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Effects of the Interaction of Hardness, Resilience, and Fatigue Properties on the Abrasion Properties of Rubber Blends

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ABSTRACT: The establishment of prediction model for abrasion properties of vulcanizates, based on their simple physio-mechanical properties, is a hot research field in tribology. The hardness (H), resilience (R), and dynamic fatigue fracture parameters (m) of rubber vulcanizates were combined together in this article, named as hardness–resilience product (H^mR), and its relationships with the abrasion loss for various vulcanizates [natural rubber (NR), styrene–butadiene rubber (SBR), butadiene rubber (BR), and their blends] was investigated by using Akron and DIN abrader. The results showed that, for NR/SBR blends with different SBR content, compared with log(H^4R), the abrasion loss had much better linear relationship with log(H^mR) for both Akron and DIN abrasion. This good linear relationship, for both Akron and DIN abrasion, also appeared in the SBR/BR blends with different BR content. Furthermore, for both blending systems (NR/SBR and SBR/BR), when all the data above were put together, the abrasion loss also had good linear relationships with its log(H^mR) no matter for Akron or DIN abrasion, which indicated that this linear relationship had some universality. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 130: 1212–1219, 2013

KEYWORDS: hardness; resilience; dynamic fatigue fracture parameters; abrasion resistance

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INTRODUCTION

Abrasion resistance is very important for rubber products, because it directly determinate their service lives. How to improve the abrasion resistance and how to predict their abrasion characteristics are two hot issues in the field of tribology.[1–3] The abrasion properties of vulcanizates essentially depend on their physio-mechanical properties, such as strength, hysteresis, hardness, fatigue, modulus of elasticity, etc. Therefore, based on the simple physio-mechanical properties, the establishment of prediction model for abrasion properties has obtained extensive attention.

Rubber abrasion was a very complicated process, and it was affected by a variety of intrinsic and extrinsic factors, such as physio-mechanical properties and working conditions. There are important theoretical and practical significance to find the governing factors of rubber abrasion resistance to predict the abrasion characteristics and abrasion lives of rubber products under certain conditions. The relationships between hardness,[4,5] resilience,[6,7] breaking energy,[8] modulus of elasticity,[9,10] viscoelasticity,[11–13] and abrasion properties of vulcanizates have been investigated in detail, however, no clear regularity were found. The scientific understanding needed to predict the wear of a rubber product under specified conditions according to its basic physio-mechanical properties is still lacking. Recently, studies focus on the combination of two or more physio-mechanical properties, such as $\sigma\varepsilon$ (ε, elongation at break), $E\sigma$, $H\sigma\varepsilon$ (H, Shore A hardness), to establish the relationships with abrasion loss.[14,15]

Hardness (H) and resilience (R) are two important physical and mechanical properties of rubber vulcanizates. In our previous studies,[16] the synergistic effects of hardness and resilience on the abrasion properties of SBR vulcanizates were investigated, and the linear relationship between abrasion loss and log(H^4R) had been established. However, the data obviously deviated from this linear relationship when the hardness (H) were high (>80), which indicated that the power exponent of hardness should not be a constant.

Based on the studies on rail corrugation, the tribo-fatigue theory was developed by L. A. Sosnovskiy.[17,18] This theory focused on the interaction of abrasion resistance and fatigue properties, and had been used successfully in rail abrasion process. For most of rubber products, the abrasion process also is a dynamic fatigue process, and this fatigue process will deteriorate the abrasion properties. Therefore, fatigue properties were very important for rubber abrasion. In this article, the effects of the interaction of hardness, resilience, and fatigue properties on the abrasion properties of rubber composites were investigated. One object was to provide an available and universal criterion for prediction of the abrasion properties and abrasion life under certain conditions. The other object was to reveal the relationships between abrasion properties and dynamic fatigue properties.

EXPERIMENTAL

Materials

Table I gives the compositions of the compounds studied, all of which were cured with the optimum cure times. The elastomers were NR (SMR20) and SBR (ESBR1502), BR (BR9000) received from Deligon. Sdn. Bhd (Malaysia) and Sinopec Qilu (China), respectively. Carbon black was obtained from Philips Carbon Black (India). Other materials, such as zinc oxide, stearic acid, sulphur, antioxidants, etc., were chemically pure.

