A PHYSICAL CONSIDERATION OF THE MECHANISM OF THE CRACKING OF SWEET CHERRIES

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(With 5 text-figures)

Introduction

It has long been known that cherries are liable to crack when it is rainy during their harvest time. It is not of rare occurrence that they are injured so severely and extensively that they are abandoned to remain on the tree without being harvested, since their disagreeable appearance, poor taste and increased susceptibility to fungus infection render them almost worthless for sale. Such being the case, it is most natural that some American and Japanese horticulturists [1,2,3,4] have attempted to determine the conditions which induce the cracking.

The writer has engaged in the study of the present problem since 1928, attacking it from the following points of view.

1. Cause of the cracking of cherries after rainfall.
2. Physical mechanism of the cracking.
3. Susceptibility and resistance of cherry varieties to cracking.

With regard to the first problem the writer has already reported in 1931 [5], that the absorption of water through the stomata of the skin results in increased turgidity of the fruit cells and eventually in the cracking of the fruit.

The next year he published a paper entitled "Butsurigakuteki ni kansatsu shita Mizakura-miware no Kiko" (On the mechanism of the cracking of cherries studied from physical points of view.) and discussed mainly on the second problem.

In the present paper the writer intends to give the outlines of the latter report.

The writer wishes to express his sincere thanks to Prof. Y. Hoshino, under whose direction this investigation was carried out, and Prof. S. Ito, for his valuable critisism and encouragement given during the progress of this study.

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He wishes also to acknowledge his indebtedness to Prof. U. NAKAYA, who gave helpful guidance concerning the physical problems.

Observation on the Cracking

Before a description of the types of cracking, it seems desirable to describe the morphological aspects of cherry fruit and the terms used in this paper. The cherry fruit can be divided into the following three parts: cavity, body and apex. It has three different sides, namely, ventral, lateral and dorsal. On the ventral side runs a distinct longitudinal line, called the ventral suture. In the middle part of the dorsal side, there is also a longitudinal line called the dorsal suture. Although no more lines can actually be seen the writer assumes, for the convenience of explanation, three other longitudinal lines named as follows: the first line is supposed to pass through the middle part of the lateral side and is called the lateral line, the second on the middle line between the ventral suture and the lateral line and called the V-L line, and the third likewise between the dorsal suture and the lateral line and called the D-L line (Fig. 1).

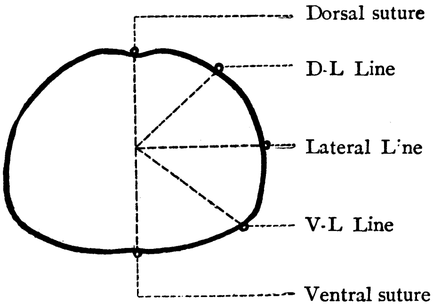

Fig. 1. Cross section of cherry fruit indicating diagrammatically the position of the longitudinal lines including ventral and dorsal suture.

On July 28, 1931, the day after a rainfall, all fruits, without regard to their maturity, were gathered from certain branches of Black Tartarian, Elton and Hokko cherry trees, and classified according to their maturity and types of cracking. The results are summarized in Table 1.

Table 1. The classification of the splits of affected fruits according to the part of fruit.

Variety	Number of fruits Observed	Maturity		Number of affected Fruits	Percentage of affected Fruits	Number of Splits in the 3 parts of fruit							
						Cavity			Body				Apex
						V-L	Lateral	D-L.	Ventral suture	V-L	Lateral	D-L	
Black Tartarian	1255	Unripe	808	65	8	0	43	10	1	38	13	11	0
		Ripe	447	210	47	18	177	82	1	164	43	34	21
Elton	495	Unripe	223	2	1	0	2	0	0	2	0	0	0
		Ripe	272	13	5	0	9	0	0	7	0	1	1
Hokko *	1173	Unripe	542	38	7	0	30	10	3	18	3	4	0
		Ripe	631	146	23	1	133	53	12	90	8	27	1

* This seems to be a variety appeared in Hokkaido as a chance seedling of Elton.

