



The Study on the Slurry Wear Behavior of Rubber Vulcanizates

Kyungho Chung[†], Youngkeun Hong, and Moonsoo Park

Department of Polymer Engineering, The University of Suwon, Suwon, Korea
(Received March 4, 2011, Revised March 14, 2011, Accepted March 21, 2011)

고무 소재의 슬러리 마모 거동에 관한 연구

정경호[†] · 홍영근 · 박문수

수원대학교 공과대학 신소재공학과

접수일(2011년 3월 4일), 수정일(2011년 3월 14일), 게재확정일(2011년 3월 21일)

ABSTRACT : A new piece of test equipment, the slurry wear tester (SWT), was proposed in this study to evaluate the wear behavior of rubber vulcanizate in environmental contact with slurry. Natural rubber (NR) and chloroprene rubber (CR) were chosen as the basic matrices to test the slurry wear. The fluids used to fill the chamber of the SWT were 35% HCl and NaCl solution. The Akron abrasion test was used for comparison with SWT. According to the results of the Akron abrasion test, CR vulcanizate abraded more rapidly than NR vulcanizate under same test condition. It was found that the hysteresis of rubber was key factor contribute to the wear behavior. However, the slurry wear rate of the NR and CR vulcanizates did not change significantly, even with changes in the concentration of acid and the immersion time in both HCl and NaCl solutions; the fluid decreased the friction between the abrasive paper and the specimen. It also reduced the heat generated from repeated deformation and wear debris at the surface of the SWT's abrasion arm. Thus, these phenomena affected the wear behavior of rubber vulcanizate and caused different results in the conventional Akron abrasion test. This outcome could have resulted in an incorrect analysis if the slurry wear behavior of the rubber vulcanizate was estimated by the conventional abrasion tests, which are operated under dry conditions.

요약 : 슬러리와 접하는 환경에서 사용되는 고무 소재의 슬러리 마모 거동을 평가하기 위해 새로운 형태의 슬러리 마모시험기(Slurry Wear Tester; SWT)가 본 연구에서 제안되었다. 슬러리 마모 거동을 평가하기 위한 기본 매트릭스로 천연고무(NR)와 클로로프렌고무(CR)가 선정되었다. SWT 장치의 챔버를 채우기 위한 유체로는 35% HCl 용액과 NaCl 용액이 사용되었다. SWT의 결과는 기존의 고무 마모시험 방법들중의 하나인 건식 상태에서 시험이 진행되는 Akron 마모시험의 결과와 비교를 하였다. Akron 마모 시험의 결과에 따르면 CR이 NR 보다 더 빠른 속도로 마모가 됨을 알 수 있었으며 재료의 히스테레시스 특성이 마모에 영향을 미침을 알 수 있었다. 그러나 SWT 결과에 따르면 CR과 NR의 슬러리 마모거동은 큰 차이가 없었으며 더구나 산의 농도와 HCl 용액과 NaCl 용액에 침지된 시간에 따라서도 슬러리 마모속도에는 큰 영향이 없었다. 이는 슬러리에 포함된 유체가 마모지와 시편 사이의 마찰을 감소시켰기 때문이라고 사료되었다. 또한 Akron 마모 시험의 경우 고무 소재의 히스테레시스가 마모에 영향을 미쳤지만, SWT의 경우 유체는 반복 변형에 의해 발생하는 열을 감소시키고 마모지 표면에 남아있는 마모 찌꺼기들을 제거하였기 때문에 Akron 마모 시험의 결과와는 다른 결과를 나타내었다. 따라서 슬러리에 의한 고무 소재의 마모를 평가하는데 있어서 기존의 방식인 건식방법으로 마모 거동을 평가할 경우 잘못된 결과를 초래할 수 있음을 알 수 있었다.

Keywords : two-body abrasion; rolling friction; polymers; polymer-matrix composite; wear testing

1. Introduction

The rubber products used in industry deteriorate through various means. Generally, materials wear because of the frictional force between contacting materials. Temperature, humidity, and fatigue as well as the type and age of the material can affect the deterioration of rubber products. Therefore, false wear behavior can result if a single wear test is applied ex-

clusively in evaluating all wear behaviors of rubber products.