Sample Preparation

All the compounds given in Table I were mixed in a two-roll laboratory mill as per the standard procedure. Vulcanization was carried out at 150°C, in a hydraulic press having electrically heated platens. The physical properties of the vulcanizates were determined following ASTM (American Society for Testing Material) test methods. The rubber specimens for abrasion (233.6 ± 2 mm in length, 12.7 ± 0.2 mm in width, and 3.2 ± 0.2 mm in thicknesses) were prepared by molding in an electrically heated hydraulic press at 150°C to their optimum cure state (as determined from rheometry). Then the rubber specimens were bonded on a circular rubber wheels as test specimens.

Akron Abrasion Process

In the Akron abrader (GT-7012-A, Gotech Testing Machines Co, Taiwan), the contour of the circular test specimen, mounted on a motor-driven spindle, was brought into contact with the periphery of an abrasive wheel (150Φ × 38 mm, abrasive media: 36# grit wheel), which was mounted on another spindle. Rotation of the specimen causes the abrasive wheel to rotate and the two were held together under a force of 2.72 kgf. The axis of the specimen and the axis of the abrasive wheel were at an angle of 15°, which causes a rubbing action. The weight loss was recorded after a specified number of revolutions (the whole trip was 1.61 km, 3418 revolutions) of the abrasive wheel. The abrasion resistance of the specimen was calculated from its volume loss in terms of it weight loss and rubber's density. The specimen was first abraded by 500 revolutions before the Akron abrasion measurement. During the test, the abrasive wheel was cleaned manually with a brush and the specimen surface was continuously cleaned with a circular brush which was running in contact with the specimen. The testing temperature was 23 ± 2°C.

Table I. Compositions of the Compounds Used by Weight

Compounds	Compositions (phr)	
	NR	BR
Rubber	100	100
Carbon Black	50	50
Zinc oxide	5.0	3.0
Stearic acid	2.0	2.0
TBBS	0.7	0.9
Sulfur	2.25	1.5
Oil	0	15

TBBS: *tert*-Butyl-2-benzothiazolesulfenamide.

DIN Abrasion Process

The abrasion test was carried out in a DlN abrader (GT-7012-D, Gotech Testing Machines Co, Taiwan) according to ASTM D5963 and IS0 4649 standards. In DIN method of determining abrasion resistance of vulcanized rubber, a cylindrical rubber test specimen, 16 mm in diameter, is abraded against an abrasive surface mounted on a rotating cylindrical drum in such a manner that abrasion takes place on one of the flat ends of the test specimen which is held against the abrasive surface under a specified load, ranged from 5 to 17.5 N, while being traversed across it. The cylindrical specimen is gripped in a steel collet chuck so that a minimum length of about 6 mm protrudes, and the sample was clamped tightly into the specimen holder with a portion of it protruding 2 mm from the camping aperture with a gauge. The drum, 150 mm in diameter, rotates at about 40 revs/min, and the chuck moves parallel to the axis of the drum at about 3 mm/sec, simultaneously. During the whole experiment, the sample slides about 120 s, equivalent to about 84 revolutions. The mass loss of the test specimen and its density are measured and its volume loss calculated. The test was carried out at room temperature and no earlier than 16 h after vulcanization.

Dynamic Fatigue Fracture Parameters

The dynamic fatigue fracture parameters were measured using strain–fatigue life curves (*S–N* curves) methods which was put forward by D. G. Young,[19] based on the superposition principle of viscoelasticity and fracture mechanics of rubberlike materials. The $\lambda - lg\ N$ curves (λ is draw ratio and N is fatigue life) of a series of samples pre-cut with different size were obtained using tensile fatigue model according ASTM D4482. These curves parallel moved along the axle of fatigue life until they overlap with the $\lambda \sim lgN$ curve of un-cut samples, then the standard *S–N* curve can be obtained. The dynamic fatigue fracture parameters can be calculated by this *S–N* curve.

The samples were respectively pre-cut with 0, 1.0, 1.2 and 1.4 mm in length (C_i), and tested by using tensile fatigue model with different λ value. The fatigue times were recorded, and the dynamic fatigue fracture parameters (m) can be calculated by the following equation[19]:

$$a_i=(m-1)(\log C_i-\log C_0) \quad (1)$$

where a_i is shift quantum and C_0 is a constant related to potential defect size of rubber vulcanizates.

