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Title: Measurement and Fissuring of Rice Kernels During Quasi-moisture Sorption by Image Analysis

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Corresponding Author: Dr Naoto Shimizu,

Corresponding Author's Institution: University of Tsukuba

First Author: Naoto Shimizu

Order of Authors: Naoto Shimizu; Md. Ashraful Haque; Martin Andesson; Toshinori Kimura

Abstract: Fissuring associated with kernel elongation was evident in a moisture-adsorbing environment at 15°C of relative humidity $88.72 \pm 0.28\%$ with moisture content from 6% (d.b.) to 16.3% (d.b.). The average length and width of 800 kernels was measured during the sorption test using a Cervitec Grain Inspector equipped with two digital cameras. Samples were exposed to both a moisture-adsorbing and desorbing environments at 15°C with relative humidities of 23.4 ± 0.53 , 55.9 ± 0.27 , 70.98 ± 0.28 and $88.72 \pm 0.28\%$. On image analysis, the kernels changed in size from 5.13 mm to 4.84 mm in length and 2.9 mm to 2.73 mm in width. Both length and width changed as expected during moisture-adsorbing and moisture-desorbing tests. Fissured kernel percent was related to changes in the average length of the kernels during the moisture-adsorbing tests. The average length and fissured kernel percent of rice kernels measured by image analysis may be considered as a reliable indicator of changes in their dimensions during quasi-static moisture sorption processes.

1 **1. Introduction**

2 Inspectors have started to use image analysis methods to support the
3 classification of brown rice. As the most delicate of the cereals, rice needs the
4 utmost care during post-harvest handling and processing, as it is consumed
5 as a whole kernel. The surrounding environment greatly affects its quality,
6 especially the head rice yield (HRY). The economic importance of
7 maintaining a high HRY is critical during drying, storage, and milling
8 operations (Sharma and Kunze, 1982; Write and Warnock, 1983). Inadequate
9 quality control measures during any of the aforementioned steps can result
10 in fissuring which decreases the yield of milled rice. An image analysis
11 method is required to determine the mechanism of fissure formation.

12 Fissuring of rice kernels during drying in air with a high temperature and
13 low relative humidity (RH) (e.g. 60°C and <20%) has been addressed in
14 various studies (Sarker and Kunze, 1996; Jia et al., 2002; Sun et al., 2002;
15 Yang et al., 2002; Zhang et al., 2003) and has been explained by several
16 hypotheses.

17 The earliest work by Kondo and Okamura (1929), Stahel (1935),
18 Henderson (1954), and Deshikachar and Subrahmanyam (1961), as reviewed

1 by Kunze and Hall (1965), only commented on the phenomenon of moisture
2 adsorption by rice kernels, until the work of Siebenmorgen et al. (1998).
3 Fissures increased in number and formed more quickly in drier paddy
4 environments, particularly following a rise in moisture content (MC) of the
5 rice grains. All of these studies were based on wetting the kernels by
6 submerging them directly in water. The effect of moisture adsorption from an
7 environment with a high RH on brown rice cracking was studied by Kunze
8 and Hall (1965), who observed cracking damage from RH changes in relation
9 to response time. A study by Kunze and Choudhury (1972) showed a
10 reduction in the tensile strength of rice with increased time of exposure to a
11 humid environment. Siebenmorgen and Jindal (1986) found a significant
12 reduction in HRY due to moisture adsorption from various sources. Banaszek
13 and Siebenmorgen (1990) determined the effects of initial MC, exposure time,
14 conditioning air RH, and temperature on the HRY of rough rice.
15 Muthukumarappan et al. (1992) measured volumetric changes in rice
16 kernels during desorption and adsorption. Jindal and Siebenmorgen (1994)
17 showed that the thickness of long grain rice kernels influenced the reduction
18 in HRY resulting from moisture adsorption using high RH air. Much work on

the effect of moisture addition or drying has been done in relation to cracking and HRY.

Construction of low temperature ($\sim 15^{\circ}\text{C}$) storage systems has accelerated in Japan since around 1985 due to increased consumer interest in food safety and quality. Very few studies have addressed the recommended conditions for measuring rice kernels by image analysis and the phenomenon of fissuring of kernels during storage. The aim of this study was to clarify the process of fissure formation in kernels of Japonica rice during a quasi-static sorption (adsorption and desorption) process that was equilibrated for several months under a low temperature.