There are several test methods available to evaluate the wear of rubber material, such as the Williams, Akron, NBS, and Pico. All of these methods are applied in a dry state in which the rubber material is placed in direct contact with the source that causes wear. None of the test methods can produce reasonable wear results if the rubber products are used in wet conditions. A single test method cannot be used to evaluate all of the wear phenomena of rubber products, and the best way to evaluate wear behavior is to perform a wear test that

[†]Corresponding Author. E-mail: khchung@suwon.ac.kr

closely simulates the real conditions that rubber products experience.¹

Rubber materials have been used as base materials for hoses, belts, rolls, and linings in various industries dealing with slurry and powder. The performance of rubber products is estimated by examining basic physical properties such as hardness, tensile strength, elongation, tear strength, and wear test results in a dry state, which is why conventional test methods may not give reasonable results when used to evaluate the wear behavior of rubber products in wet conditions. For example, the lifetime of rubber products known to have better physical properties, as determined by conventional test methods, could be short compared with rubber products with poorer physical properties. The results might come from the incorrect application of test methods. Thus, several wear testing procedures have been proposed to explore wear behavior under different conditions because one wear test method cannot be applied equally to estimate all of the wear behaviors of the rubber products used in various environments.^{2,4} The method for evaluating the wear behavior of rubber materials should be simple and manageable, with results that are easy to interpret.¹

In this study, a test method is proposed to evaluate the wear behavior of the rubber materials used in industries that deal with fluid slurry. A slurry is defined as the suspension state in which solid particles are dispersed within a fluid. Currently, there is no test method for evaluating the wear behavior of rubber material exposed to slurry. In the remaining sections of this paper, the basic formulations of slurry and rubber compound used in new test equipment are introduced to quantify the slurry wear behavior of the rubber material. Then the results are compared with those obtained from the Akron abrasion test, one of the conventional abrasion tests for rubber vulcanizate. Finally, the differences between the new and conventional test methods are analyzed. It is expected that the results will contribute to more reliable wear analysis and give insights into the additional improvements of the proposed wear test method.

II. Experimental Design

1. Materials

In this study, two types of rubber widely used in industries dealing with fluid slurry were chosen as the basic matrices for slurry wear testing. For natural rubber (NR, RSS#1), the sulfur curing system was used, while magnesium oxide was used as the curing agent for chloroprene rubber (CR, PM 40NS). Carbon black (HAF, N330) was used as the reinforcing filler in both types of rubber. The detailed formulation is listed in Table 1. This formulation was chosen through preliminary experiments after examining the formulation of a real rubber

Table 1. The Basic Formulation of the Rubber Compound

Ingredients	Type of rubber	
	NR	CR
RSS #1	100	-
PM 40NS	-	100
ZnO	5	5
Stearic acid	2	1
MgO	-	4
Carbon black (N330)	30	30
Sulfenamide	0.8	-
Sulfur	2.5	-

lining used with slurry. The fluids in contact with the rubber vulcanizates were prepared using 35 wt.% HCl and NaCl to provide an acidic and artificial seawater-like condition, respectively. The concentrations of the acid formulated were 0.01, 0.1, and 1 N. For the NaCl solution, the concentration was adjusted to 3 wt.% (30 g of NaCl/1 L of distilled water). The NaCl solution concentration was determined by considering the general concentration of seawater.

2. Rubber Compounding and Cure Characteristics

Basic rubber compounding was performed with a two-roll mill. The ingredients listed in Table 1 were mixed into the rubber after it was masticated thoroughly on the mill. The rubber compounds were stored at room temperature for 24 hours. The cure characteristics of the rubber compound, such as scorch time (t_{s2}) and 90% cure time (T_{90}), were measured by a rubber rheometer (DaeKyung DRM-100, Korea) at 160 °C. The specimens for the slurry wear test and the test of the physical properties were prepared by hydraulic press at 160 °C according to T_{90} .

3. Physical Tests

The change in the mechanical properties of the rubber vulcanizate as a function of the immersion time in the fluid was examined by measuring the tensile strength, rebound resilience, and hardness of the rubber vulcanizate. The tensile test was performed under the following conditions: 20 mm gauge length, 500 mm/min crosshead speed, and 24 °C. The rebound resilience was measured using a cylindrical specimen according to KSMISO 4662. In addition, the hardness of the rubber vulcanizate was measured using a Shore A durometer.

4. Design of the Slurry Wear Tester

A slurry wear tester (SWT)⁵ was introduced in this study

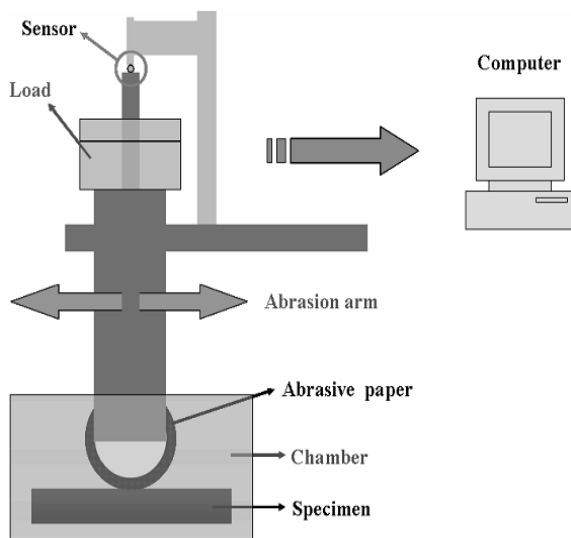


Figure 1. Schematic diagram of the slurry wear tester.



