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Kinetic Studies on Hydration and Cooking of Rice

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쌀의 수화 및 취반특성에 관한 속도론적 연구

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Abstract

The hydration and cooking rate of two rice varieties, Akibare (*Japonica*) and Milyang 23 (*Indica*), were investigated in terms of mathematical rate equations. The hydration rate at temperatures of 10~40°C was examined by weighing method. The absorption of liquid water by rice grain was directly proportional to the square root of the hydration time. The diffusion coefficient was given by the Arrhenius relation : $D=3.151\times10^{-3}\exp(-4\,000/RT)$ for Akibare and $D=5.853\times10^{-3}\exp(-5\,700/RT)$ for Milyang 23. Milyang 23 was cooked at a faster rate than Akibare. The activation energies for cooking were in the range of 18 000 *cal/mole* at 90~100°C and 9,000 *cal/mole* at 100~120°C. However, Milyang 23 showed slightly higher activation energy of cooking at 90~100°C. Adhesiveness and amylograph viscosities at all reference points for Milyang 23 were higher than those for Akibare.

Introduction

Rice is frequently hydrated for 0.5~1.0 hr prior to cooking. Hydration rate of rice depends on variety[1], cultivation conditions and storage period[2,3]. It is known that hydration time and water temperature affect the color, smell and taste of cooked rice as well as the cooking rate[4]. Although a few studies are available on the moisture diffusion by wheat[5], paddy[6] and wheat flour[7], studies on rice hydration are scarce. Recently, Suzuki *et al*[8] reported the diffusion rate parameters of rice at various soaking temperatures on the assumption that rice grain was spherical. The diffusion coefficients of water during cooking of rice were also reported[9].

Cooking kinetics of rice were investigated with a parallel plate plastomer[9] and texturometer[10]. These results showed that cooking process of rice comprises two mechanisms: at temperatures below 100°C, the cooking rate is limited by the reaction rate of rice components with water and at temperatures above 100°C, it is limited by the rate of diffusion of water through the cooked layer toward the interface of uncooked core where the reaction occurs.

The purpose of this study was to compare the hydration and cooking kinetics of two Korean rice varieties : a traditional *Japonica* variety of Akibare and an *Indica* variety of Milyang 23. The absorption of water by rice was investigated as a function of soaking time, temperature and initial moisture content of grain. The diffusion equation proposed by Becker[5] was utilized to analyze data on the absorption of water by rice grain. The effect of hydration on cooking rate was investigated with the method of Cheigh *et al*[10].

Theory

Nonstationary-state diffusion in solids of arbitrary shape

Mathematical analysis[5] of nonstationary-state diffusion in solids of arbitrary shape can be expressed by a generalized form of Eq. (1):

$$\overline{M}=1-2X/\sqrt{\pi}+BX^2 \quad (1)$$

where

$$\overline{M}=(m_s-\overline{m})/(m_s-m_0)$$

$$X=(S/V)\sqrt{Dt}$$

At small values of X, Eq. (1) approximates to

$$1-\overline{M}=2X/\sqrt{\pi} \quad (2)$$

or, in terms of the experimental variables,

$$\overline{m}-m_0=k_0\sqrt{t} \quad (3)$$

where

$$k_0=(2/\sqrt{\pi})(m_s-m_0)(S/V)\sqrt{D}.$$

Hence,

$$k_0(V/S)=(2/\sqrt{\pi})(m_s-m_0)\sqrt{D}. \quad (4)$$

To calculate the surface area and volume of rice grain it was assumed to be a prolate spheroid. Therefore, the volume and the surface area of rice grain can be calculated by Eqs. (5) and (6), respectively[11]:

$$V=(4/3)\pi ab^2 \quad (5)$$

and

$$S=2\pi b^2+2\pi(ab/e)\sin^{-1}e \quad (6)$$

where

$$e=(\sqrt{a^2-b^2})/a.$$

Since the absorption of moisture by rice grain is influenced by water temperature, the diffusion coefficient obeys to Arrhenius relations[12]:

$$D=D_0\exp(-E/RT) \quad (7)$$

Cooking rate equation

On the assumption that the reciprocal hardness of the cooked rice is proportional to the degree of cooking, the following relation can be established [10]:

$$\alpha=(H_t-H_0)/(H_L-H_0) \quad (8)$$

The rate of uncooked portion of rice, $(1-\alpha)$, as a function of cooking time shows a first-order reaction:

$$\ln(1-\alpha)=-kt \quad (9)$$

The relation between k and the reciprocal cooking temperatures follows the Arrhenius equation[9,10].