In this study, we relate fissuring to the change in length and width of kernels during sorption, which were measured using image analysis.

2. Experimental

2.1. Samples

Brown Japonica rice (Kirara 397, Akitakomachi, Koshihikari), provided by the Japan Grain Storage Association, was harvested in the

Hokkaido, Akita and Ibaraki prefectures, Japan in 2001. Samples were sacked in craft paper bags (30 kg) and stored in a chamber (MC: Kirara 397 14.9%, Akitakomachi 15.2%, Koshihikari 14.3%) at 5°C before testing. The appearance, quality, and MC of the brown rice are shown in Table 1. Kirara 397, Akitakomachi and Koshihikari were characterized as grade 1 by the national standard for domestic agricultural products in Japan.

2.2. Set-up

Table 2 shows the scheme used for the measurement, within the prescribed time interval, of grain sample weight and kernel length and width. The sorption experiments consisted of conditioning (I or II), desorption, and adsorption processes. Measurements were first taken on August 5, 2003 and ended on February 19, 2004.

2.3. Conditioning process

Brown rice samples (5 g) with an initial MC of about 15% were transferred

1 from the craft paper bags to polyethylene bags (thickness of the film: 0.04
2 mm, width: 85 mm, height: 120 mm) in a chamber. Inside the bags, the
3 samples were approximately two kernels deep. They were equilibrated for 64
4 days in a refrigerated warehouse maintained at a temperature of 5°C, then
5 the bags were opened widely by folding down the upper half before being
6 placed inside a desiccator containing ion exchange water under the
7 desiccator plate in a moisture-adsorbing environment (conditioning process
8 I). Half of the polyethylene holders were used for the moisture-desorbing
9 tests.

10 The samples in polyethylene bags with an MC of about 23% were then
11 dried for 1 day in an LC-122 chamber (Tabai Espec Co., Japan) at a
12 temperature of 40°C, and the bags were opened widely by folding down the
13 upper half before being placed inside a vacuum desiccator. These samples in
14 polyethylene bags were subsequently equilibrated for 72 days in a
15 refrigerated warehouse maintained at a temperature of 5°C and in a
16 desiccator containing silica gel under the desiccator plate in a
17 moisture-desorbing environment (conditioning process II).

18

1 2.4. *Desorption and adsorption tests*

2

3 The RHs of four saturated salt (Wako Chemical Industry Co., Osaka,
4 Japan) solutions are shown in Table 3. Samples with an MC of 23% in
5 polyethylene bags were equilibrated for 65 days or more in a chamber
6 maintained at a temperature of 15°C and in four desiccators maintained at of
7 23.4±0.53, 55.9±0.27, 70.98±0.28 and 88.72±0.28% RH in a
8 moisture-desorbing environment.

9 Samples with an MC of 6% in polyethylene bags holders were equilibrated
10 for at least 65 days in a chamber maintained at 15°C and in four desiccators
11 maintained at 23.4±0.53, 55.9±0.27, 70.98±0.28 and 88.72±0.28% RH in
12 moisture-adsorbing environments.

13

14 2.5. *Analysis*

15

16 Within the prescribed time interval (Table 2), the MC, length, width,
17 and fissuring of kernels were determined by the following methods.

18 ISO R712 standard method (ISO, 1979) was followed to determine

1 the moisture content of the kernels at the start and end of the process when
2 a 5 g ground sample was dried at 130°C for 2 hours in a forced-air oven. The
3 margin of error was less than 0.04%. Weight loss or gain of each sample was
4 measured by an electronic balance with an accuracy of 0.1 mg (LIBROR
5 AEG-220G; Shimadzu Co., Japan) and then the lengths and widths of
6 kernels were measured using a 1625 Cervitec Grain Inspector (Foss-Tecator
7 AB, Höganäs, Sweden) at approximately 1 week intervals over a period of
8 199 days (Table 2). The average lengths and widths of 800 kernels were
9 determined. Standard deviations were 0.35 mm and 0.15 mm for the average
10 length and width, respectively. Top view (length and width) measurements
11 using this image system had high reproducibility and were very rapid (1000
12 kernels/minute). The analysis process involved sample presentation, image
13 collection by two CCD cameras, image processing, and kernel classification.
14 From the images obtained, the instrument could detect fissures on the
15 kernels. Figure 1 shows the length-width plane used for the determination of
16 the average length and width of rice kernels by image analysis.