RESULTS AND DISCUSSION

The Relationships Between Hardness–Resilience Product and Abrasion Loss of BR and NR Vulcanizates

In our previous studies, it was found that the hardness–resilience product ($\log(H^4R)$) has good linear relationship with

Table II. Effects of Carbon Types on the Physio-Mechanical Properties of NR and BR

	Properties							
	Hardness (Shore A)		Resilience (%)		Akron abrasion loss (cm^3)		DIN abrasion loss (cm^3)	
Carbon type	NR	BR	NR	BR	NR	BR	NR	BR
N115	61	62	59	40	0.637	0.035	0.153	0.025
N134	61	65	58	40	0.63	0.012	0.152	0.038
N220	60	62	68	44	0.691	0.035	0.17	0.039
N234	62	66	60	41	0.61	0.012	0.155	0.039
N326	60	60	64	43	0.71	0.029	0.158	0.049
N330	63	63	63	45	0.633	0.031	0.151	0.043
N375	61	64	63	42	0.649	0.028	0.149	0.041
N550	61	62	67	51	0.781	0.076	0.162	0.053
N660	58	58	69	53	0.897	0.132	0.181	0.059
N774	57	50	71	53	0.844	0.171	0.174	0.06

Akron abrasion loss when different SBR vulcanizates possessing specific hardness and resilience were used as test samples.[9] However, it was no discussed whether this linear relationship suited for all kinds of rubber. Therefore, this relationship for NR and BR vulcanizates were studied in this section.

The hardness, resilience, abrasion loss of NR and BR vulcanizates filled with different types of carbon black (N110, N134, N220, N234, N326, N330, N375, N550, N660, and N774 respectively) were shown in Table II.

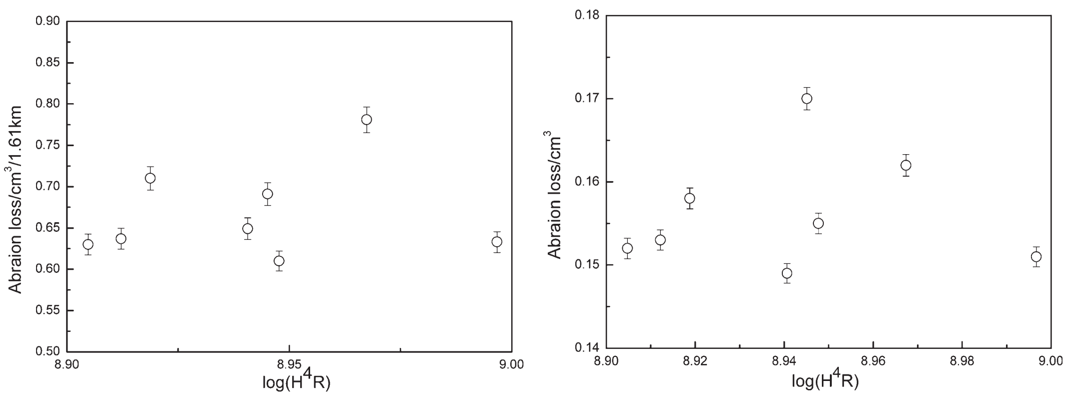
In Table II, for both NR and BR vulcanizates, the hardness and resilience were quite different when filled with different types carbon black. Generally, the particle size was smaller, the hardness of vulcanizates was higher and the resilience was lower. According our previous study, the relationships between $\log(H^4R)$ and abrasion loss (Akron and DIN abrasion) of NR and BR vulcanizates were shown in Figures 1(a,b) and 2(a,b) respectively.

In Figure 1(a,b), there was no obvious linear relationships between $\log(H^4R)$ and abrasion loss for NR vulcanizates, no matter Akron or DIN abrasion. So did the BR vulcanizates, as shown in Figure 2. These results indicated that the linear relationships between $\log(H^4R)$ and abrasion loss was appropriate for SBR vulcanizates, but not suited for NR and BR vulcanizates. Therefore, this linear relationship was not universal. The possible reason is that the exponent of hardness might not be a constant value 4, while be inter-related with certain physio-mechanical properties.