Materials and Methods

Materials

Commercially milled rice Akibare(*Japonica*) and Milyang 23 (*Indica*) were used throughout the study.

Control of initial moisture content

Rice was stored in desiccator containing various concentrations of H_2SO_4 solution until equilibrium moisture content was obtained. The moisture content was determined by oven method at 105°C[13].

Rate of hydration

1 *g* of rice was added to a beaker containing 50 *ml* of distilled water. In time intervals of 1~60 min, the weight of the grains after draining on a filter paper was determined. From the weight gain the moisture content of rice was calculated as dry basis. These experiments were performed at temperature from 10~40°C.

Cooking of Rice

Cooking experiments were carried out with the method of Cheigh *et al*[10] with soaking times of 0, 20, and 40 min and cooking temperatures of 90 ~120°C.

Texture profile of cooked rice

25 *g* of rice were taken into a brass vessel (60 *mm* inner diameter × 30 *mm* height) and soaked for 20 min with 35 *ml* of distilled water at room temperature. The rice was then cooked in an oil bath for 20 min at 100°C and cooled for 1 min in an ice bath.

The texture of cooked rice was examined with a Texturometer (General Foods Co., USA). The conditions for the Texturometer were: plunger, 18 *mm* lucite ; voltage, 1.0 *V* ; attenuator, 1.0 ; clearance, 2.0 *mm* ; bite speed, 12 cycles/min ;

chart speed, 750 *mm*/min and sample height, 29 *mm*.

Pasting properties of rice flour

Pasting properties of rice flour which was passed through a 60 mesh sieve were investigated with the Brabender Visco/Amylo/Graph. The method employed was that of Nedcalf and Gilks[13]. The solid concentration was 8.1% (dry basis).

Results and Discussion

Hydration rate

The variation of the moisture content of Akibare and Milyang 23 during hydration is shown in Fig. 1. At the soaking temperature between 10~40°C rice grain did not absorb water more than 30% during 1 hr soaking. A similar result was reported by Suzuki *et al*[8] with Japanese rice. Hydration rate for Milyang 23 was greater than that for Akibare at the same temperature. Milyang 23 reached the maximum moisture content after 35 min, while Akibare after 60 min at 20°C (Fig. 1). At 40°C and above, Milyang 23 was cracked and became fragile after soaking. This physical property may in part explain the greater hydration rate for Milyang 23 than Akibare.

If Eq. (3) is applicable, the moisture gain of rice grain immersed in water should be approximately proportional to the square root of the absorption time. Fig. 2 shows that such a relation is indeed held. However, the curves did not extrapolate to zero moisture gain at time zero and experimental data were analyzed to obtain k_o. In wheat, the nonzero intercept clearly occurs[5]. This means that there is a very rapid initial absorption of water due to the structure of wheat kernel. The pericarp of wheat is highly porous and quickly becomes saturated by capillary imbibition[15]. Therefore, the occurrence of the intercept from the curves in Fig. 2 may indicate the rapid abosrption of liquid water by rice grain. It remains to be elucidated whether capillary imbibition occurs in rice grain.

Eqs. (3) and (4) indicate that if D is independent of moisture content in the range investigated, $k_o(V/S)$ should be a linear function of m_o and

