Rice Quality Preservation during On-Farm Storage Using Fresh Chilly Air

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Abstract

A new technique for storing rice at a temperature below ice point using fresh chilly air was developed. Freezing temperatures and extents of freezing injury of rice with various levels of moisture content were studied, and effects of temperature below ice point during a four-year storage period on the physiological properties of rice were investigated. Rice with moisture content of less than 17.8% did not freeze even at a temperature of –80°C. Low temperature maintained the vitality of rice, minimized physiological activities and starch deterioration in rice, and preserved rice quality.

One thousand tons of rough rice was stored in two silos from the end of November 1999 and was aerated from the bottom to top of each silo using fresh chilly air in January 2000. The rough rice temperature fell below ice point. At the end of July 2000, the rough rice temperature in the center of each silo was still below ice point. The rice quality stored in the silos was preserved at a level similar to that of freshly harvested rice. A combination of rice storage below ice point and utilization of fresh chilly air enables the rice quality to be preserved at a high level without the requirement of a cooling unit or electricity. The use of this storage technique has been increasing in cold regions after the on-farm experiment. In Hokkaido, the northernmost island in Japan, 26 grain-elevators have been constructed since 1996. The storage capacity of rough rice was 115,000 t at the end of 2003.

Introduction

The temperature and moisture content of rice grains greatly affect the quality of rice during storage. In Japan, the moisture content of brown rice during storage is maintained at a level of 16%. There are two commercial brown rice storage systems in Japan: an environment-temperature storage system, in which the temperature during storage is not controlled, and a low-temperature storage system, in which the temperature is maintained below 15°C during storage. The low-temperature storage system minimizes insect activities and mold growth, and fumigants are therefore not required during storage. However, this system requires electricity to cool the stored brown rice. The total capacity of brown rice storage structures equipped with cooling units in Japan in 2001 was 6.6 million t, about 70% of rice consumption in Japan in that year.

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A previous basic study (Kawamura et al., 1997) revealed that the quality of rice stored at a temperature below ice point is comparable to that of newly harvested rice. We previously reported (Kawamura et al., 2000) that a temperature below ice point minimized the physiological activities in rice and hence minimized the deterioration of rice quality. Rice storage at a temperature below ice point was named “super-low-temperature storage” by Kawamura et al. (1997, 1999) due to the fact that the storage temperature was much lower than that of low-temperature storage. It was clearly shown that rice storage at a temperature below ice point could preserve rice quality, but freezing temperature and freezing injury of rice were not clear. A basic study was therefore conducted to determine the freezing temperature of and the extent of freezing injury of rice and the effects of temperature below ice point on the physiological properties of rice during four-year storage.

In 1996, a grain elevator was constructed in Hokkaido, the northernmost island of Japan, where the temperature in winter is always below ice point. This grain elevator, called Kamikawa grain elevator, was the first grain elevator to be constructed in Hokkaido. Based on the results of the studies mentioned above (Kawamura et al., 1997, 2000), an on-farm experiment was conducted at Kamikawa grain elevator from 1996 to 1998 in order to develop a new rice storage technique for cold regions such as Hokkaido. In the experiment, rough rice was cooled to a temperature below ice point by aerating it in a silo with chilly fresh air in winter, and super-low-temperature storage of rice on a farm scale was thus realized (Kawamura et al., 1999; Takekura et al., 2003a; Takekura et al., 2003b; Takekura et al., 2003c). The quality of rough rice that had been stored at a super-low temperature was higher than the quality of rice samples that had been stored at a conventional low temperature and at room temperature. Various techniques were used in the on-farm experiment at Kamikawa grain elevator. These techniques included automatic ventilation in the upper vacant space of the silo during storage to avoid moisture condensation on the inside surface of the silo, aeration through the silo to cool the rice grains, rewarming of the rice grains after storage, and safe hulling conditions to prevent the occurrence of fissures in brown rice. One problem with the on-farm super-low-temperature storage system was that the temperature of the rice grains near the inner silo wall gradually increased in spring and summer, whereas the temperature of rice grains in the center of the silo remained below ice point. However, it was not clear whether this difference in the temperatures of rice grains in the silo affected the rice quality.

In 1999, a new grain elevator, called Uryuu grain elevator, started operation in Hokkaido. Another on-farm experiment was conducted in this grain elevator from 1999 to 2000 to try to establish a new rice storage technique at a temperature below ice point using ambient naturally cold fresh air in winter. In this experiment, the super-low-temperature storage technique that had been developed in Kamikawa grain elevator was used, and the effect of the difference in temperatures of rice grains near the silo wall and in the center of the silo on rice quality was investigated.

Materials and Methods

Freezing Temperature

The rice samples used to determine freezing temperature were Kirara397 and Hoshinoyume, which are commercial Japonica non-waxy varieties. Rough rice samples were collected at six moisture content levels during the drying process: 26.5%, 24.2%, 23.1%, 22.1%, 20.8% and 19.5%. Moisture content (m.c.) was determined by the standard method of the Japanese Society

of Agricultural Machinery (JSAM): about 10 g of a whole-grain rice sample was placed in a forced-air oven at 135°C for 24 h, and the moisture content was calculated on a wet basis.

A differential scanning calorimeter (DSC 3100 S, Mac Science Co., Tokyo, Japan) was used to measure the freezing temperature of rough rice. The cooling rate was controlled at 2°C/min and the temperature was decreased to –55°C. One grain of rough rice was used for each scan, and five to six grains at each moisture content level were used to measure the freezing temperature.