From the data shown in Table 1, it appears that the severity of the injury depends much on the maturity of fruits. However that point will not be discussed here, because it is not significant for the present study. Of the three parts of the fruit, the body as well as the cavity is most generally and severely affected, while the apex is injured only rarely and slightly except in some special varieties. The type of crack occurring in each part of the fruit having characteristic features and moreover having an important connection with the later discussion, it seems desirable to describe the cracks in detail. When the cavity is injured it is usual that a semicircular split occurs, tracing the shoulder part of fruit as shown in Fig. 2. (A). When the split occurs on the body, it is usually parallel to the fruit axis, extending longitudinally through the body

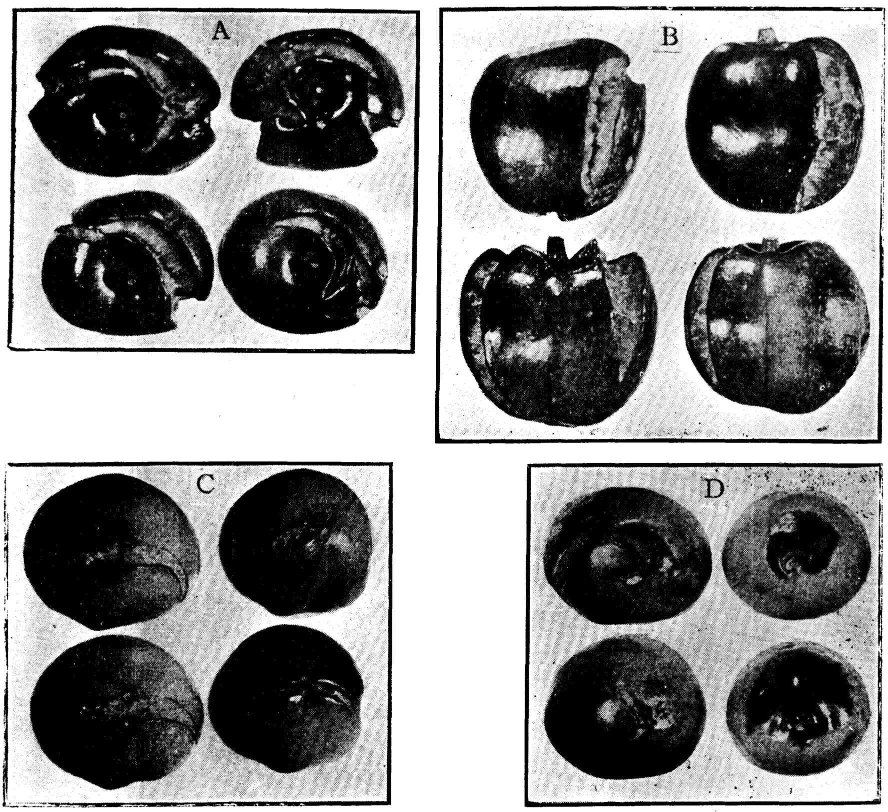

Fig. 2. The most usual type of cracking
(A) in the cavity.
(B) in the body.
(C) and (D) in the apex.

as shown in Fig. 2. (B). In the above two parts, the portion, where a split occurs most frequently, it is almost always confined to a definite side of the fruit. Fore instance, it is the lateral side on the cavity and the V-L line region on the body, as is shown in Table 1. On the other hand, the type of crack on the apex, being variable according to the individual variation of fruit shape as well as to the varietal differences, does not seem to have such a definite tendency as in the above two parts. It appears that there exist at least two types of injury. The first type, which occurs mostly in fruits having a depressed stylar scar, is characterized by a circular or a semicircular split surrounding the scar, as indicated in Fig. 2. (D). In this case, the split occurs with almost equal frequency on all sides of the apex except the ventral. In the second type, the scar is divided into halves by a linear split as shown in Fig. 2. (C). It is very common that this sort of split connects with that of the body. As the split of the body takes place mostly along the V-L line, the split of the apex is also apt to occur on the same side of the apex. However the cracking is not confined to that side only, splits in other directions occuring rather frequently. Thus, in the apex, the crack type is less distinct as compared with that of the body and the cavity.

When the type of crack in each part is examined, taking the curvature of the fruit shape into consideration, splitting occurs, in each part, along the most acute-angled part of fruit. For instance, in the body, as shown in the cross section of the fruit, (Fig. 1.) the peripheral line curves at the V-L line part most acutely, and it is the part where the cracking appears most frequently. This is the reason why the present investigation was undertaken.

Material and Method

Two healthy cherry trees of the variety Bigarreau Jabouley, grown in the Orchard of the Hokkaido Imperial University at Sapporo, were chosen for the study. Fully ripened fruits were gathered from these trees separately and brought into the laboratory. Fruits of uniform size and maturity, were selected and divided into three groups each of twenty fruits. The first and second groups designated as A and B in Table 2, consist of the fruits collected from one of the two trees and third group, C. from the other. Experiments were conducted in parallel with these groups. The weight and dimensions of the materials are presented in Table 2.