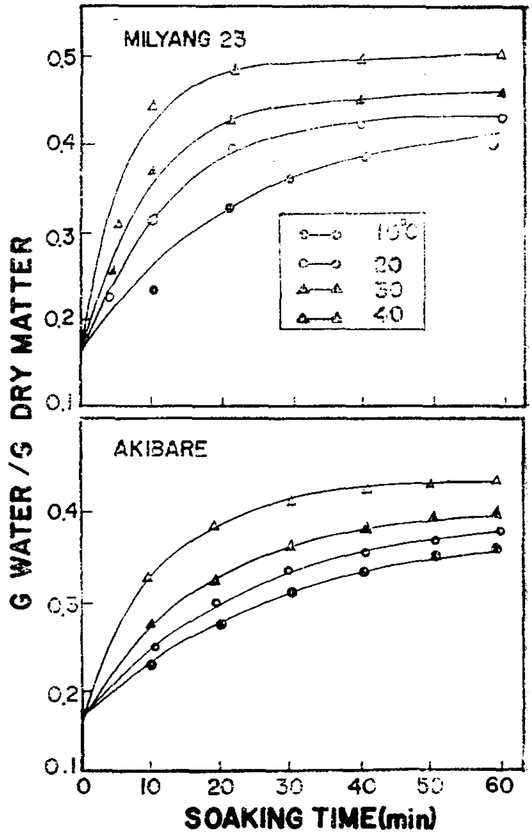

Fig. 1. Water absorption during nydration of rice grain

should extrapolate to an interecept $m_o=m_s$ at $k_o(V/S)=0$. The values for V and S were calculated from Eqs. (5) and (6), respectively. The values for a and b were respectively 0.2325 *cm* and 0.1390 *cm* for Akibare, and 0.2815 *cm* and 0.1290 *cm* for Milyang 23. Fig. 3 shows the relation between $k_o(V/S)$ and m_o. The values for m_s for Akibare and Milyang 23 calculated from Fig. 3 were 0.273 and 0.330 *g/g* (dry basis), respectively.

D values at various soaking temperatures were calculated from Eq. (4). Milyang 23 showed greater D values than Akibare (Table 1) as expected from Fig. 1. Fig. 4 shows the relation between D and the reciprocal absolute temperature. The activation energies of soaking for Akibare and Milyang 23 calculated from the slopes of Fig. 4 were 4 000 and 5 700 *cal/mole*, respectively. The D_o calculated by substituting the experimental data into Eq. (7) were 3.151×10^{-3} for Akibare and

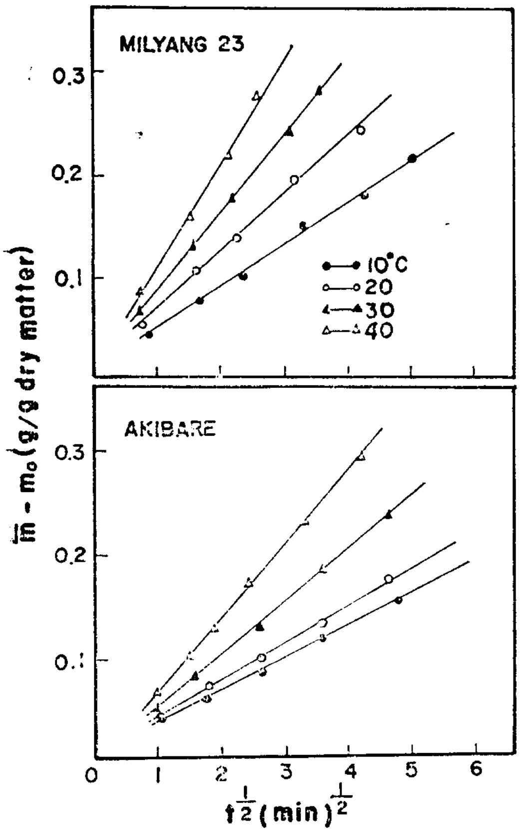

Fig. 2. Relation between the moisture gain and the square root of the abosorption time
The initial moisture content for Akibare and Milyang 23 was 0.163 *g/g* dry matter.

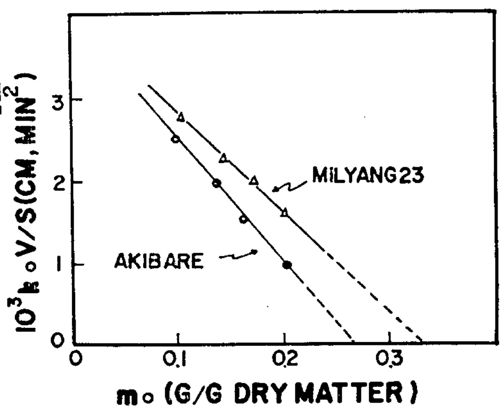

Fig. 3. k_oV/S as a function of initial moisture content at soaking temperature of 20°C

5.853 $\times 10^{-3}$ for Milyang 23. Therefore, the average D values as a function of temperature can be expressed as follows:

Table 1. Average values of the diffusion coefficients at various soaking temperatures

	Soaking temperature (°C)	Diffusion coefficient (cm^2/sec)
Milyang 23	10	2.25×10^{-6}
	20	3.18×10^{-6}
	30	4.40×10^{-6}
	40	6.00×10^{-6}
Akibare	10	2.36×10^{-6}
	20	3.02×10^{-6}
	30	3.80×10^{-6}
	40	4.71×10^{-6}

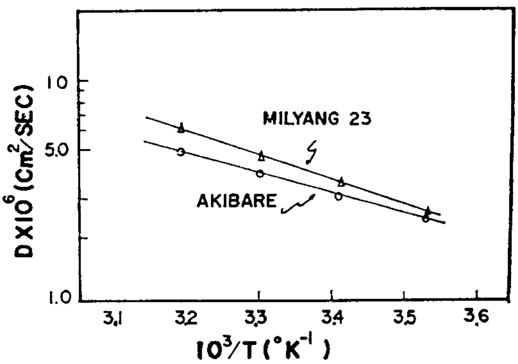

Fig. 4. Diffusion coefficient as a function of the reciprocal absolute temperature

$D=3.151\times10^{-3}\exp(-4\,000/RT)$ for Akibare

and

$D=5.853\times10^{-3}\exp(-5\,700/RT)$ for Milyang.

D values in Table 1 were lower by more than half compared with the values reported by Suzuki et al[8]. They also reported that the activation energy of soaking was approximately equal to 3 000 *cal/mole* on the assumption that rice grain was spherical. These differences in D values and activation energies of soaking may be due to the different varieties and the differences in the shape of rice grain employed between two studies.

Cooking of rice

The relation between 1/H and cooking time is shown in Fig. 5. Each curve showed a clear relationship. Milyang 23 reached to the bending point, which was defined as the terminal point of cooking at each cooking temperature, about 5 min faster than Akibare (Figs. 5 and 6).

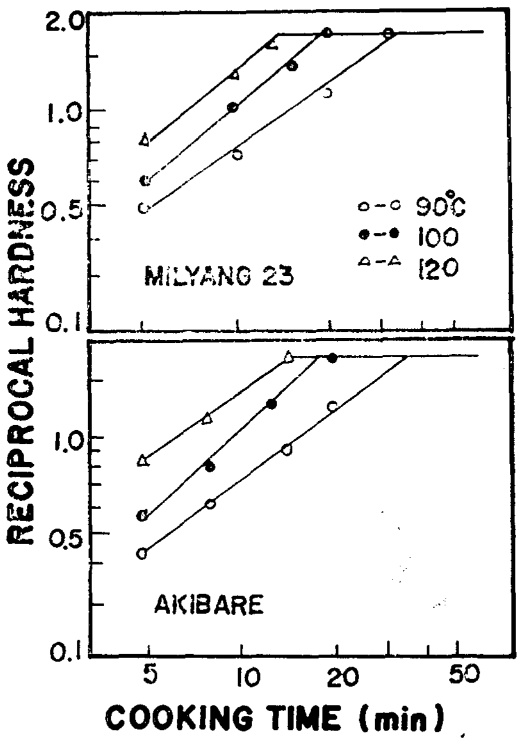

Fig. 5. Relation between the reciprocal hardness of cooked rice grains and cooking time at various cooking temperatures (soaking time, 40min)

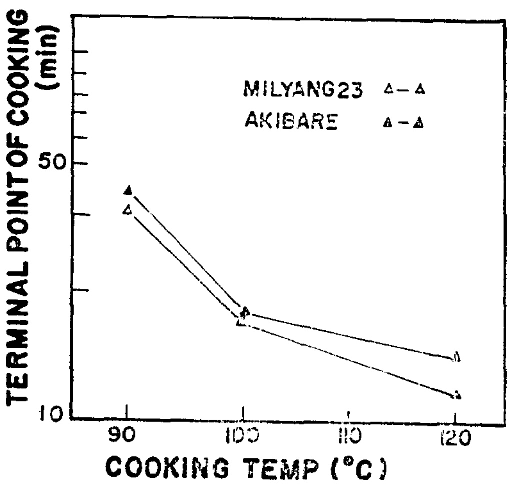

Fig. 6. Relation between the terminal point of cooking and cooking temperature (soaking time, 40min)

The relation between the terminal point of cooking and cooking temperature is shown in Fig. 6. The cooking time held a linear function of the cooking temperature, but the slopes of the curves changed at 100°C. These results were in good agreement with those of Cheigh et al[10]. At a temperature below 100°C the slopes for Akibare and Milyang 23 showed about the same trend. However, at temperatures between 100~120°C the slope for Milyang 23 was steeper than that for Akibare(Fig. 6).