17

18 *2.6. Sample preparation*

1

2 The changes in the MC of brown rice during the moisture-desorbing
3 and moisture-adsorbing tests are shown in Fig. 2. Samples were prepared
4 using the Tsutsumi method (1965), in which a reduction of equilibrium
5 moisture content (EMC) is caused by a hysteresis effect. The hysteresis effect
6 could be constant, after more than 20% of the moisture had been adsorbed
7 from the brown rice, when the EMC was measured under the
8 moisture-desorbing and moisture-adsorbing tests. The brown rice with the
9 highest MC, about 23%, was prepared by conditioning process I. That with
10 the lowest MC, about 6%, was conditioned by process II. Kernel fissures were
11 not observed as a result of the conditioning processes.

12

13 **3. Results and discussion**

14

15 *3.1. Equilibrium moisture content, length, width, and fissured kernel* 16 *percent during moisture-adsorbing and desorbing tests*

17

18 Samples were exposed to a moisture-desorbing environment at 15°C

1 and 23.4 ± 0.53 , 55.9 ± 0.27 , 70.98 ± 0.28 and $88.72 \pm 0.28\%$ RH (Fig. 2). There
2 were large differences between the highest MC and the EMC. The brown rice
3 with the highest MC was equilibrated for at least 65 days during the
4 moisture-desorbing tests at 15°C and $23.4 \pm 0.53\%$ RH.

5 Samples were exposed to a moisture-adsorbing environment with a
6 temperature of 15°C and 23.4 ± 0.53 , 55.9 ± 0.27 , 70.98 ± 0.28 and $88.72 \pm 0.28\%$
7 RH. There was a large difference between the lowest MC and the EMC. The
8 brown rice with the highest MC was equilibrated for 63 days or more during
9 the moisture-adsorbing test at a temperature of 15°C and $88.7 \pm 0.28\%$ RH.

10 The time required to reach EMC is at least 20 days at 20°C (Tsutsumi,
11 1965), and the results of the present study were due to the low temperatures
12 and the large differences between the initial MC and EMC.

13 The average length of the kernels and fissured kernel percent as
14 determined by the Cervitec during the moisture-desorbing and
15 moisture-adsorbing tests are shown in Figs 3 and 4. The average length of
16 the kernels decreased during the moisture-desorbing tests and increased
17 during the moisture-adsorbing tests. Muthukumarappan et al. (1992)
18 proposed models for the effects of moisture and temperature on the volume

1 expansion of rough, brown, and milled long grain rice. The length and width
2 of the kernels were measured during conditioning processes I and II, which
3 produced large differences in initial MC contents and EMC. Fissuring of
4 kernels was evident in the initial stages of the moisture-adsorbing tests (Fig.
5 4). The percentage of fissured kernels was highest in the moisture-adsorbing
6 test at 88.72% RH.

7 The lengths, widths, and fissured kernel percent at MCs of 9.0–18.2%
8 are shown in Table 4. The average length and width of the kernels increased
9 proportionally with increasing EMC. The average length of the kernels
10 showed a more pronounced change than the average width during the
11 sorption process. It was anticipated that the average length and width of the
12 kernels was closely related to the EMC. Fissured kernel percent was related
13 to changes in the average length of the kernels during the
14 moisture-adsorbing tests. This image analysis method can be applied to the
15 measurement of kernel dimensions during moisture-desorbing and
16 moisture-adsorbing tests. The percentage of fissured Kirara 397 kernels was
17 higher than that of Akitakomachi and Koshihikari in the moisture-adsorbing
18 tests. This resistance to fissuring might be caused by differences between the

1 varieties and the areas in which they were cultivated.

2

3 3.2. Kernel dimension changes, and longitudinal and transverse strain

4

5 Changes in the kernel length and width with EMC are shown in Fig.

6 5. The longitudinal strain of a kernel is given by:

7

$$8 \quad \varepsilon_l = \frac{\lambda_l}{l_l} \quad (1)$$

9

10 ε_l : longitudinal strain,

11 λ_l : difference in length between after and before moisture-sorption tests, mm,

12 l_l : length before moisture-sorption tests, mm.

