drying time. The exponential relationship for the cocoa bean dried with seed coat revealed very high R^2 values of -0.984, -0.965 and -0.982 for the respective temperatures of 55℃, 70℃ and 81℃, respectively, which implies that R^2 value fits well with the moisture ratio data. For the cocoa bean without seed coat, the R^2 values were -0.982 and -0.970, for the drying temperatures of 55℃ and 70℃, respectively. Further statistical analyses showed that no significant difference (p > 0.05) was found among the oven dried samples at the various drying temperatures used for both cocoa bean with seed coat and that without seed coat. Drying curves was steeper within the first one hour of drying and increases with the increasing air temperature thus resulting in considerable decrease in drying time. Drying followed falling rate trends in all drying conditions. No constant drying rate period was observed. This is in consonance with the results obtained by the previous researchers[15,16,20].

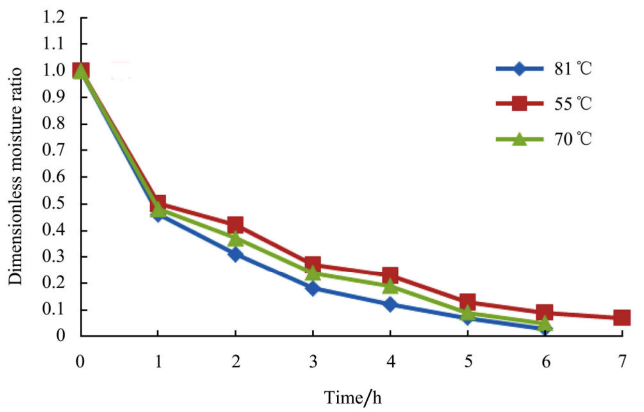

Figure 2 Dimensionless moisture ratio of cocoa bean with seed coat at different temperatures

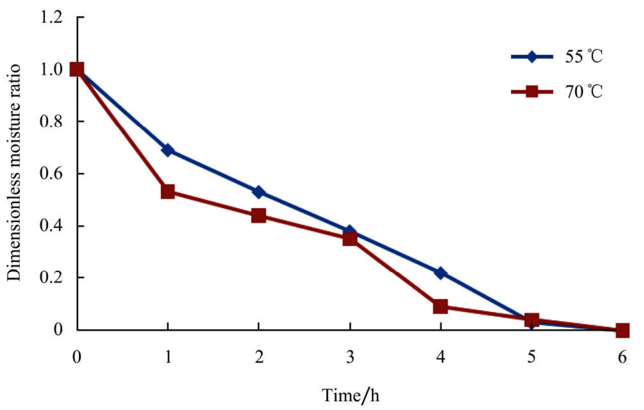

Figure 3 Dimensionless moisture ratio of cocoa bean without seed coat at different temperatures

3.2 Swelling and shrinkage

Area and volume changes of the cocoa bean with and without seed coat are presented in Figures 4-8. The magnitude of volume change and area change increased as the moisture ratio decreased for all temperatures for the bean with coat before tempering (the first four-hourh of drying). For 55℃, the magnitude of volume change and area change increased from 1.0 to 2.57 and 1.0 to 1.88, respectively, for moisture ratio of 1.0 to 0.23 for the first period of drying before tempering as shown in Figure 4. For 70℃ the volume and area change increased from 0.82 to 2.77 and 0.88 to 1.96, respectively, for moisture ratio of 0.48 to 0.19 for the first period of drying before tempering as shown in Figure 6. This trend can also be found in Figure 8 for drying temperature of 81℃. For 81℃ the volume and area change increased from 1.0 to 3.04 and 1.0 to 2.09, respectively, for moisture ratio of 1.0 to 0.12.

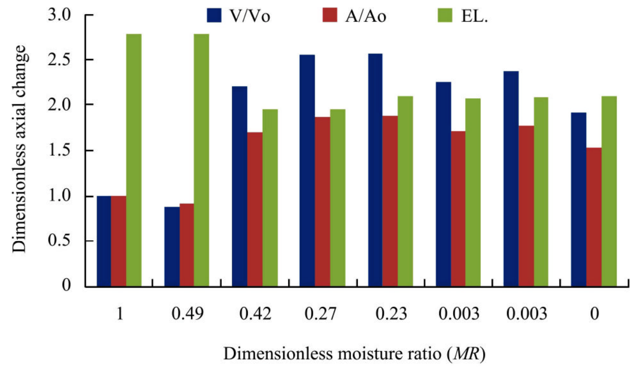

Figure 4 Dimensionless axial change versus dimensionless moisture ratio for the cocoa bean with seed coat at 55℃