Freezing Injury

The rice used to determine freezing injury was Kirara397 variety. Rough rice samples were collected at seven moisture content levels during the drying process: 26.5%, 23.1%, 20.8%, 19.5%, 17.8%, 16.8% and 15.7%. Freezing injury of grain seed such as rice is usually determined by the germination rate. Grains that suffer freezing injury do not germinate.

Rice samples (about 50 g per sample) were stored in refrigerators controlled at 2°C, –10°C, –20°C, –30°C, –40°C or –80°C for 11 days. The samples were then dried to about 16% m.c. in a forced-air oven at 40 - 45°C and hulled. Germination rate was determined according to the standard method of the Japan Food Agency (JFA): three hundred sound brown rice grains were soaked in a hydrogen peroxide solution (1% [w/w] concentration) and placed in an incubator at 20°C. The germination rate was calculated by counting the number of grains that had germinated within a period of seven days.

Laboratory Rice Storage Experiment

The rice used for the laboratory rice storage experiment was Hoshinoyume variety. The moisture content of rough rice sample was 16.2%. About 15 kg of rough rice was stored in a polyethylene container with a screw lid, and the containers were stored in incubators or refrigerators controlled at 25°C, 15°C, 5°C, –5°C, –20°C or –50°C for a period of 48 months, from October 1998 until October 2002.

To understand the physiological properties and quality characteristics of the rice samples, germination rate, free fat acidity and texturogram property were determined. Some grains were periodically taken from the rough rice samples and hulled. Germination rate was determined according to the standard method of JFA. Grains that have lost their vitality do not germinate (dead seeds). Free fat acidity was determined by the rapid method of the American Association of Cereal Chemists (AACC, method 02-02): free fat acid was extracted from ground brown rice in a benzene solution, and the extracted solution was then titrated with potassium hydroxide solution. Texturogram property (hardness/stickiness ratio) of cooked rice was defined as the ratio of the first positive peak to the first negative peak of the texture profile measured by a texturometer (Zenken, Tokyo, Japan).

On-farm Rice Storage Experiment

Storage Structure

Figure 1 shows a grand plan of Uryuu grain elevator constructed in 1999 and Figure 2 shows a side view of the grain elevator. Two of the 12 silos of Uryuu grain elevator were used for the on-farm experiment. The two silos used for the experiment are marked “S1” and “S2” in Figure 1. Each silo was round in shape with a hopper bottom and had a diameter of 7.4 m, a height of 23.2 m, and a capacity for rough rice storage of 480 t. Each silo was made of steel with a 75-mm insulation layer on the outside of the wall. An automatic system was installed in each silo for

aeration from the bottom through to the top of the silo, and an automatic system was installed in each silo for ventilation in the upper vacant space of the silo.

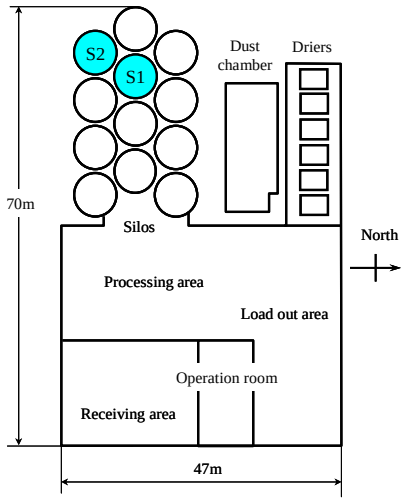

Figure 1. Grand plan of Uryuu grain elevator.

Rice Samples

Kirara397 and Hoshinoyume were used for the on-farm storage experiment. The moisture content of each rough rice sample was 15.4%.

Storage Conditions

Five hundred tons of Kirara397 rough rice was stored in the S1 silo, and 494 t of Hoshinoyume rough rice was stored in the S2 silo. The storage period was about 8 months, from the end of November 1999 until the end of July 2000. The rough rice in the two silos was simultaneously aerated in January 2000. Aeration from the bottom to the top of each silo was automatically carried out when the temperature of fresh air was below –7°C and it was continued until the cooling front had moved through all of the rough rice in the silo. The static pressure of the air was 260 mmAq, air velocity at the grain surface was 0.03 m/s, volume quantity of airflow was 160 m^3/min, airflow rate was 0.16 m^3/min/t, and total aerating time (fan time) was 91 h.

Three control storage experiments were also carried out at the same time: a room-temperature storage experiment, in which rice samples were stored in a laboratory room; a low-temperature storage experiment, in which rice samples were stored in a commercial rice warehouse and kept at a temperature below 15°C; and a storage experiment at –5°C, in which rice samples were stored in a refrigerator and kept at –5°C. About 15 kg each of rough rice and brown rice were stored in polyethylene containers with lids in each control experiment.

Temperature Measurement and Sampling

The temperatures of rough rice in the center of silo and at 10 cm from the silo wall were measured by thermocouples set at 2.2-meter intervals from the bottom to the top of the silo. The temperatures of rough rice and brown rice in each container in the control storage experiments were also measured.

The rice was sampled and tested for quality before, during and after storage. Rough rice samples (100 g each) were taken from the center of the silo and at four points 15 cm from the silo wall (north, west, south and east in the silo) at the end of the storage period. Sampling depths below the surface of the rough rice were 0.1, 0.5, 1.0, 2.0 and 4.0 m.

The rate of rough rice flow during unloading after storage was 30 t/h. A sample (100 g) was taken from every 10 t of rough rice (every 20 min) during unloading.

Quality Assessment

Moisture content, germination rate, free fat acidity and texturogram property were determined to assess rice quality.