13

14 The transverse strain is given by:

15

$$16 \quad \varepsilon_t = \frac{\lambda_t}{l_t} \quad (2)$$

17

18 ε_t : transverse strain,

1 λ_t : difference in length between after and before moisture-sorption tests, mm,

2 l_t : length before moisture-sorption tests, mm.

3 The longitudinal strain was –6.0% to 0.4% in the desorption and 0.4% to
4 4.4% in the adsorption moisture environments. The transverse strain was
5 –5.2% to –0.7% in the desorption and –1.0% to 4.3% in the adsorption
6 moisture environments (Fig. 6). The effect of longitudinal strain on kernel
7 fissuring was similar to that of transverse strain. Changes in strain occurred
8 when the kernels were exposed to both adsorbing and desorbing moisture
9 environments. Kernel fissuring was not observed when rice was equilibrated
10 for at least 65 days during the desorption stage and the final MC was greater
11 than 20% and such as that which occurred during conditioning processes I
12 and II. This analysis was clearer when there was representative kernel
13 thickness information.

14 Rice kernels may fissure if they are dried too fast (Ban, 1971), and the
15 kernels in the study of Miwa et al. (1979) did not fissure during drying under
16 their experimental conditions. Yamaguchi et al. (1980) suggested that, in the
17 moisture adsorption process, as the MC increases in the surface layer of the
18 rice kernel, tensile stress is produced at the center of the kernel. In our

experiments, conditioning process II and the desorption stage generated stress within the kernel during rice desorption (drying).

Fissuring associated with kernel elongation, when the initial MC was about 6%, was observed by image analysis under the moisture-adsorbing conditions used in our study. These moisture-adsorbing conditions generated tensile stress through the changing dimensions of the kernels during adsorption.

4. Conclusion

The Tsutsumi method for sample preparation was applied in which the EMC is reduced by a hysteresis effect. The image analysis method used can be applied to the measurement of kernel size changes during moisture-desorbing and moisture-adsorbing tests. The average length of rice kernels may be considered as a reliable indicator of changes in the dimensions of kernels during quasi-moisture sorption processes. Kernel fissuring was not observed during as a result of the conditioning processes. Fissuring associated with expansion of the kernels when the initial MC was

1 about 6% was observed by image analysis under the moisture-adsorbing
2 conditions. The rice kernel dimensions changed in the moisture-adsorbing
3 and moisture-desorbing environments as measured by image analysis.

4

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7 Association. We express our gratitude to Mr A. Haba for his advice on this
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14

1 Figure Captions

2 Fig. 1. Length-width plane on rice kernel image.

3

4 Fig. 2. Moisture content of brown rice in moisture-desorbing and
5 moisture-adsorbing environments (variety: Akirakomachi).

6

7 Fig. 3. Average length of 800 brown rice kernels in moisture-desorbing and
8 moisture-adsorbing environments (variety: Akirakomachi).

9

10 Fig. 4. Fissured kernel percent in moisture-desorbing and
11 moisture-adsorbing environments (variety: Akirakomachi).

12

13 Fig. 5. Effect of moisture content during the sorption process on the length
14 and width of the kernels (variety: Akitakomachi).

15

16 Fig. 6. Relationship between strain of kernels and fissured kernel percent in
17 the equilibrium stage.

Table 1
The appearance, quality, and moisture content of the brown rice

	Moisture	Whole	Fissured	Damaged	Length	Width
	(%)	(%)	kernels	(%)	(mm)	(mm)
			(%)			
Kirara 397	14.9	78.6	2.1	0.9	5.14	2.85
Akitakomachi	15.2	87.1	1.5	0.8	5.07	2.84
Koshihikari	14.3	70.2	2.5	2.3	5.03	2.86

Table 2
The scheme used for the measurement, within the prescribed time interval, of grain weight and kernel length and width