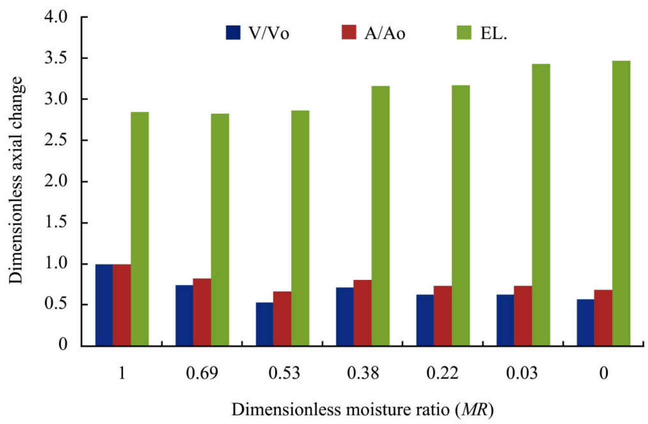

Figure 5 Dimensionless axial change versus dimensionless moisture ratio for the cocoa bean without seed coat at 55℃

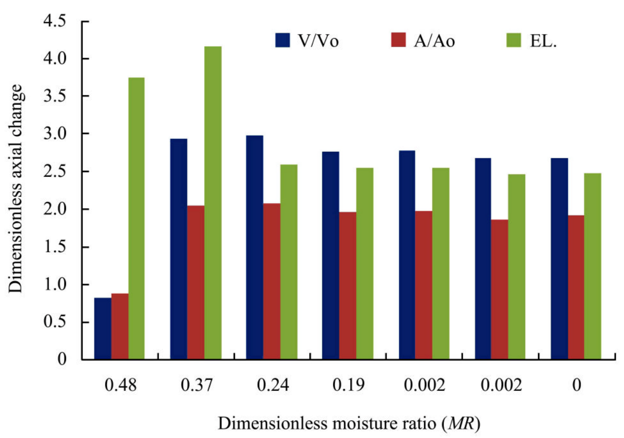

Figure 6 Dimensionless axial change versus dimensionless moisture ratio for the cocoa bean with seed coat at 70℃

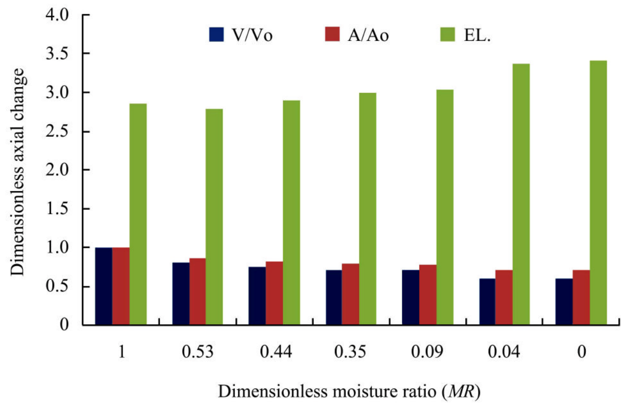

Figure 7 Dimensionless axial change versus dimensionless moisture ratio for the cocoa bean without seed coat at 70℃

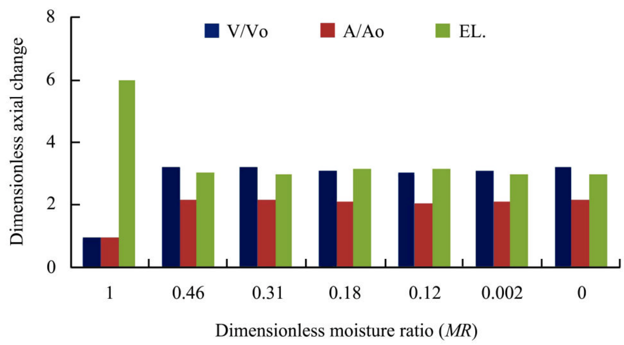

Figure 8 Dimensionless axial change versus dimensionless moisture ratio for the cocoa bean with seed coat at 81℃

However, for the cocoa bean without seed coat, the volume and area change decreased with decreasing moisture ratio for all temperature as shown in Figures 5 and 7. This implied that for bean with seed coat, the minor diameters increased as the moisture content decreased. This indicated swelling while the minor diameters decreased for the bean without seed coat, showing shrinkage.