According to the tribo-fatigue theory, the abrasion properties were affected by fatigue properties greatly in most cases. For fatigue abrasion, the relationships between physio-mechanical properties and abrasion properties were show in following equation[20]:

$$I = k\left(\frac{\mu E}{\sigma}\right) m \left(\frac{p}{E}\right) 1+\beta m \qquad (2)$$

where k is a constant, μ is the friction coefficient, E is the tensile modulus, σ is the tensile strength, m is the dynamic fatigue fracture parameters, β is the surface roughness of friction pair, and P is the load. Every parameter in this equation has been



(a) Akron (b) DIN

Figure 1. Relationships between $\log(H^4R)$ and Akron (a) and DIN (b) abrasion loss for NR.

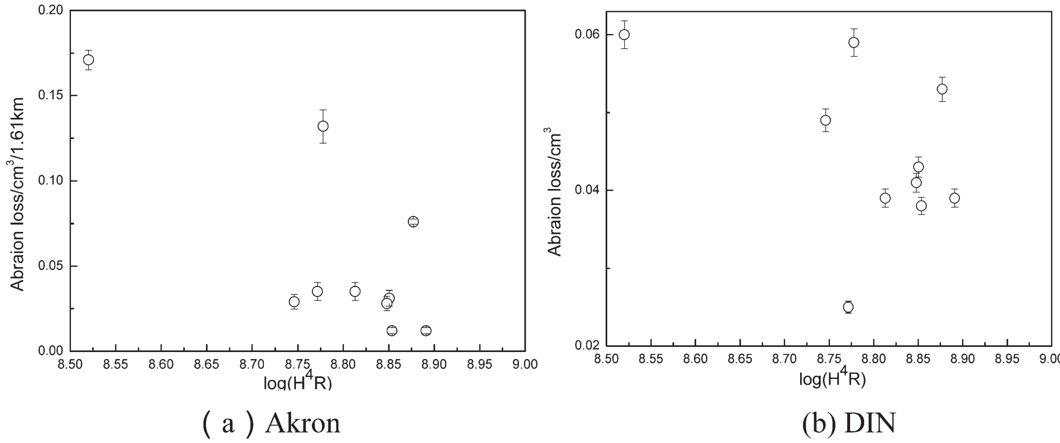


Figure 2. Relationships between log(H^4R) and Akron (a) and DIN (b) abrasion loss for BR.

Table III. The Recipes of NR/SBR Compounds

	Composites (phr)							
Ingredients	1	2	3	4	5	6	7	8
NR (SMR20)	100	80	70	60	40	30	20	0
SBR (1502)	0	20	30	40	60	70	80	100
Carbon black(N330)	30	30	30	30	30	30	30	30
Carbon black(N110)	20	20	20	20	20	20	20	20
Sulfur	2.0	1.8	1.8	1.7	1.7	1.6	1.6	1.4
MBT	0.5	0.6	0.6	0.7	0.7	0.8	0.8	1.0
TBBS	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3
Zinc oxide	5	5	5	5	5	5	5	5
Stearic acid	3	3	3	3	3	3	3	3
Oil	3	3	3	3	3	3	3	3
Antidegradants 4010	1	1	1	1	1	1	1	1
Antidegradants D	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

MBT: 2-Mercaptobenzothiazole; TBBS: *tert*-Butyl-2-benzothiazolesulfenamide.

well defined, and can be measured using other experiments. Therefore, this equation was very important to forecast the abrasion properties of vulcanizates, however the friction coefficient μ is not a constant for rubber products, having non-linear relationships with temperature, moisture, velocity, and loads, which limits its application. According to D. F. Moore's work,[21] μ value depended on tan δ value, and so resilience (R). The deformation factor (P/E) in eq. (2) is controlled by hardness (H). Therefore, according to the eq. (1) and our previous results, the hardness–resilience product (H^4R) was substituted for H^mR (m being the dynamic fatigue fracture parameters obtained by S–N curves).

The Relationships Between H^mR and Abrasion Loss of NR/SBR Vulcanizates

NR/SBR and BR/SBR blends were the most commonly used tread compounds, and studies on the forecast of their abrasion resistance were very important. The recipes of NR/SBR system were shown in Table III. In contrast, the vulcanizing system was modified according to the ratio the NR/SBR and BR/SBR.

The Physio-Mechanical Properties of NR/SBR Vulcanizates. According to the recipes of Table III, the physio-mechanical properties of NR/SBR vulcanizates were shown in Table IV.