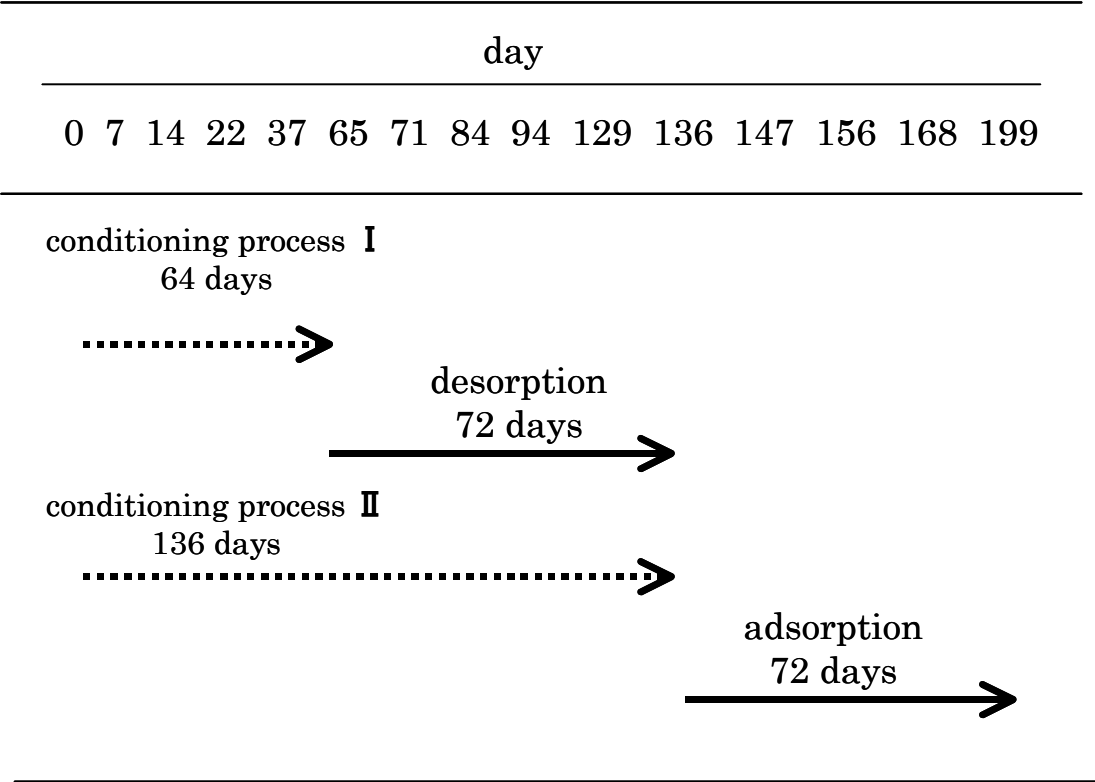


Table 3 The RHs of four saturated salt solutions

Saturated salt solutions	RH (%)
CH ₃ COOK	23.38±0.53
Mg(NO ₃) ₂ 6H ₂ O	55.87±0.27
KI	70.98±0.28
Sr(NO ₃) ₂	88.72±0.28

Table 4
The length, width, and fissured kernel percent at EMCs of 9.0-18.2%

Variety	RH (%)	Desorption				Adsorption			
		Moisture content (%, d.b.)	Length (mm)	Width (mm)	Fissured kernels (%)	Moisture content (%, d.b.)	Length (mm)	Width (mm)	Fissured kernels (%)
Kirara 397	23.4	9.7	4.94	2.76	0.8	9.2	4.84	2.73	0.7
	55.9	13.9	5.07	2.81	0.8	13.3	5.00	2.79	15.7
	70.98	16.2	5.15	2.83	0.8	15.0	5.07	2.81	26.3
	88.72	18.2	5.22	2.87	1.1	17.4	5.15	2.84	51.7
Akitakomachi	23.4	9.6	4.84	2.73	0.3	9.0	4.84	2.77	1.9
	55.9	13.7	4.98	2.80	0.7	13.2	4.91	2.81	9.2
	70.98	16.0	5.07	2.84	0.1	14.8	4.98	2.83	13.2
	88.72	18.2	5.11	2.85	1.2	17.3	5.05	2.87	26.1
Koshihikari	23.4	9.6	4.90	2.78	1.1	9.0	4.84	2.76	1.3
	55.9	13.7	4.98	2.82	2.1	13.2	4.90	2.81	3.7
	70.98	15.9	5.04	2.87	2.0	14.8	4.98	2.84	6.4
	88.72	18.1	5.10	2.89	2.7	17.3	5.05	2.86	34.0