Figure 2. Side view of Uryuu grain elevator. (The silo on the left is one of the silos used in the experiment.)

Results and Discussion

Freezing Temperature

Rice of 26.5% m.c. froze at temperatures in the range of –13°C to –25°C (Figure 3). The moisture content of each sample was measured using 10 g of rough rice. There were about 350 grains in 10 g of rough rice. Although each grain had various moisture contents, the average moisture content value of 350 grains (26.5%) was used for analysis. The freezing temperature was measured using one grain for each scan. The freezing temperatures of rice of 26.5% m.c. were distributed in the range of –13°C to –25°C. Rice of 22.1% m.c. froze at about –35°C. Rice samples of 20.8% m.c. and 19.5% m.c. did not freeze even at a temperature of –55°C.

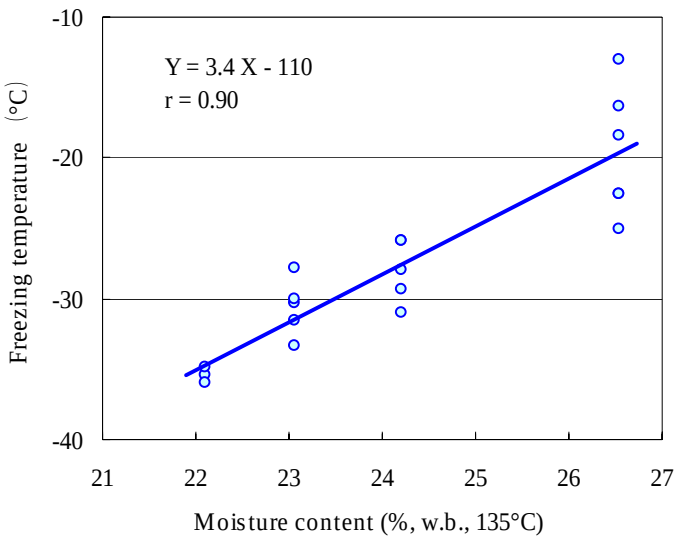

Figure 3. Relationship between moisture content and freezing temperature of rice.

Freezing Injury

Freezing injury did not occur in any of the rice grains stored at 2°C because the germination rate of these rice grains was almost 100%, while freezing injury occurred in all of the rice grains of 26.5% m.c. stored at the temperatures below –20°C because the germination rates were 0% (Figure 4). There was no freezing injury in 64% of the rice grains of 23.1% m.c. stored at –20°C. Rice grains with a moisture content of less than 17.8% germinated after being stored at –80°C. Thus, no grain with a moisture content of less than 17.8% froze even at a temperature of –80°C.

In Japan, rice for long-term storage is always dried until the moisture content is less than 16%. Thus, there is no need for concern about the freezing of rice stored in farm silos at temperatures below ice point.

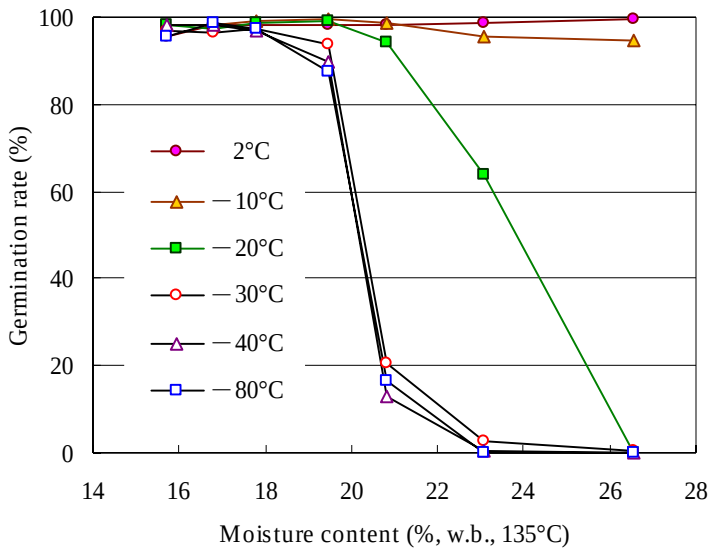

Figure 4. Germination rates of rice stored at six different temperatures for 11 days.

Laboratory Rice Storage Experiment

Grains that do not germinate do not have any vitality as rice seeds (dead seeds). The germination rate of rice stored at 25°C rapidly decreased to 0% over a period of 12 months of storage (Figure 5). The germination rate of rice stored at 15°C gradually decreased to 0% over a storage period of 48 months. On the other hand, the germination rate of rice stored at temperatures below 5°C was almost 100%.

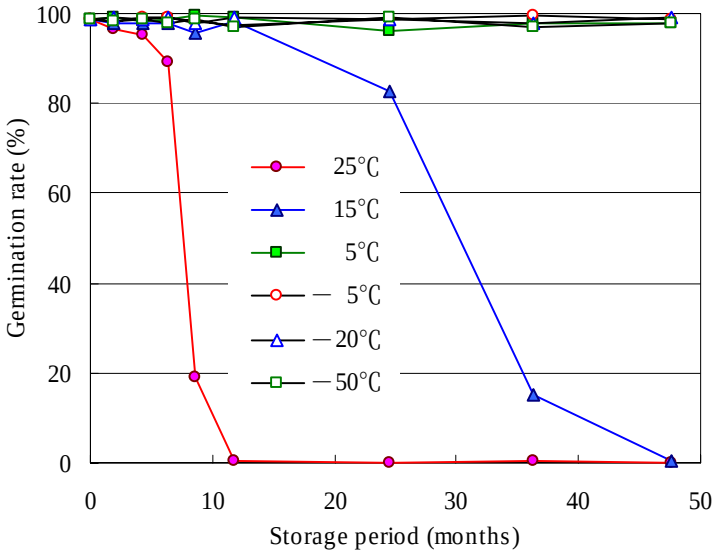

Figure 5. Changes in germination rates of rice stored at six different temperatures.