Figure 2. Photograph of the slurry wear tester.

to evaluate the wear behavior of the rubber vulcanizate used in environment contacts with slurry. The schematic diagram and the details of the sections of the SWT are shown in Figure 1. A photograph of the SWT is shown in Figure 2. The specimen was mounted in a chamber containing fluid, and the dimensions of specimen were 10x75x10 mm (widthxlengthxheight). The wear of the specimen occurred through the reciprocation of the SWT abrasion arm with abrasive paper attached. Various loads were mounted on the abrasion arm to control the degree and rate of wear. The slurry consisted of solids and liquid. The fluid in the SWT chamber acted as the liquid slurry, and the abrasive paper attached to the SWT abrasion arm acted as the solid slurry, which made simulating various slurries possible by changing the fluid and abrasive paper. As the test

progressed, the thickness of the specimen decreased, and the degree of decrease was detected by a sensor, which sent the results to a computer in real time. Several factors such as the magnitude of load, the test cycle, the types of fluids, the immersion time in the fluid, and the types of rubber compound were considered in the application of the SWT. The magnitude of the load used in the SWT was chosen as 3 kg because the test duration would be too long if a load weighing less than 3 kg was applied. The wear rate (W) by the SWT was obtained using the following equation (1);

$$W (mm/cycle) = \frac{D_{3,000} - D_{500}}{2,500} \quad (1)$$

$D_{3,000}$: center depth of the specimen after 3,000 cycles of the abrasion arm

D_{500} : center depth of the specimen after 500 cycles of the abrasion arm

As shown in Equation (1), the preliminary number of test cycles was 500. This value was chosen because the wear of the specimen was not consistent at the beginning of the test.

The Akron abrasion test, conducted according to the KSM6624 (ISO4649), was performed for comparison with the results of the SWT. The abrasion loss volume from the Akron test was obtained from equation (2);

$$abrasion \ loss \ volume (mm^3) = \frac{W_o - W_1}{\rho} \quad (2)$$

ρ : density of specimen (g/mm^3)

w_o : weight of specimen before test

w_1 : weight of specimen after test

III. Results and Discussion

1. Cure Characteristics and Physical Properties of the Rubber Compounds

In this study, NR and CR were chosen as the matrix rubber because NR and CR are typical rubber materials that show good mechanical properties and chemical resistance, respectively. The cure characteristics of the rubber compounds used in this study are listed in Table 2. As shown in Table 2, the ΔM of the CR compound was greater than that of NR, and the cure rate index (CRI) of the CR compound was lower than that of NR. However, it was expected that the CRI would not affect the wear behavior of the rubber vulcanizate. All of the test specimens were vulcanized by T_{90} as shown in Table 2.

The mechanical properties of the rubber vulcanizates are listed in Table 3. As expected, the tensile strength of the NR

Table 2. Cure Behavior of Rubber Compound

Type of rubber Property	NR	CR
M _H	5.37	21.63
M _L	0.34	1.18
ΔM	5.03	20.45
t _{s2}	1min 17sec	1min 08sec
T ₉₀	2min 22sec	8min 31sec
CRI	95.24	13.83

(note) M_H : maximum torque (N.m),
M_L : minimum torque (N.m)
ΔM : M_H - M_L, t_{s2} : scorch time
T₉₀ : 90% cure time, CRI : 100/(T₉₀ - t_{s2})

Table 3. The Physical Properties of Rubber Compounds

Type of rubber Properties	NR	CR
Tensile strength (MPa)	29.50 ± 1.74	12.42 ± 3.06
Rebound resilience (%)	61	31
Hardness (Shore A)	45	65