Table 2. Weight and dimensions of the materials (var. Bigarreau Jabouley) used for the determination of the curvature.

Group	Average weight of fruit in Gm.	Dimensions of fruits		
		Longitudinal diameter	Suture diameter	Lateral diameter
		mm	mm	mm
A	4.905 ± 0.068	20.1 ± 0.095	17.7 ± 0.072	21.6 ± 0.133
B	4.430 ± 0.039	19.6 ± 0.080	17.1 ± 0.127	21.0 ± 0.121
C	5.905 ± 0.065	21.1 ± 0.134	18.8 ± 0.136	22.4 ± 0.118
Mean	5.080 ± 0.064	20.3 ± 0.076	17.8 ± 0.088	21.7 ± 0.084

The investigation mainly consisted in the determination of the curvature of the fruit. The spherometer was not used in order to avoid the experimental error due to the smallness and softness of the material, which might be great when this apparatus was employed. The determination of the curvature by means of cutting also seemed almost impossible, because both a longisection and a transection from one fruit could not be made owing to the hard stone.

So the writer devised another method. Namely, the vertical view* (Fig. 3) of fruit was used as a substitute for its transection for the reason that the outline of the vertical view is nearly the same as the transection through the largest transverse diameter of the fruit. Actual sectioning was done only in getting longisections. In order to obtain longisections, the fruit was cut first longitudinally along the V-L line and the ventral suture with a Valet-razor blade, and a small spherical wedge was cut out; then the newly cut surface was photographed in such a manner as to show the V-L line as in Fig. 4. (A). Next, the same fruit was cut along the lateral line, then along the D-L line, and finally through the dorsal and ventral suture, and each newly cut surface was photographed successively as shown in Fig. 4. (B, C, D). In photographing, 4 fruits were treated simultaneously in each case, and much care was taken to keep them in their respective position within the square rim.

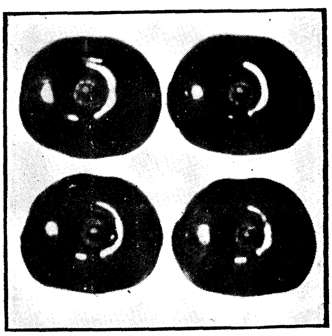

Fig. 3. Vertical view of fruits, which was used as a substitute of the transection of the fruit.

*) The visual angle of the camera to the square rim, in which the fruits were arranged, was adjusted as small as 7°8′. So it may be said that the images are vertical.

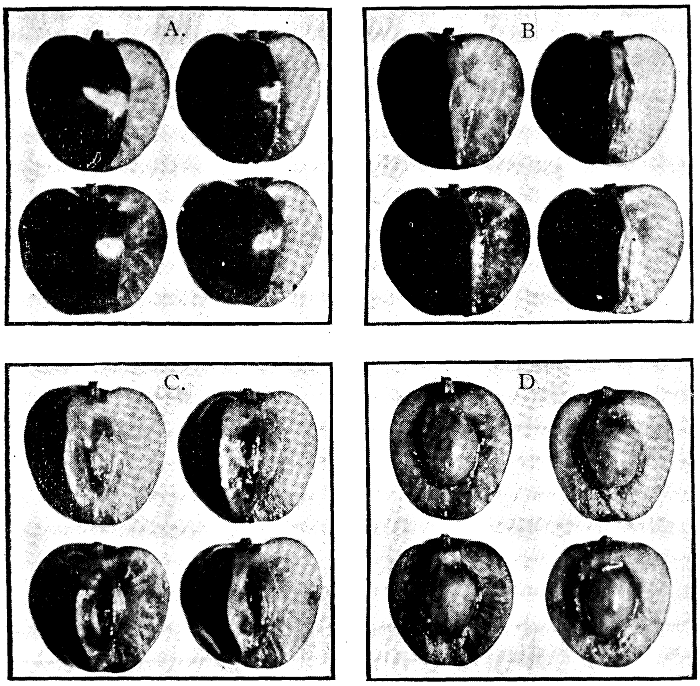

Fig. 4. Longitudinal sections of fruit showing
(A) the V-L line.
(B) the lateral line.
(C) the D-L line.
(D) the ventral and dorsal suture.