Lipase hydrolyzes fat in rice grains to fatty acid. When the activity level of lipase in rice is high, the amount of free fat acidity increases during storage. This increase in the amount of free fat acidity causes deterioration of the quality of rice during storage. The free fat acidity of rice stored at temperatures below 5°C was almost the same as that at the beginning of storage (Figure 6). However, the free fat acidity of rice stored at 25°C dramatically increased during storage.

Generally, the hardness of cooked rice increases and the stickiness of cooked rice decreases during storage. The texturogram property (hardness/stickiness ratio) increases accordingly as rice ages. The changes in the texture of cooked rice are caused by deterioration in rice starch. There was no change in hardness/stickiness ratio of rice stored at temperatures below 5°C (Figure 7).

These results indicate that low temperature maintains vitality of rice, minimizes physiological (enzyme) activities and starch deterioration in rice, and preserves rice quality.

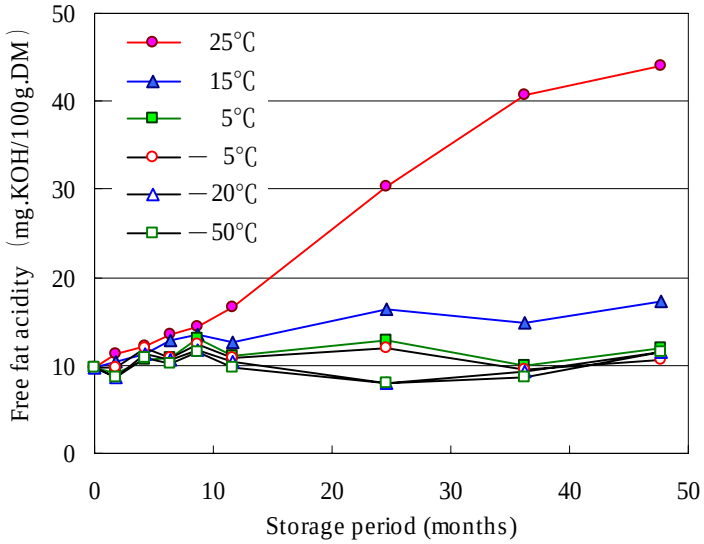

Figure 6. Changes in free fat acidities of rice stored at six different temperatures.

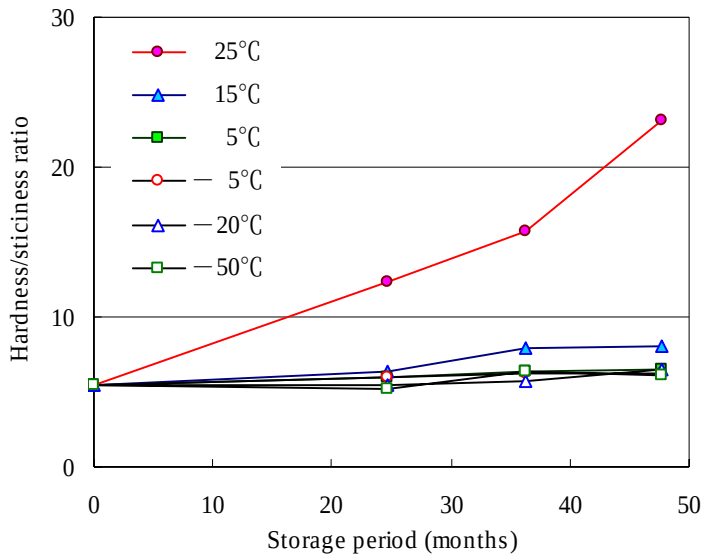

Figure 7. Changes in texturogram properties of rice stored at six different temperatures.

On-farm Rice Storage Experiment

Grain Temperature during Storage

The range of grain temperatures in the vertical direction in each silo was less than 3°C, and there was no tendency in the grain temperature distribution. The temperatures recorded in the center and near the wall of each silo were averaged respectively, and the average values were used as indicators of changes in grain temperature during on-farm storage (Figure 8).

The grain temperature in each silo was 10°C at the beginning of storage. The temperature of rice grains near the wall gradually decreased as the ambient temperature fell. The minimum temperature of rice grains near the wall in the middle of February was –2°C. From the end of March until the end of the storage period (at the end of July), the temperature of rice grains near the wall gradually increased. The maximum temperature of rice grains near the wall in the middle of July was 21°C. The temperature of the rice grains in the center of the silo remained constant (10°C) at the beginning of storage and fell to –2°C when aerated at the end of January. The temperature of rice grains in the center of the silo remained below ice point until the end of July. After aeration, the grain temperature throughout the silo remained below ice point until the end of March. These results indicate that super-low-temperature storage of rice in a farm-scale silo can be achieved by using aeration and chilly fresh air in winter.