Figure1

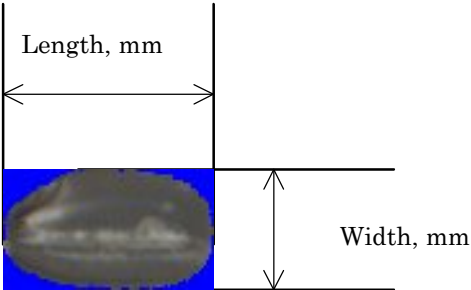


Figure2

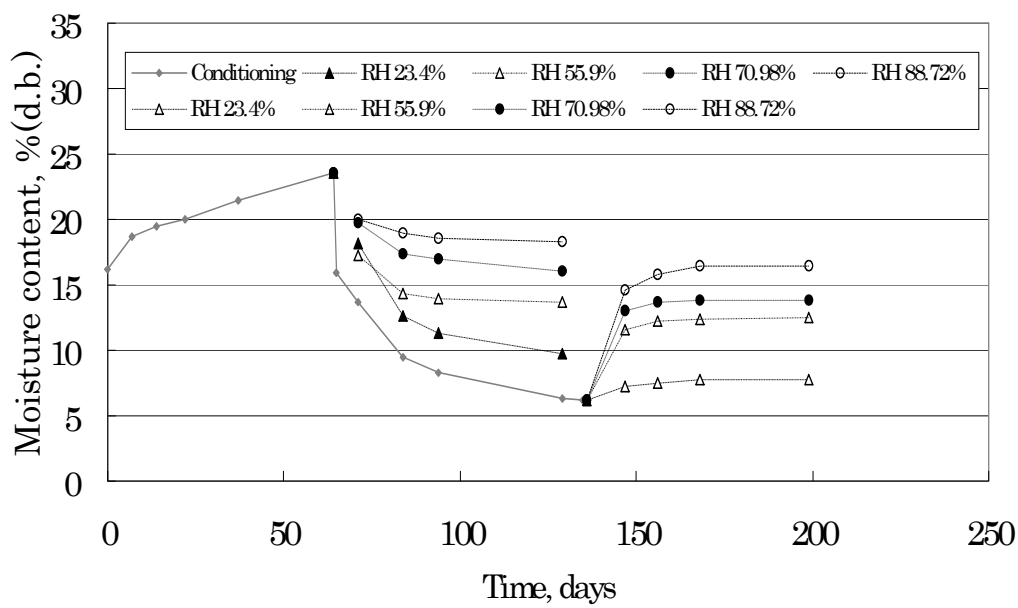


Figure3

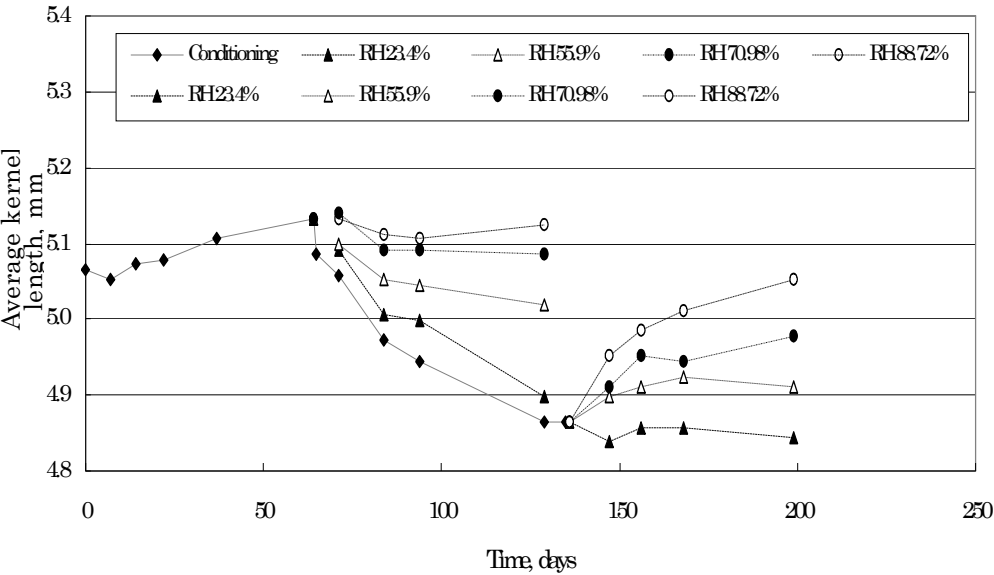