(Note) rebound resilience (%) = (rebound height / initial drop height) x 100

vulcanizate was higher than that of the CR vulcanizate. However, the hardness of the NR vulcanizate was lower than that of the CR vulcanizate, which may have been caused by the typical phenomenon of NR's strain-induced crystallization. The properties such as tensile strength, rebound resilience, and hardness would affect the wear behavior of the rubber vulcanizate. The rebound resilience, the ratio of restore energy to input energy when a force of impact deforms rubber, of NR vulcanizate was higher than that of CR vulcanizate. The rebound resilience was measured by reading the rebound height of a steel ball after dropping it onto the specimen at a specified height. The loss energy, which cannot be restored, dissipates as heat and is called hysteresis. The wear test was followed by cyclic deformation. Therefore, heat was generated in the specimen by cyclic deformation and became one of the factors affecting the wear behavior of the rubber vulcanizate. In this study, it was expected that the wear of CR vulcanizate would progress more rapidly than that of NR vulcanizate because the hysteresis of the CR vulcanizate was greater than that of the NR vulcanizate. However, there was doubt about the theoretical results because the heat generated could be compensated by fluid in the case of slurry wear. When a rubber

vulcanizate comes in contact with a fluid, the fluid can affect the physical properties of the rubber vulcanizate. The wear behavior of rubber vulcanizate can then be modified if the contacting fluid changes the physical properties of the rubber vulcanizate.

The effects of fluid on the wear behavior and mechanical properties of rubber vulcanizate were examined by immersing the rubber vulcanizate into a specified fluid. The control factors were the following: type of fluid, concentration of fluid, and immersion time. Three different concentrations 0.01, 0.1, 1 N were used in the case of the HCl solution, while the concentration of NaCl solution was fixed at 3 wt.% to simulate seawater.

The mechanical properties of the rubber vulcanizates were also examined using a specimen immersed in fluid. This test was done to investigate the effects of changes in physical properties through fluid contact on wear behavior. All specimens were immersed in fluids and then dried at room temperature before testing. The tensile strength of the specimen, along with the concentration and immersion time of the contacting fluid, is shown in Figure 3. The results with as a function of acid concentration are shown in Figure 3(a). In this case, the specimens were immersed in acid for 24 hours. The results with as a function of immersion time in 0.1 N HCl and 3 wt.% NaCl solution are shown in Figures 3(b) and (c), respectively. As shown in Figure 3(a), the tensile strength of the NR vulcanizate decreased under acidic conditions. However, the tensile strength of the CR vulcanizate did not change significantly. Additionally, the acid concentration was not a critical factor affecting the tensile strength in both either cases. Similar results were obtained in for the case of immersion time. Generally, the tensile strength of the CR vulcanizate did not decrease significantly compared with that of the NR vulcanizate. The tensile strength of the NR vulcanizate decreased by almost half during the first day of immersion and then did not change significantly with further immersion time. Although the tensile strength of the CR vulcanizate was lower than that of the NR vulcanizate, the tensile strength of the CR vulcanizate did not change greatly in after contact with fluid, which may have been caused by the polarity of CR.

Figure 4 shows the change of the rebound resilience of the rubber vulcanizates as a function of the condition of the contacting fluids. As shown in Figure 4, the rebound resilience did not change greatly, regardless of fluid conditions. The results were quite different for the tensile strength. It was found that the rebound resilience depended not on fluid contact, but on the type of rubber.