After the above photographs were taken, the curvature was determined at five peripheral points by combining the photographs of longi-section with that of the vertical view.

Hereafter, the vertical view of fruits will be referred to as 'transection' for convenience of contrasting with longi-sections.

In order to measure the radius of curvature, the photographs were enlarged 3.85 times (in length) to the natrual size of the fruit. The instruments used were rulers, compasses, needles and a Zeiss magnifying glass with micrometer. Needles were used for drawing lines and points. A micrometer was used for measuring the height of arc and length of the chord.

Let h = height of arc cut as short and equidistantly as possible from the point where the radius of curvature is to be measured.

l = half length of the chord connecting both feet of the arc.

Then the radius of curvature r will be

$$r = \frac{h}{2} + \frac{l^2}{2h}$$

Presentation and Discussion of Results

The measurement of the radius of curvature are presented in Table 3.

Table 3. Length of the radius of curvature of the transverse line and five longitudinal lines measured at their intersecting points. The curvature of those points is shown in the last column by the ratio of the radii in both directions.

Side of Fruit	Group	Radius of Curvature of		Ratio
		Longitudinal Line	Transverse Line	
		mm	mm	
Ventral Suture	A	9.69±0.208	8.75±0.784	1.107
	B	9.82±0.226	8.50±0916	1.155
	C	10 92±0.248	10.39±0.298	1.c51
	Mean	10.14±0.142	9.21±0.468	1.104
V-L Line	A	9.96±0.273	6.54±0.119	1.523
	B	9.12±0.176	6.25±0.107	1.459
	C	10.38±0.239	6.72±0.132	1.545
	Mean	9.82±0.140	6.50±0.070	1 509
Lateral Line	A	10.63±0.277	9.08±0.241	1.171
	B	10.90±0.316	9.07±0.252	1.202
	C	11.29±0.258	9.85±0 300	1.143
	Mean	10.94±0.162	9.33±0.165	1.173
D-L Line	A	10.29±0.275	9.00±0.277	1.143
	B	9.81±0.252	7.99±0.167	1.228
	C	10.83±0 252	9.55±0.271	1.134
	Mean	10.31±0.152	8.85±0.151	1.168
Dorsal Suture	A	10.85±0.284	−21.86±2 316	−0.496
	B	11.34±0.322	−20.39±2.202	−0.556
	C	11.61±0.478	−13.64±1.676	−0.851
	Mean	11.27±0.215	−18.63±1.210	−0.634

In the above table it will be noted that the results are quite in agreement in each group, considering the larger size of the materials of group C. It is also obvious that the radius of curvature of longisections is almost equal in length at five peripheral points, while in the 'transection' it differs according to the point. Moreover, when both radii of curvature of the longisection and of the transection, which mutually bisect each other, are compared, it will be found that the former surpasses the latter in length in each point except the dorsal part. Hence it follows that the curvature, expressed by their ratio, exceeds 1. This means that the body of the cherry is composed of ellipsoidal surfaces whose axes of rotation are directed all alike in the longitudinal direction of the fruit. Another outstanding characteristic of the transection is the negative sign of the radius of curvature at the dorsal part. This is because of the concave surface at that part. But in this investigation this part of fruit was treated as an exception, because there are some evidences to indicate that the cracking would not occur at that part as shown by its anatomical features.

The next problem to be studied, is the relation between curvature and the mechanism of the cracking of the fruit. As the surfaces of the fruit are of ellipsoidal nature, this problem will become more simple, if an ellipsoid, instead of the fruit, is studied in such a relation, assuming the inner pressure of the fruit to be hydrostatic in its nature. However, as far as an ellipsoid in general is concerned, there is no formula which show the relation between the hydrostatic pressure and the tension caused by it. So an attempt was made to apply the solutions in the case of a sphere and a cylinder for ellipsoid, because either a sphere or a cylinder is considered as a special case of ellipsoid, a sphere being formed when the axis of rotation and the transverse axis of an ellipsoid become equal in length, whereas a cylinder is likewise produced when the axis of rotation of an ellipsoid is prolonged infinitely.