The thermal conductivity of rough rice (about 0.09 W/m/K, Seno et al., 1976) is nearly equal to that of lumber (0.15 W/m/K) and glass wool (0.04 W/m/K) and is smaller than that of steel (80 W/m/K) and concrete (1 W/m/K). This means that rough rice is a thermal insulating material. On the other hand, the specific heat of rough rice (about 1.7 J/K/g, Morita et al., 1979) is larger than that of lumber (1.3 J/K/g), concrete (0.8 J/K/g) and steel (0.5 J/K/g). This means that rough rice is also a refrigerant material. Because of these physical properties of rough rice, the grain temperature in the center of each silo remained below ice point until the end of July despite the increase in outside temperature in summer.

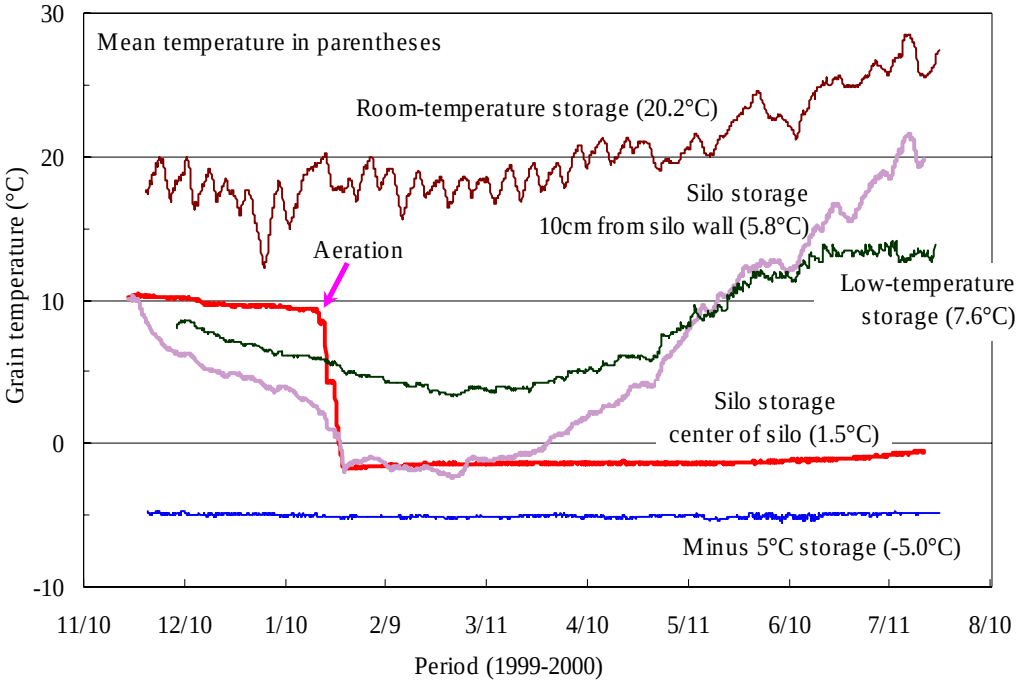

Figure 8. Rice grain temperatures during on-farm silo storage and control storage (Kirara397).

In the experiments, the mean temperatures of rice grains during room-temperature storage, during low-temperature storage, at 10 cm from the silo wall during on-farm silo storage, in the center of the silo during on-farm silo storage and during –5°C storage were 20.2°C, 7.6°C, 5.8°C, 1.5°C and –5.0°C, respectively (Figure 8).

Quality of Rice Grains Sampled from Different Parts of the Silo at the End of the Storage Period

The germination rates and free fat acidities of rice samples taken from different parts of the silo at the end of the storage period are shown in Figures 9 and 10, respectively. The germination rates of all samples were more than 97%. Free fat acidities of all samples ranged from 12 mg to 15 mg. A germination rate of rice grains of more than 90% and free fat acidity of rice grains of less than 20 mg means that there has been no deterioration in the quality of the rice. The temperature of rice grains near the silo wall increased to about 20°C in July. However, the temperature of rice grains near the wall was below ice point during winter, and the mean temperature of rice grains near the silo wall during storage was 5.8°C. The results of measurements of germination rates and free fat acidities showed that there was no deterioration in the quality of rice grains near the silo wall.

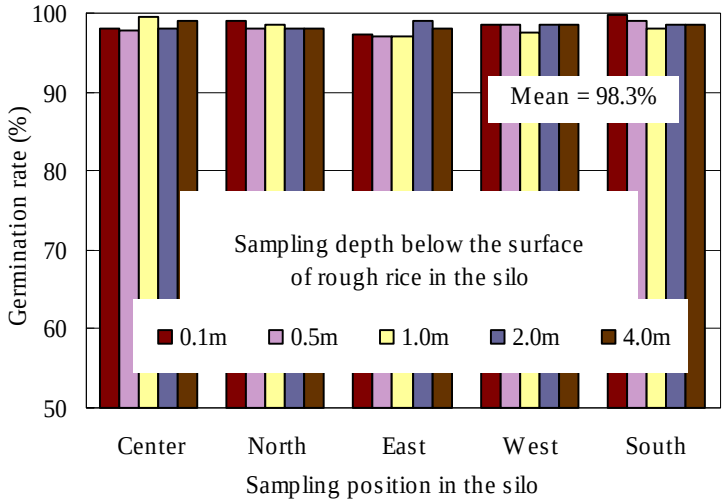

Figure 9. Germination rates of rice grains sampled from different parts of the silo (Hoshinoyume).