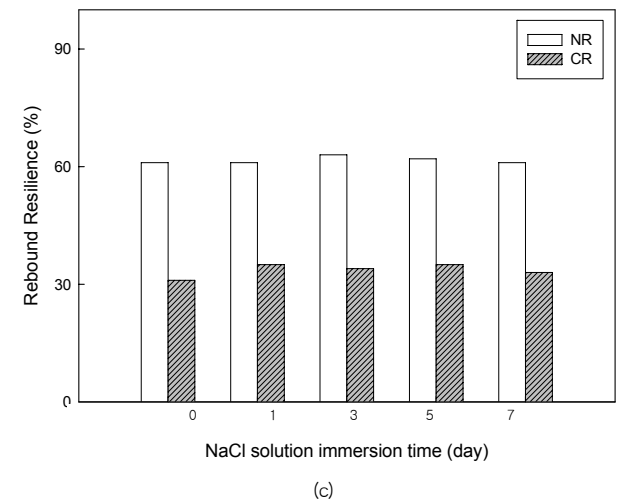
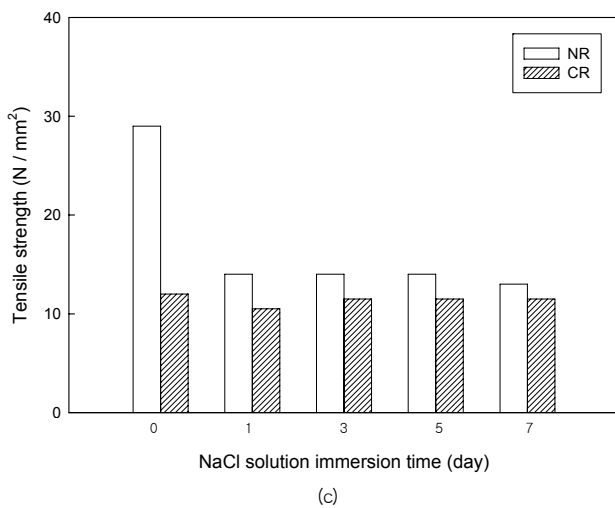
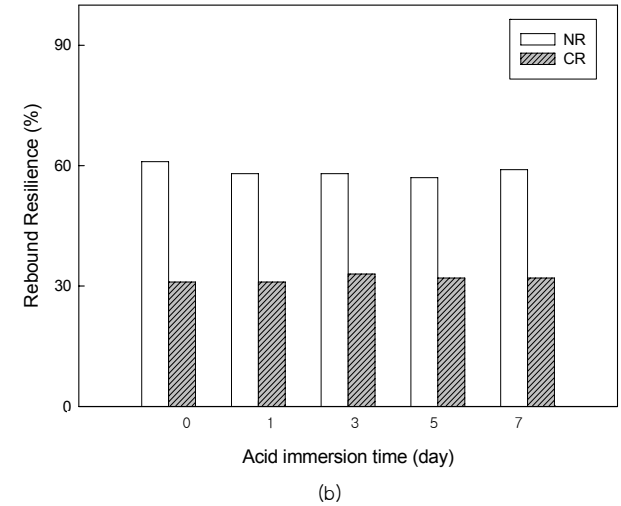
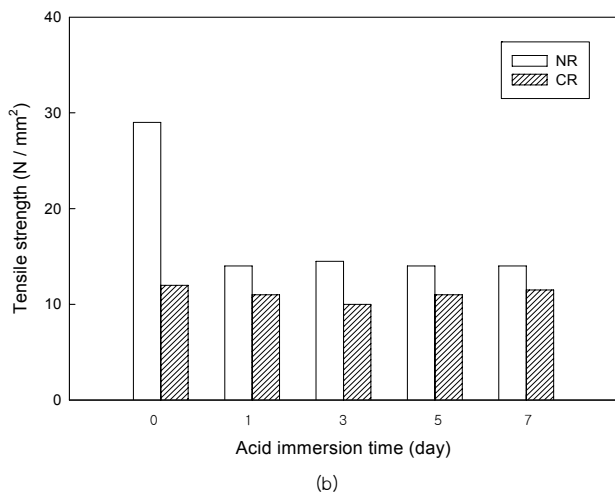
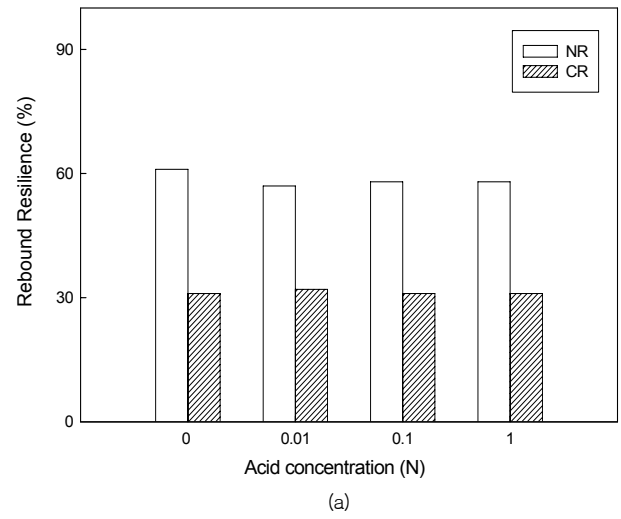
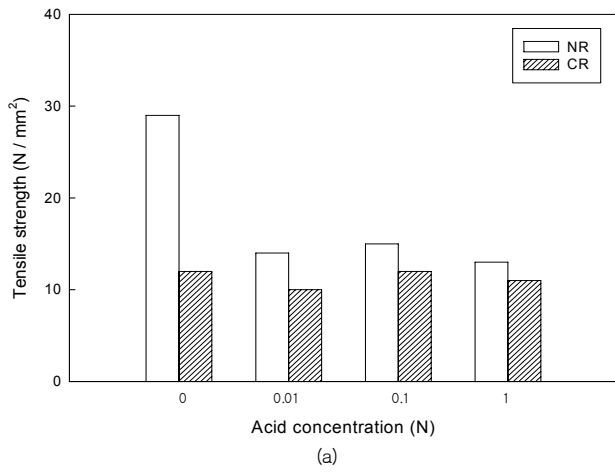


Figure 3. Change of tensile strength as a function of the concentration and immersion time of the contact fluid: (a) acid concentration, (b) immersion time in acid, (c) immersion time in NaCl solution.

Figure 4. Change of the rebound resilience as a function of the concentration and immersion time of the contact fluid: (a) acid concentration, (b) immersion time in acid, (c) immersion time in NaCl solution.