Let P_o = Strength of the inner hydrostatic pressure
b = length of the internal radius
d = thickness of the wall

then in the case of a sphere, the tension $\theta\theta$, caused by the inner overpressure, is expressed theoretically by the following formula:

$$\theta\theta = \frac{1}{2} P_o \frac{b}{d}$$

In a sphere, all of its nature being independent of the directions, the strength of the tension remains always constant in all directions. But in the case of a cylinder the relation becomes more complex than in a sphere. The strength of the tension varies according to the directions. From theoretical calculation the maximum strength acts in the direction at right angle to the altitude and its strength ($\theta\theta$) is expressed by the following formula:

$$\theta\,\theta = P_o \frac{b}{d}$$

In this formula the terms other than $\theta\,\theta$ are the same as mentioned before. The tension decreases gradually as the angle between the altitude and the direction of the tension decreases until at last it diminishes to zero when the direction of the tension coincides with that of the altitude. When the above two formulae are compared with each other, it will be soon understood that the transverse tension of the cylinder is stronger than that of the sphere just as much as the cylinder is surpassed by the latter in the tension of longitudinal direction. So, in both sphere and cylinder, the sum of the tensions in both directions is the same. Considering the above relation, it is very likely that in an ellipsoid, which is intermediate between a sphere and a cylinder in its nature, the tension is stronger in the transverse direction than in the longitudinal. Moreover as the shape of an ellipsoid becomes longer, or in other words, as the curvature at a certain point increases, the tension seems to increase in the transverse direction whereas the tension in the longitudinal direction decreases gradually.

As already stated the body of cherry fruit is composed of ellipsoidal surfaces lying longitudinally, and, besides, its curvature is the highest at the V-L line region. Hence the cherry fruit, for the reason described above, should crack longitudinally and especially at the V-L line region. This is actually the case of the cracking of cherries. This seems to indicate that the types of cracking are mainly determined by the curvature of the surface of the fruit. If it is true, it must be applied to the strength of the tension too. When a cherry fruit is cut, while it is fresh, at any part and in any direction with a cutting tool such as a razor, a split wider than the thickness of the blade is formed. This is presumably due to the contraction of the skin. Moreover, the width of the split varies not only according to the part of fruit but also to the direction of the cut even at the same point. So the width of the split was considered reliable as an index of the strength of tension at different parts of fruit, provided that uniformity in the length and depth of the split is secured. The data presented in Table 4 show the distribution of the tension upon the fruit, as measured by the width of split. In obtaining data only one cut was made on each fruit, because the contraction of the whole skin may be affected by cutting at one part, and each figure in the table represents average of twenty-five measurements. The width of each split was measured twice under a low power microscope, immediately after the cutting and fifteen minutes later, since the split is apt to become wider as time elapses. The mean of these two measurements is given to represent the width of each split.

Table 4. The tension of the skin as measured by the width of split artificially made at various parts of the cherry fruit (var Napolon Bigarreau.)

Part of Fruit	Width of Split \ Side of Fruit	Ventral Suture	V-L Line	Lateral Line	D-L Line	Dorsal Suture
		μ	μ	μ	μ	μ
Cavity	Longitudinal	70.37±0.29	....	480.74±0.90	....	204.44±0.61
	Transversal	350.37±1.27	....	665.92±1.55	....	378.51±0.98
	Ratio	0.210	....	0.722	....	0.540
Body	Longitudinal	264.07±0.97	740.00±1.82	678.52±1.89	540.74±0.91	291.85±0.89
	Transversal	274.07±0.59	526.67±1.28	568.15±1.09	451.85±0.79	177.78±0.67
	Ratio	0.964	1.405	1.194	1.197	1.642
Apex	Longitudinal	357.78±0.53	....	382.96±0.62	....	395.56±0.64
	Transversal	365 93±0.49	....	414.07±0.54	....	361.48±1.30
	Ratio	0.687	....	0.925	....	1.c94

Now, let us discuss whether the above measured tensions agree with the theoretical induction based on the curvature of the fruit surface. In this connection, the body only will be dealt with, since the curvature was measured only in the body. In the first place, the longitudinal split is witer than the transverse in each point except the ventral part. This may be attributed to the fact that the tension is larger in the transverse direction than in the longitudinal. This is quite in accod with the theoretical expectation and gives a sufficient basis to explain why the body of a cherry fruit cracks longitudinally but not transversely. It is evident from Fig. 5, a graphical presentation of the data in Table 4, that the longitudinal split is the widest at the place of the V-L line. This also offers adequate evidence for the theoretical expectation, and the reason why cherries usually crack at that part is easily understood. Finally, if the strength of the tension on the surface of the fruit is determined primarily by the curvature of the surface, there should exist complete harmony between the curvature and the ratio of longitudinal and transverse tension In reality, there can be found an almost exact ageement between them, when the data given in Tables 3 and 4 are compared with each other, in spite of the varietal difference of the materials. Accordingly it seems that the strength of the tension does correspond decidedly to the curvature of the surface of the fruit.