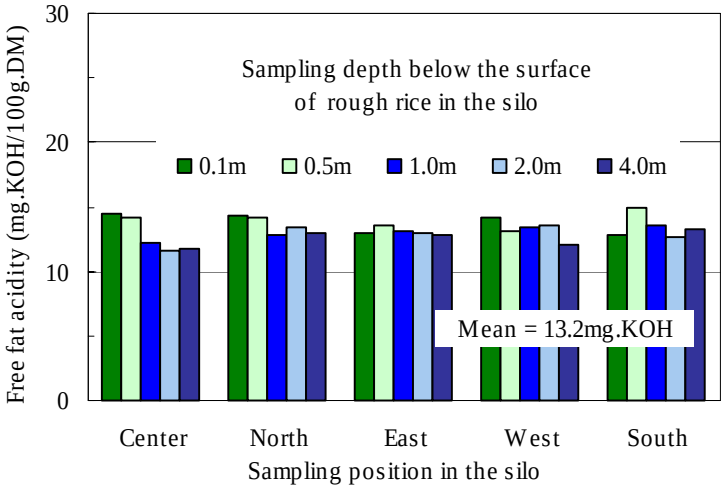

Figure 10. Free fat acidities of rice grains sampled from different parts of the silo (Hoshinoyume).

Grain Temperature during Unloading and Quality of Unloaded Rice

Grain temperature at the beginning of unloading was 15°C. Soon after the beginning of unloading, it decreased to 1°C and then remained at 1 - 3°C for 2 h (60 t of rough rice). The grain temperature increased to about 18°C from 4 h to 6 h after the start of unloading and then fluctuated in the range of 5 - 15°C until the end of unloading (Figure 11). The fluctuations in the grain temperature during unloading indicated that the low-temperature grains in the center of the silo and the high-temperature grains near the silo wall were mixed together when unloaded.

The germination rates and free fat acidities of rice samples taken during unloading are shown in Figures 12 and 13, respectively. The germination rates of all samples were more than 95%. Free

fat acidities of the samples ranged from 12 mg to 15 mg. These results indicate that the quality of the rice grains in the silo was uniform and that there was no deterioration in the quality.

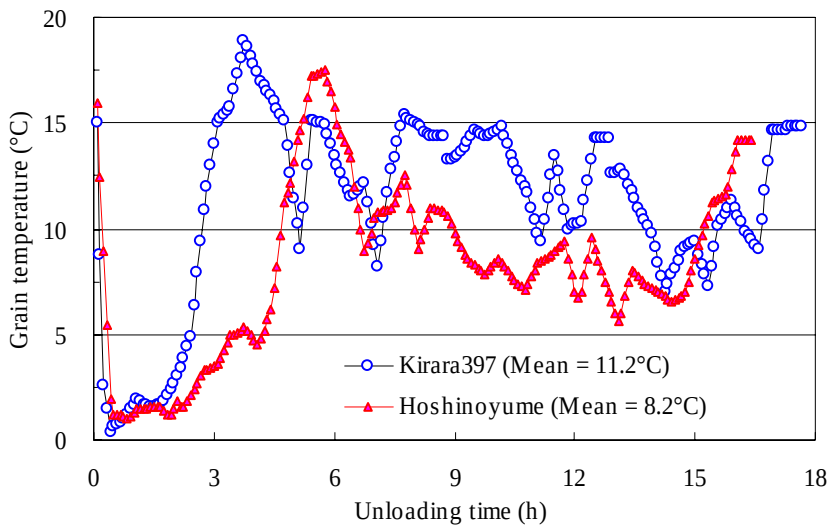

Figure 11. Rough rice temperature just after unloading from the silos.

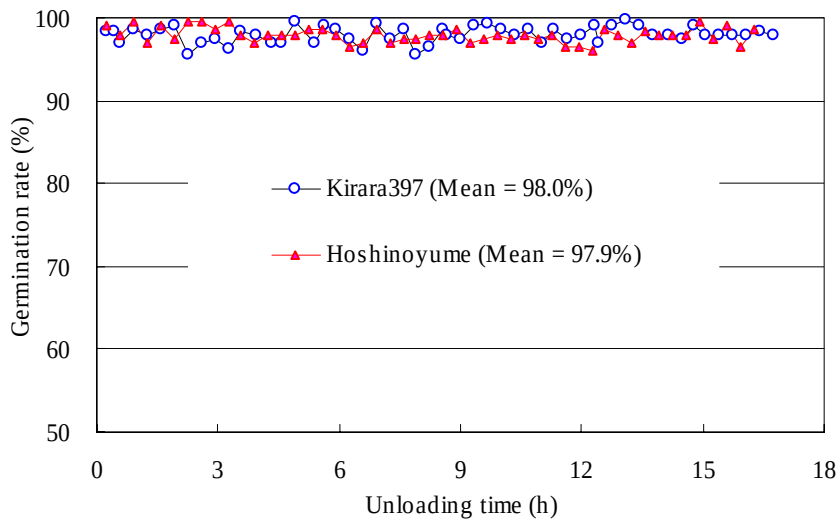

Figure 12. Germination rates of rice grains unloaded from the silos.