2. Effect of Contacting Fluid on the Wear Behavior of Rubber Vulcanizate

The Akron abrasion test was performed using a specimen immersed in fluid for 24 hours. The wet specimen, obtained after a 24 hour immersion in fluid, was used in this test to simulate real slurry conditions because the Akron abrasion test could not be conducted while immersing the specimen in fluid. The results of the Akron abrasion test are shown in Figure 5. The black circles show the results for the NR vulcanizate, and the white circles represent the results of the CR vulcanizate. The x-axis in Figure 5(a) is the concentration of acid, and 0 refers to the results of the specimen without contacting fluid. Although the direct comparison between the NR and CR vulcanizates did not have great significance, it was interesting to compare the wear trends between the two vulcanizates. As shown in Figure 5, the abrasion volume loss of the CR vulcanizate was greater than that of the NR vulcanizate, regardless of acid concentration. Considering the rebound resilience of both rubber vulcanizates, these results were expected. The abrasion of the CR vulcanizate proceeded more rapidly than the abrasion of the NR vulcanizate because of its low rebound resilience or high hysteresis properties. The abrasion behavior of the NR vulcanizate was not affected by acid, but the abrasion volume loss increased with acid concentration for the CR vulcanizate. It is well-known that the chemical resistance of the CR compound to freon gas, aliphatic hydrocarbons, oil, and grease is good. However, it was found that the abrasion resistance of CR vulcanizate was affected by acid, which may be due to the high heat generation of the CR vulcanizate during the abrasion test. Similar results were obtained in the test that estimated the abrasion behavior of rubber vulcanizate as a function of immersion time in 0.1 N HCl and 3 wt.% NaCl solution. As shown in Figures 5(b) and (c), the abrasion of the NR vulcanizate did not depend on immersion time until the third day of immersion, but the abrasion of the CR vulcanizate increased slightly with increasing immersion time in an acidic solution and artificial seawater. In the case of NR, the abrasion volume loss increased when the NR vulcanizate was immersed in fluid for over 5 days. Thus, it was deduced that the abrasion behavior of the rubber vulcanizates depended on the contact time rather than the concentration and type of fluid.

The abrasion resistance of the NR vulcanizate was better than that of the CR vulcanizate according to the results of the Akron abrasion test. In this experiment, it was difficult to find the relationship between the physical properties and the abrasion behavior of the rubber vulcanizate. However, it was found that the rebound resilience results were similar to the Akron abrasion test results. Thus, it was very worthwhile to evaluate the wear behavior of rubber vulcanizate by comparing the SWT results with the results of the Akron abrasion

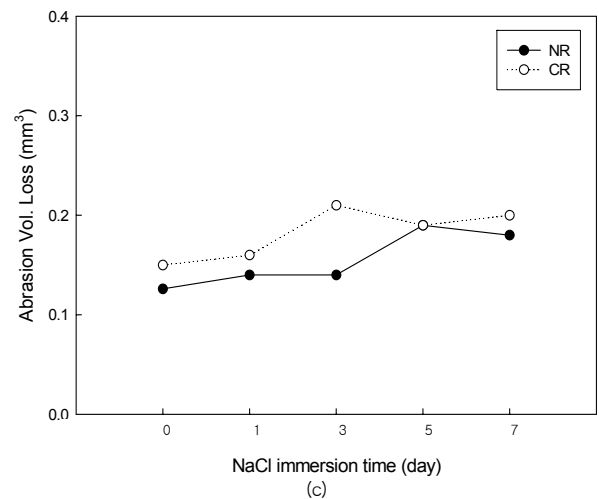
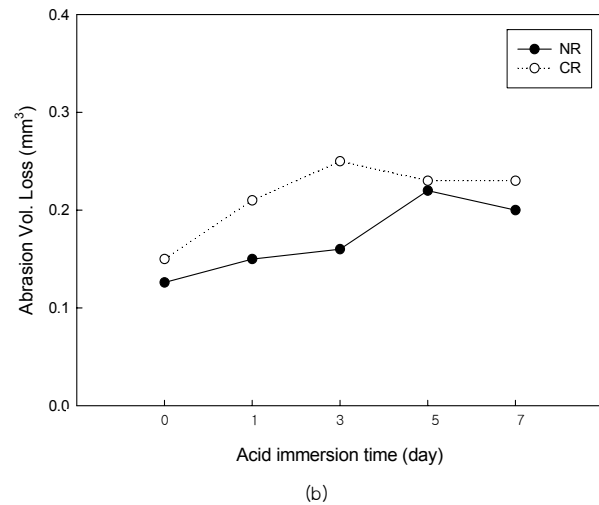
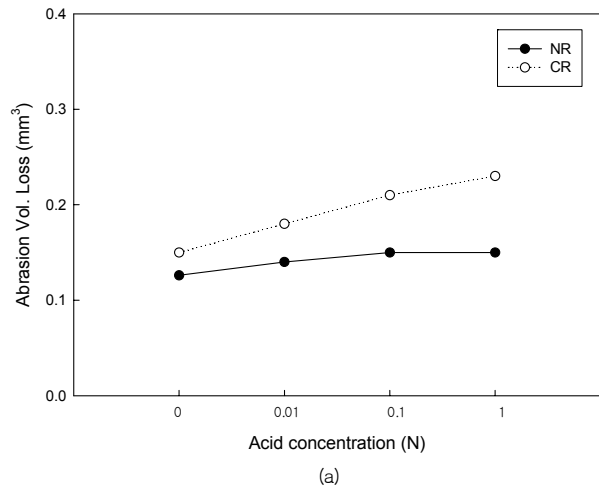