Figure4

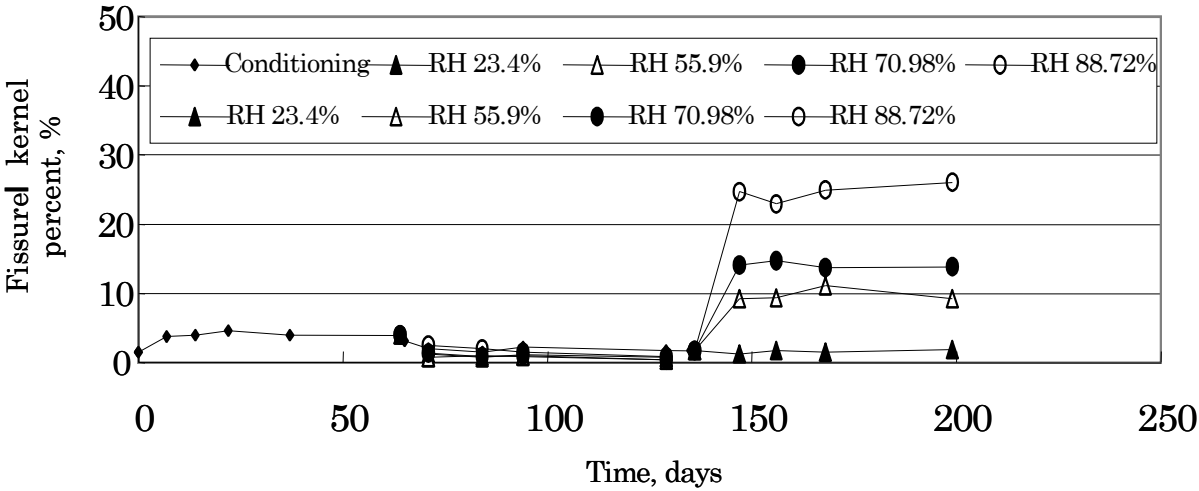


Figure5

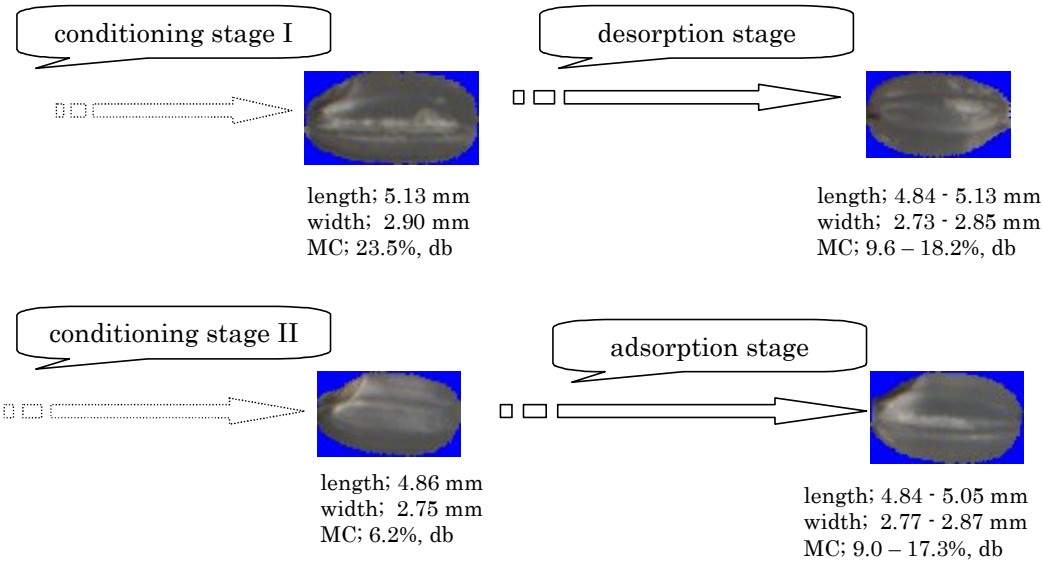


Figure6