A plot of the rate of uncooked portion of rice as a function of cooking time is shown in Fig. 7. As evident from this figure, the rate of uncooked portion of rice showed a linear relationship with the cooking time, which can be expressed as Eq. (9).

The values for k calculated form Fig. 7 are presented in Table 2. As the cooking temperature increased, k also increased. Milyang 23 showed slightly higher k than Akibare at all cooking temperatures. The temperature coefficient of k between 90 and 100°C for both Akibare and Milyang 23 was about 2 (Table 2), which is closer to the value by chemical reaction than biochemical reaction[9].

The activation energies of cooking calculated from Arrhenius plot of k are given in Table 3. The activation energies between 90~100°C and 100~120°C for Akiabare and Milyang 23 were

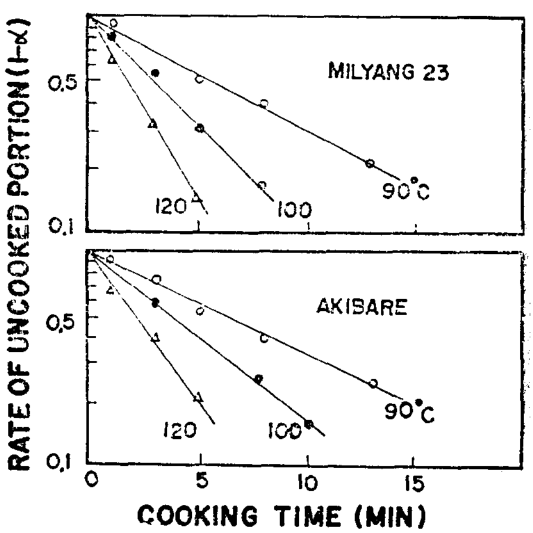

Fig. 7. The rate of uncooked portion of rice grains as a function of cooking temperature (soaking time, 40 min)

about 18 000 and 9 000 *cal/mole*, respectively. These results were in good agreement with those of Suzuki *et al*[9] and of Cheigh *et al*[10]. It appears that soaking time did not affect the activation energy of cooking (Table 3), as previously reported[10].

Textural profile of cooked rice grains

A typical textural profile of cooked rice grains is shown in Fig. 8. The low initial slope of the first peak indicates that cooked rice grains deform easily and tend to flow rather than break. The values for H and A_2/A_1 were similar for both Akibare and Milyang 23. However, Milyang 23 showed somewhat greater value for A_3 than Akibare.

Amylogram patterns for Akibare and Milyang 23 showed that the latter had higher viscosities than the former at all reference points (Fig. 9). Although it is not clearly understood the relationship between the pasting properites of rice flour and the textural characteristics of cooked rice grains, it is not completely exclusive that the

Table 2. Average values of the reaction rate constant

	Cooking temperature (°C)	Soaking time(min)	Reaction rate constant (*cm*/min)
Milyang 23	90	0	4.5×10^{-2}
		20	4.7×10^{-2}
		40	4.7×10^{-2}
	100	0	9.0×10^{-2}
		20	9.4×10^{-2}
		40	9.4×10^{-2}
	120	0	16.4×10^{-2}
		20	16.9×10^{-2}
		40	17.1×10^{-2}
Akibare	90	0	4.2×10^{-2}
		20	4.2×10^{-2}
		40	4.4×10^{-2}
	100	0	7.9×10^{-2}
		20	8.2×10^{-2}
		40	8.3×10^{-2}
	120	0	14.8×10^{-2}
		20	15.3×10^{-2}
		40	15.4×10^{-2}