Figure 5. Abrasion volume loss as a function of the concentration and immersion time of contact fluid: (a) acid concentration, (b) immersion time in acid, (c) immersion time in NaCl solution.

test performed in a dry state. It was thought that a new type of abrasion test would be necessary to better evaluate the wear behavior of rubber vulcanizate exposed to slurry.

3. Slurry Wear Test

The wear behavior of rubber vulcanizate by slurry was examined by the SWT. As mentioned previously, fluid was poured into the SWT chamber, and the specimen was immersed in fluid for 24 hours. The results obtained using Equation (1) are shown in Figure 6. The slurry wear results as a function of the acid concentration are shown in Figure 6(a). Figures 6(b) and (c) show the results of immersion time in acid and NaCl solution, respectively. The data shown at 0 on the x-axis in Figure 6 are the results obtained by operating the SWT without adding the fluids into the chamber. According to the results, the wear rate of the CR vulcanizate was slightly higher than that of the NR vulcanizate, concurring with previous results. However, the wear rate of the NR and CR vulcanizates did not change significantly as a function of the concentration of acid and immersion time in either fluid, as shown in Figure 6. Strictly speaking, the wear rate decreased rather than increased when the rubbers were in contact with fluids, regardless of acid concentration, acid immersion time, and NaCl solution immersion time. This outcome may have been caused by the fluid decreasing the friction between the abrasive arm and the specimen in the SWT. It may have also been due to the fluid reducing the heat generated from repeated deformation and wear debris at the surface of the SWT's abrasion arm. These phenomena could have affected the overall wear behavior of the rubber vulcanizate and caused results that differed from the results of the Akron abrasion test. From this information, it can be concluded that estimating the slurry wear behavior of rubber vulcanizates using conventional abrasion tests could lead to an incorrect analysis.

It was expected that the slurry abrasion of the rubber vulcanizate would occur through both chemical actions from contact with the fluid and the physical action of the solids. However, it was found that only physical action could be a key factor for slurry abrasion because changing the chemical conditions did not affect the physical properties of the rubber vulcanizate in this system. The lubricating action and wear debris washing action of the fluid were also factors affecting the wear behavior of the rubber vulcanizate. In future studies, the researchers will operate the SWT under more severe chemical conditions, which could cause a chemical effect on the rubber vulcanizate. In addition, to obtain more reliable results, the real slurries used in industry will be employed in future experiments. It is expected that the SWT can be applied to various industries dealing with slurry if reliable data are established in future studies. Additionally, the reliability of the SWT will be de-