The mechanism of the cracking of both cavity and apex appears to be identical in principle with that of the body. Since the ratio of width of splits in both directions is less than 1 as shown in Table 4, the cavity seems to be composed of ellipsoidal surfaces lying in the transverse direction. The apex, judging from the fact that its ratio is nearly 1, seems to be nearly like a sphere in its nature. The reason why the cracking in the cavity tends to occur transversely and why the apex fails to show so distinct a tendency in cracking direction, may be explained by these specialities of the curvature of those parts. Another type of cracking in the apex, namely the semicircular splitting, may be accounted for by the same reason as in the case of the cracking of the cavity.

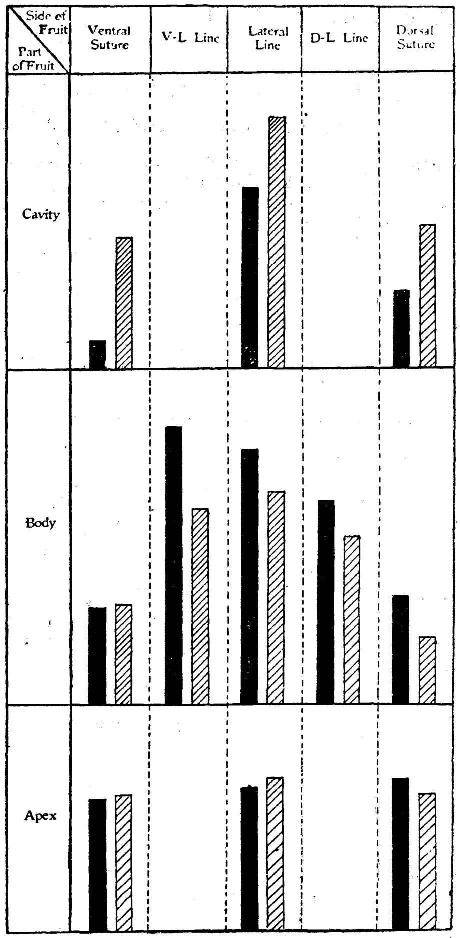

Fig. 5. Diagramatical presentation of the results shown in Table 4.
...... denotes the width of the transversely cut split.
...... denotes the width of the longitudinally cut split.

Though the discussion in this paper was confined to the cracking of cherries, it should not be taken to mean that this sort of injury is restricted to cherries only. There are some other fruits and vegetables that are affected by cracking. Grapes and plums, especially those varieties which produce large fruits, are sometimes injured seriously by cracking. In tomatoes the cracking is of rather usual occurrence in the field, though it does not necessarily injure their quality. On the other hand, cracking is a fatal defect in muskmelons, as they are rendered almost worthless for sale. Cracking can be seen also in root crops such as radishes and carrots. It is also a well known fact that vegetable growers suffer from the bursting of cabbages after rainfall. This can be regarded as one sort of cracking. When the types of cracking of those fruits and crops are observed carefully, it is found that the cracking occurs mostly at the part of high curvature and in the longitudinal direction as in the cracking of cherries. For instance tomatoes crack longitudinelly or transversally, even in the same variety, according to the individual shape of the fruit, and radishes and carrots always crack longitudinally. From these facts, it is evident that the curvature is an important factor in those crops in determination of the types of cracking.

Summary

After a heavy rainfall cherries are affected, sometimes seriously, by cracking. The cracking occurs usually at a difinite part of the fruit and in a definite direction. This investigation was undertaken for the purpose of examining the relation between the curvature of the fruit and the types of cracking. As a result of the measurement of the curvature of the body of the fruit, it was found that the body is composed of ellipsoidal surfaces lying all alike in the longitudinal direction of the fruit. Hence the relation of the curvature to the tension in an ellipsoid under hydrostatic pressure was studied and some deductions were made in regard to the strength and direction of the tension. The theoretical deductions are quite in agreement with the actual nature of the cracking. Moreover, the comparison of the curvature and the strength of the tension within the fruit, as measured by the width of artificial cuts, offered sufficient evidence to indicate that the types of cracking are determined primarily by the curvrture of the fruit surface.

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