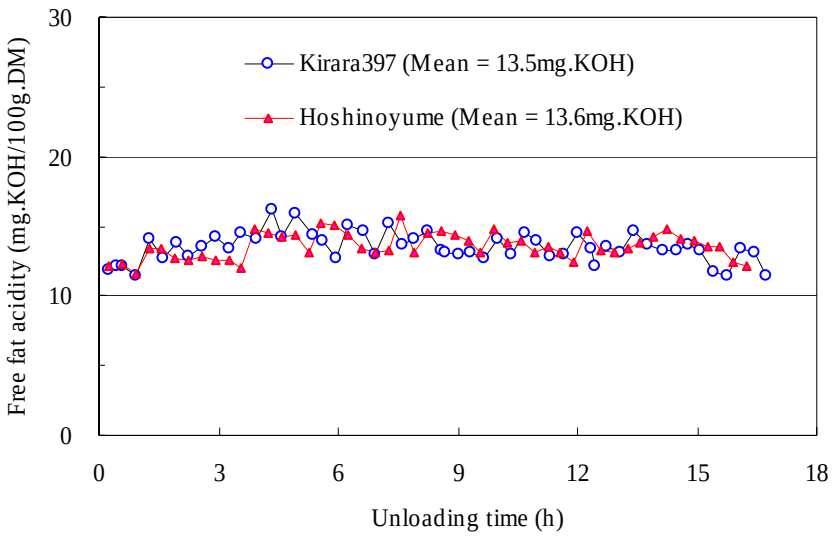

Figure 13. Free fat acidities of rice grains unloaded from the silos.

Moisture Contents and Cracked Kernel Rates of Rice Grains before and after Storage

The moisture contents of Kirara397 and Hoshinoyume were both 15.4% before loading (before storage). The moisture contents of Kirara397 and Hoshinoyume just after unloading from each silo (just after the end of the storage period) were 14.9% and 15.0%, respectively. An automatic system for ventilation of the upper vacant space of the silo was used to prevent moisture condensation on the inside surface of the silo. The moisture content of grain at the top surface in the silo decreased mainly due to the ventilation of this vacant space during storage, and the moisture content of grain at the bottom of the hopper of the silo decreased due to the aeration in January. However, by the time of shelling, the moisture contents of Kirara397 and Hoshinoyume had increased to 15.4% and 15.3%, respectively, due to moisture condensation during the rewarming process of cold rough rice after unloading.

The cracked kernel rates of Kirara397 and Hoshinoyume were 2.6% and 1.4% before storage, respectively. Those after the rewarming process were 2.5% and 1.3%, respectively. The proportion of cracked kernels did not increase after the rewarming process, indicating that the moisture condensation on rough rice during the rewarming process did not cause any problems.

Quality Assessment

The germination rates of rice subjected to silo, –5°C and low-temperature storage were more than 98%, as high as that of samples taken before storage (Figure 14). On the other hand, the germination rate of rice subjected to room-temperature storage decreased to about 50%, indicating that the rice had lost vitality during room-temperature storage.

The free fat acidities of rice increased in all of the storage experiments (Figure 15). However, there were differences in the rates of increase in free fat acidity: the rate of increase in rough rice during storage was less than that of brown rice during storage. Moreover, the rate of increase in free fat acidity was highest for rice stored at a room temperature, next-highest for rice stored at a low temperature and in the silo, and lowest for rice stored at –5°C. These results indicate that the

decomposition process of fat is slower in rough rice during storage and in rice during storage at lower temperatures.

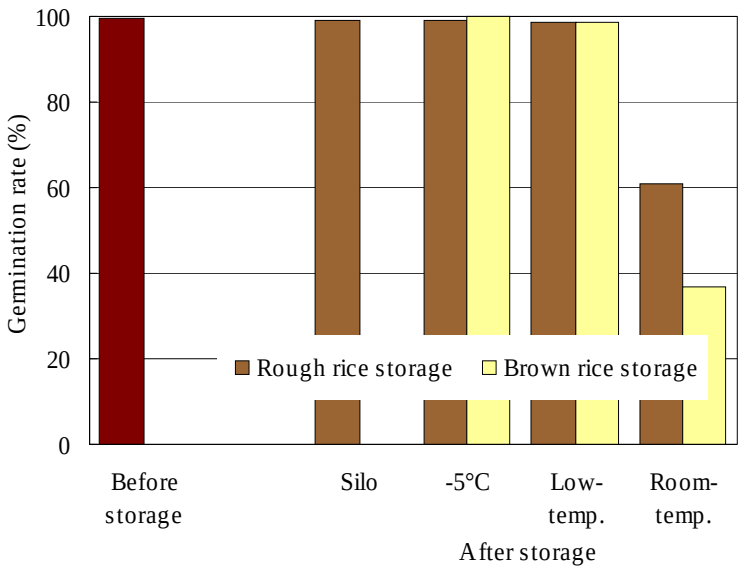

Figure 14. Germination rates of rice before and after storage (Kirara397).

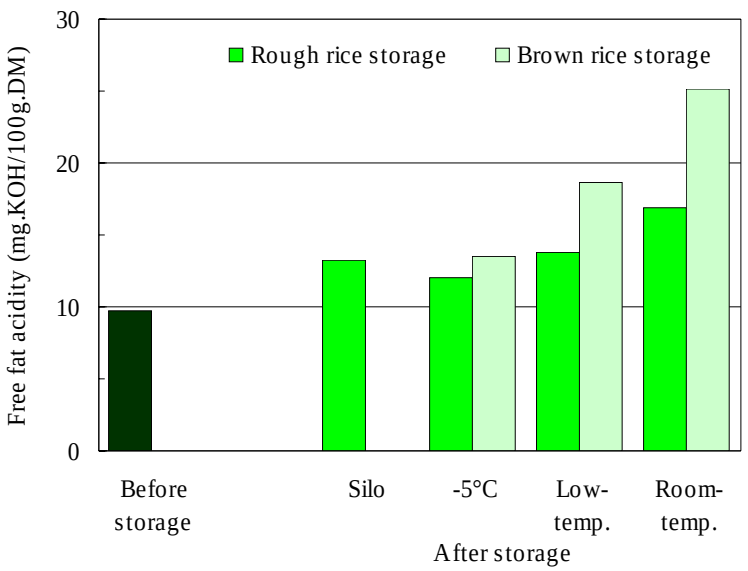

Figure 15. Free fat acidities of rice before and after storage (Kirara397).