Table 3. Activation energies of cooking rice

	Cooking temperature (°C)	Soaking time(min)	Activation energy (*cal/mole*)
Milyang 23	90~100	0	18 400
		20	18 700
		40	18 600
	100~200	0	8 700
		20	8 600
		40	8 700
Akibare	90~100	0	17 300
		20	17 400
		40	17 100
	100~120	0	9 000
		20	9 000
		40	8 900

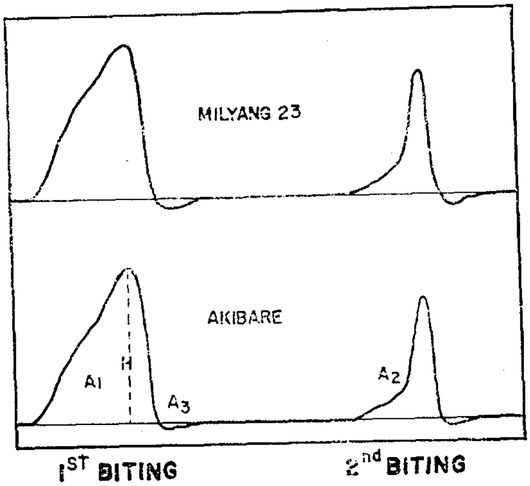

Fig. 8. Typical textural profile for cooked rice grains

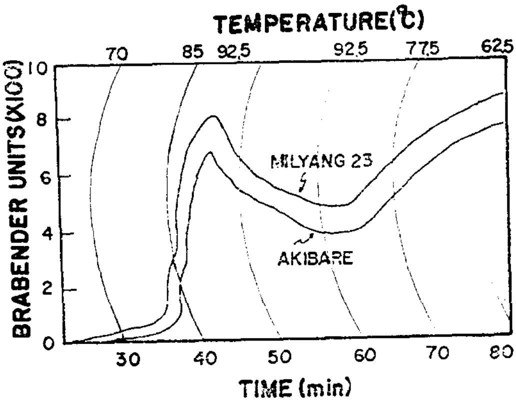

Fig. 9. Amylograph curves of rice flour

greater value for A_3 for Milyang 23 (Fig. 8) may have certain relation with the higher peak viscosity (Fig. 9).

Nomenclature

A_1	;	1st peak area in texturometer curve
A_2	;	2nd peak area in texturometer curve
A_2/A_1	;	Cohesiveness of cooked rice
A_3	;	Adhesiveness of cooked rice
a	;	Long radius of rice grain(*cm*)
B	;	Dimensionless constant
b	;	Short radius of rice grain(*cm*)
D	;	Diffusion coefficient(cm^2/sec)
D_0	;	Diffusion constant(cm^2/sec)
E	;	Activation energy(*cal/mole*)
e	;	Eccentricity
H	;	Hardness of cooked rice
H_0	;	H at cooking time 0
H_t	;	H at cooking time t
H_L	;	H at end of cooking
k	;	Reaction rate constant(*cm*/min)
k_0	;	Slope of curve of Eq. (3)
m_0	;	Initial mositure content(*g/g* dry basis)
$\overline{m}$	;	Average moisture content at given absorption time(*g/g* dry basis)
m_S	;	Effective moisture content at the binding surface at time greater than zero (*g/g* dry basis)
R	;	Gas constant(*cal/mole* °*K*)
S	;	Surface area of rice grain(cm^2)
T	;	Absolute temperature(*K*)
t	;	Absorption or cooking time(min)
V	;	Volume of rice grain(cm^3)
α	;	Degree of cooking(diminsionless)

요 약

아끼바레 및 밀양 23호의 수화 및 취반속도를 비교하였다. 수화속도는 10~40°C 범위에서 무게증가로서 측정한 결과, 수화시간의 평방근에 비례하였다. 확산계수는 Arrhenius 방정식으로 표시되었다. 아끼바레의 확산계수는 $3.151\times10^{-3}\exp(-4000/RT)$, 밀양 23호는 $5.853\times10^{-3}\exp(-5700/RT)$로 표시될 수 있었다. 취반속도는 밀양 23호가 아끼바레보다 빨랐으며 취반활성화에너지는 90~100°C에서 밀양 23호가 아끼바레보다 다소 높았다, 밥의 조직특성은 밀양 23호의 부착성이 아끼바레보다 높았고, 아밀로 그라프의 점도도 밀양 23호가 높았다.

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