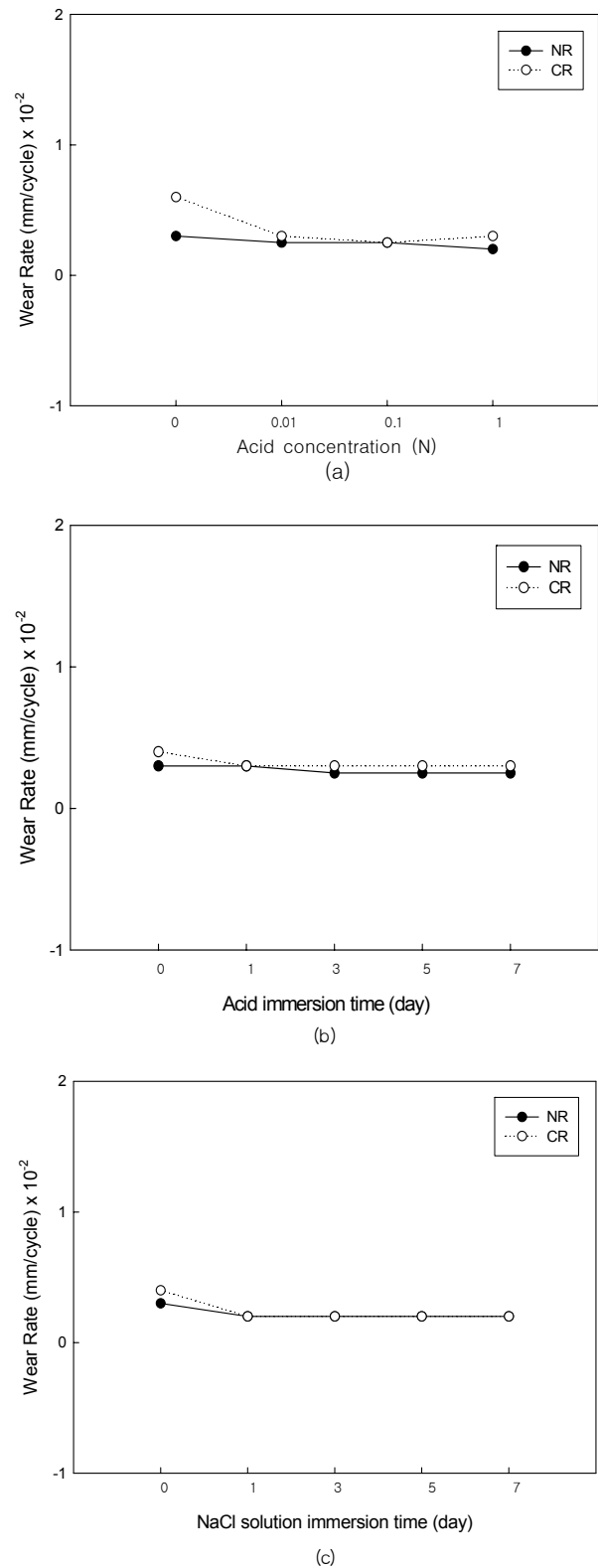


Figure 6. Wear rate as a function of the concentration and immersion time of the contact fluid: (a) acid concentration, (b) immersion time in acid, (c) immersion time in NaCl solution.

terminated by conducting many case studies in the future.

IV. Conclusions

The slurry wear test was introduced in this study to evaluate the wear behavior of rubber vulcanizates that are exposed to slurry. Generally, the abrasion volume loss of the CR vulcanizate was greater than that of the NR vulcanizate, according to the Akron abrasion test results, which was conducted without contact with any fluid. The abrasion behavior of the NR vulcanizate was not affected by fluid; however, the abrasion volume loss increased with an increasing acid concentration in the case of the CR vulcanizate. This result might have been due to the high heat generation of the CR vulcanizate during the wear test. Similar results were obtained in an experiment in which the wear behavior of the rubber vulcanizate was estimated as a function of immersion time in 0.1 N HCl and 3 wt.% NaCl solution. The wear rate of the NR vulcanizate did not depend on the immersion time until 1 day of immersion, but the wear rate of the CR vulcanizate increased slightly with an increase in immersion time in acid and artificial seawater. In the case of NR, the wear resistance decreased when the NR vulcanizate was immersed in fluid for over 5 days. Thus, the wear behavior of rubber vulcanizates depended on the contact time rather than the concentration and type of fluids. According to the results of the SWT, the wear rate of the NR and CR vulcanizates did not change significantly as a function of the concentration of acid and the immersion time of

both fluids. The wear rate decreased rather than increased in some cases. The fluid could have decreased the friction between the abrasive arm and the specimen or reduced the heat generated from repeated deformation and wear debris at the surface of the SWT's abrasion arm. These could have affected the wear behavior and decreased the wear rate of the rubber vulcanizate, causing the deviation of results from the Akron abrasion test. It is expected that a more reliable wear analysis of rubber vulcanizate can be made by improving the SWT in future studies.

References

1. T. Iwai and Y. Uchiyama, "Variations of rubber friction in the course of pattern abrasions - Relationships between ridge formation and frictional force", Proceedings of the International Tribology Conference, Nagasaki, 899, 2000.
2. Y. Fukahori and H. Yamazaki, *Wear*, **171**, 195 (1994).
3. T. Iwai and Y. Uchiyama, "Study on the formation of periodic ridges on the rubber surface by friction and wear monitoring", *Wear*, **259**, 669 (2005).
4. Y. I. Oka and T. Yoshida, "Practical estimation of erosion damage caused by solid particle impact Part 2: Mechanical properties of materials directly associated with erosion damage", *Wear*, **259**, 102 (2005).
5. K. H. Chung and Y. S. Park, *Korean Patent*, 10-0887756, 2009.