Tables 2-6 showed that the density decreased with the decrease in moisture ratio and becomes almost constant after tempering for all temperatures for the bean with seed coat, while it remained fairly constant for the bean without seed coat for all temperatures. It can be deduced that the mass of the dry matter will remain constant since the moisture is removed. This means that air and free moisture caused the volume increase which resulted in the decrease in density for the bean with seed coat. As the drying continues, the moisture and air contained inside the cocoa bean will try to escape from the kernel across the seed coat. Because the kernel and seed coat are heterogynous, the rate of moisture and air passage through them will not be the same. It was also observed that the kernel shrinks and becomes free inside the seed coat in the drying progresses, resulting in an empty space between the kernel and the seed coat as drying process continues.

Table 2 Drying data of the cocoa bean dried with the seed coat at 55℃

Time/h	*S*	*Den.*	D_g	A_m	S_{qm}	d_e
0	0.56	0.02	10.02	11.16	10.23	10.47
1	0.56	0.02	9.55	10.61	9.98	10.05
2	0.56	0.007	13.33	13.95	13.64	13.64
3	0.65	0.006	13.91	14.82	14.25	14.32
4	0.66	0.005	13.83	14.60	14.16	14.34
28			24 hours curing period			
29	0.65	0.005	13.38	14.13	13.70	13.74
30	0.66	0.005	13.62	14.35	13.93	13.97
31	0.62	0.006	10.90	14.28	13.86	13.01
sd	0.047	0.0066	1.71	1.63	1.78	1.71

Note: Den, Density (g/mm^3); sd, standard deviation.

Table 3 Drying data of the cocoa bean dried with the seed coat at 70℃

Time/h	*S*	*Den.*	D_g	A_m	S_{qm}	d_e
0	0.52	0.027	8.76	10.21	9.36	9.44
1	0.50	0.027	8.10	9.62	8.76	8.83
2	0.62	0.007	13.00	14.06	13.48	13.51
3	0.63	0.006	13.08	14.12	13.55	13.58
4	0.62	0.006	12.74	13.78	13.20	13.25
28			24 hours curing period			
29	0.63	0.005	12.79	13.74	13.22	13.25
30	0.62	0.005	12.52	13.50	12.96	12.99
31	0.61	0.005	12.58	13.64	13.05	13.09
sd	0.019	0.0004	0.96	0.359	0.427	0.414

Note: Den, Density (g/mm^3); sd, standard deviation.

Table 4 Drying data of the cocoa bean dried with the seed coat at 81℃

Time/h	*S*	*Den.*	D_g	A_m	S_{qm}	d_e
0	0.52	0.040	6.50	8.28	9.08	7.95
1	0.61	0.006	11.18	12.36	11.78	11.77
2	0.62	0.005	11.23	12.39	11.83	11.81
3	0.60	0.005	10.99	12.22	11.60	11.60
4	0.60	0.005	10.89	12.10	11.50	11.50
28			24 hours curing period			
29	0.60	0.004	11.02	12.13	11.57	11.57
30	0.61	0.004	11.24	12.32	11.79	11.78
sd	009	0.014	1.87	1.62	1.06	1.51

Note: Den, Density (g/mm^3); sd, standard deviation.

Table 5 Drying data of the cocoa bean dried without the seed coat at 55℃

Time/h	S	$Den.$	D_g	A_m	S_{qm}	d_e
0	0.6 2	0.007	11.90	13.01	12.43	12.45
1	0.57	0.003	11.06	12.17	10.50	11.24
2	0.53	0.005	10.87	11.31	8.12	10.10
3	0.58	0.003	10.53	11.77	11.10	11.13
4	0.57	0.003	10.04	11.26	10.57	10.63
28	24 hours curing period					
29	0.57	0.0025	9.7	11.04	11.18	10.64
30	0.55	0.0016	9.64	11.00	10.26	10.30
sd	0.018	0.0018	0.816	0.73	1.31	0.786

Note: Den, Density (g/mm^3); sd, standard deviation.

Table 6 Drying data of the cocoa bean dried without the seed coat at 70℃

Time/h	S	$Den.$	D_g	A_m	S_{qm}	d_e
0	0.62	0.008	13.77	15.06	14.41	14.41
1	0.64	0.005	12.87	14.00	13.44	13.44
2	0.62	0.005	12.49	13.68	13.08	13.08
3	0.61	0.004	12.23	13.49	12.85	12.86
4	0.63	0.004	12.19	13.46	12.83	12.83
28	24 hours curing period					
29	0.60	0.003	11.53	12.95	12.26	12.25
30	0.60	0.002	11.48	12.92	12.13	12.18
sd	0.015	0.0019	0.793	0.730	0.768	0.761

Note: Den, Density (g/mm^3); sd, standard deviation.