Figure 16 shows that changes in the texture of cooked rice were minimized by silo storage and –5°C storage and by storage of rough rice.

The results of quality assessment indicate that storage of rice at temperatures below ice point (silo storage and –5°C storage in this study), which is called super-low-temperature storage, preserves the quality of rice at a much higher level than that of rice stored at higher temperatures.

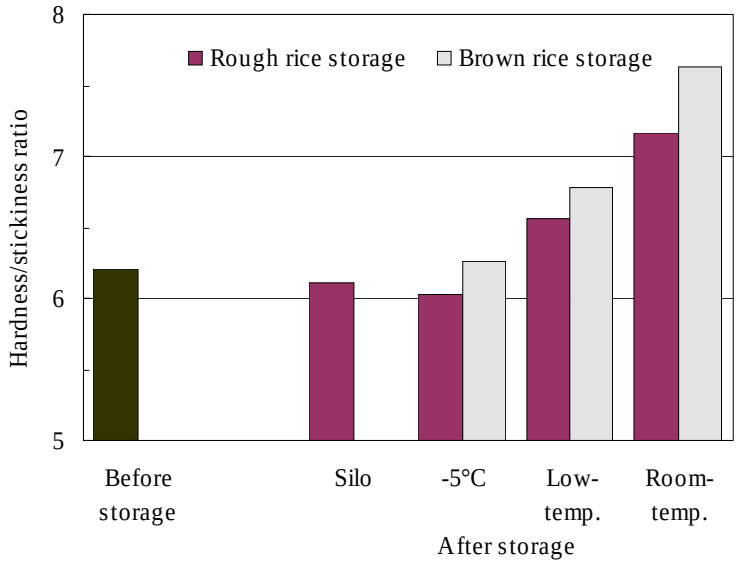

Figure 16. Texturogram properties of cooked rice before and after storage (Hoshinoyume).

Extension of Super-Low-Temperature Storage of Rice

A new technique for storing rice at a temperature below ice point using ambient fresh chilly air in winter was developed. A combination of rice storage at a temperature below ice point and utilization of chilly fresh air enables the quality of rice to be preserved at a high level without the requirement of a cooling unit or electricity. The use of the super-low-temperature storage technique has been increasing in cold regions of Japan in recent years. In Hokkaido, the northernmost island in Japan, 26 grain-elevators have been constructed since 1996. The storage capacity of rough rice in Hokkaido was 115,000 t at the end of 2003 (Figure 17).

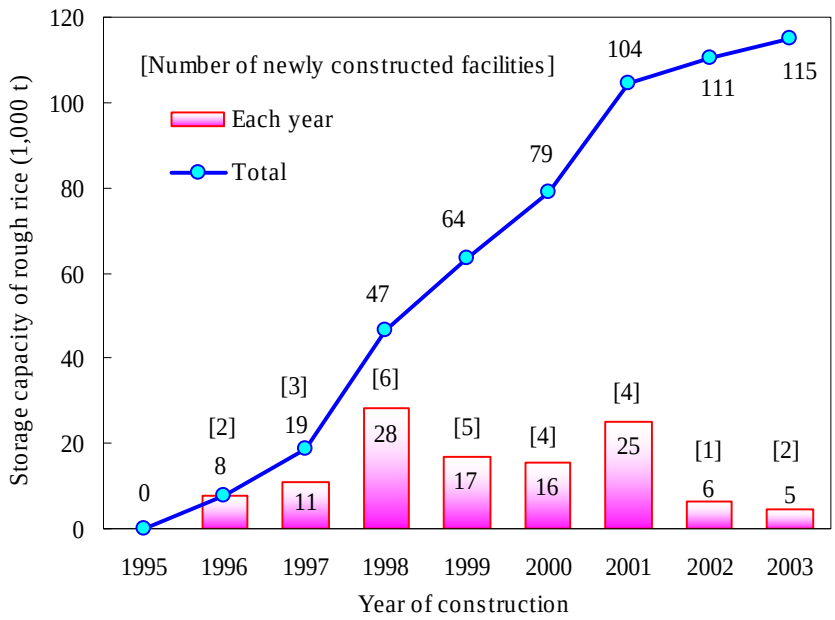

Figure 17. Storage capacity of rough rice in Hokkaido, Japan.

Conclusion

1. No grain with a moisture content of less than 17.8% froze at a temperature of –80°C. There is therefore no need for concern about the freezing of rice stored at a temperature below ice point in farm silos during winter.
2. Low temperature maintained vitality of rice, minimized physiological activities and starch deterioration in rice, and preserved rice quality.
3. Rice storage at a temperature below ice point in farm-scale silos can be achieved by using fresh chilly air in winter. The temperature of all rice grains in the silo fell below ice point. At the end of the storage period, the temperature of rice in the center of the silo was still below ice point.
4. The rice quality stored in the silo was uniform and preserved at a level similar to that of freshly harvested rice. A combination of rice storage at a temperature below ice point and utilization of fresh chilly air enables the quality of rice to be preserved at a high level without the requirement of a cooling unit or electricity.
5. The use of the new rice storage technique has been increasing in cold regions after the on-farm experiment. In Hokkaido, the northernmost island in Japan, 26 grain-elevators have been constructed since 1996. The storage capacity of rough rice in Hokkaido was 115,000 t at the end of 2003

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