Due to the heterogeneous nature of the cocoa bean as shown in Figure 9, it can be concluded that the air speed and moisture pass through the kernel and the seed coat is not the same, which depended on the rate of moisture removal under temperatures studied. As the temperature and drying time increases, the rate of moisture removal increases, resulting in faster air removal and therefore the volume and area changes decreases (shrinkage). The above behaviour is useful when modelling deep bed drying of cocoa bean with height is considered. In tempered stage, there was no heating and expansion of the air and structural matrix of both the cocoa kernel and seed coat. The air gradually goes off while the structural matrix of the kernel retracts back into the spaces that were previously occupied by the air. This results in the decrease in volume and area changes immediately after tempering[3]. After tempering, some moisture still remains within pockets of air, which results in subsequent lower increase as the drying begins. When looking at the two drying conditions, for all temperatures and when drying without seed coat, the cocoa kernel was sufficiently elastic to shrink into the space left by the evaporated moisture. However, for cocoa bean with seed coat, the cocoa kernel was sufficiently elastic to shrink into the space left by the evaporated moisture at temperatures of 70℃ and 81℃, and from three to four hours of continuous drying. As drying proceeds, it can be presumed that the structure rigidity of kernel increased. This results in the decrease of the volume and area. Change in elongation of the cocoa bean in the studied temperatures with or without seed coat is also shown in Figures 4-8. Elongation in this case indicates the movement of the cocoa bean structural matrix as the drying progresses between the minor and major diameter. An increase shows the movement of the structural matrix towards the major diameter while a decrease shows the movement towards the minor diameters[3]. For the bean with seed coat, the elongation increased within the first two hours of drying for all temperatures but decreases afterwards. However, for the bean without seed coat, it continuously increased throughout the drying period. This implies that the minor diameter was the major contributor to the area change within the first two hours of drying, while it reverses afterwards as the minor diameter becomes the major contributor as shown in Tables 2-6.

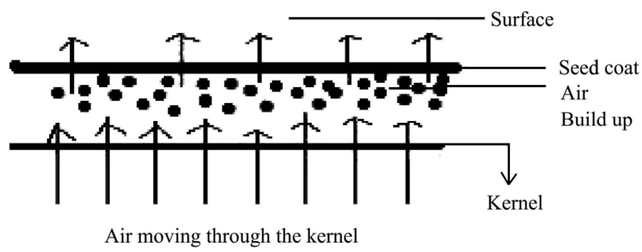

Figure 9 Air movement between the kernel and seed coat

For the bean without seed coat, the increase was continuous in the drying progresses as the major diameter is the major contributor to the volume and area change. The sphericity describing the closeness of the shape to a perfect sphere is shown in Tables 2-6. For the bean with seed coat, the sphericity increased with the decrease of moisture ratio. However, after three hours and two hours of drying at 70℃ and 81℃, the sphericity started to decrease before tempering. The sphericity at 70℃ and 81℃ approaches almost the same value from two hours of drying. This might be as a result of isotropic shrinkage at high temperature. For the cocoa bean without seed coat, the change in sphericity was not constant throughout the drying as shown in Tables 5 and 6, but ranges from 0.53 to 0.62 at drying temperature of 55℃, while it ranged from 0.60 to 0.64 at drying temperature of 70℃. The cut test performed for the dried cocoa revealed 92% deep brown kernel, 7.4% purple-brown kernel and 0.6% purple kernel. However, the cocoa bean dried without the seed coat always shatters when force is applied during cutting. This is as a result of lack of seed coat which holds the cleaved cotyledon together.

4 Conclusions

The influence of drying conditions on the dimensional matrix of cocoa bean during drying with tempering was established at an isothermal condition. The seed coat and air-moisture build up around the seed coat has obvious influence on the change in the shape of the entire heterogeneous structure of the cocoa bean at drying temperatures of 55℃, 70℃ and 81℃ at the beginning of drying. It was found that the rate of moisture diffusion between the cocoa kernel and seed coat is not the same especially at a lower temperature of 55℃ and initial drying time for all temperatures used. At the higher drying temperatures of 70℃ and 81℃, the rate of moisture and air removal depends on the rate of diffusion from the kernel as the seed coat and moisture build up becomes a less hindrance. Change in sphericity of the bean was more pronounced at a lower temperature of 55℃ for bean with seed coat. While for all the other drying conditions, it remains fairly constant after one-hour drying. The density decreased with the decrease in moisture ratio and becomes almost constant after tempering for all temperatures for the bean with seed coat. However, it decreased continuously for the bean without seed coat at the drying progresses. From the analysis of the elongation for the beans with seed coat, the minor diameter was the major contributor to the area change within the first two hours of drying but it reverses afterwards as the minor diameter becomes the major contributor.

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