Table IV. The Physio-Mechanical Properties of NR/SBR Vulcanizates

	Compound no.							
Properties	1	2	3	4	5	6	7	8
Tensile strength (MPa)	27.1	27.8	27.2	25.6	25.3	25.2	25.0	24.7
100% modulus (MPa)	2.48	2.34	2.24	2.07	2.11	2.19	2.21	1.99
300% modulus (MPa)	9.07	8.53	8.42	7.55	7.83	4.53	8.21	6.88
Tear strength (kN/m)	57.1	38.2	40.2	27.8	26.7	27.4	24.4	27.8
Hardness (Shore A)	67	68	64	63	63	64	64	65
Resilience (%)	46	42	41	41	41	40	40	39
Akron abrasion (cm^3)	0.241	0.234	0.22	0.231	0.213	0.216	0.19	0.142
DIN abrasion (cm^3)	0.133	0.13	0.127	0.121	0.113	0.114	0.106	0.102

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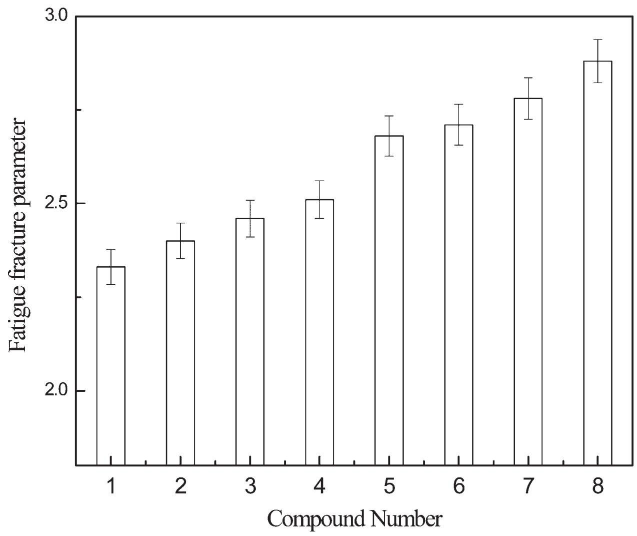


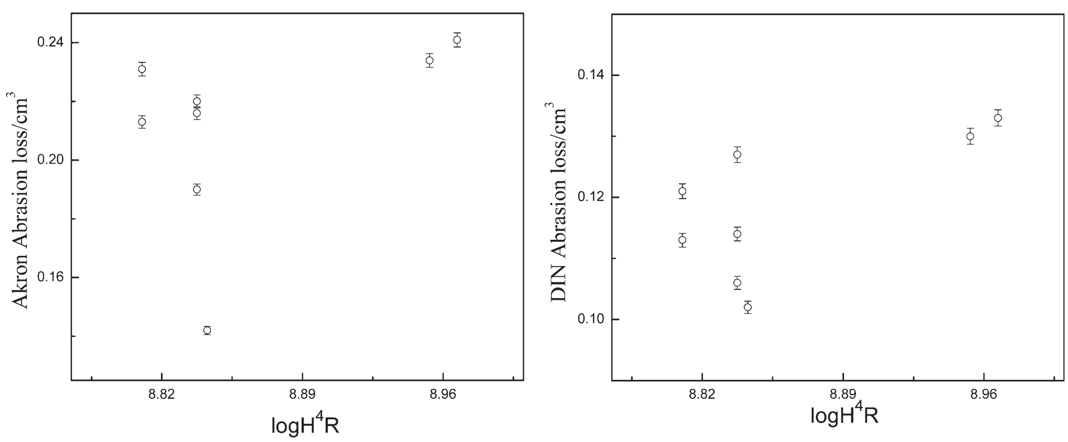
Figure 3. The dynamic fatigue fracture parameters of NR/SBR vulcanizates.

As observed from Table IV, the tensile strength, modulus, and tear strength decreased with the increase of SBR content, especially tear strength. No matter Akron or DIN abrasion, the abrasion resistance improved with the increase of SBR content, which indicated that SBR had better abrasion resistance than NR. With the increase of SBR content, the hardness and resilience decreased slightly.

The Dynamic Fatigue Fracture Parameters of NR/SBR Vulcanizates. The dynamic fatigue fracture parameters (m) of NR/SBR vulcanizates obtained from *S–N* curves were shown in Figure 3.

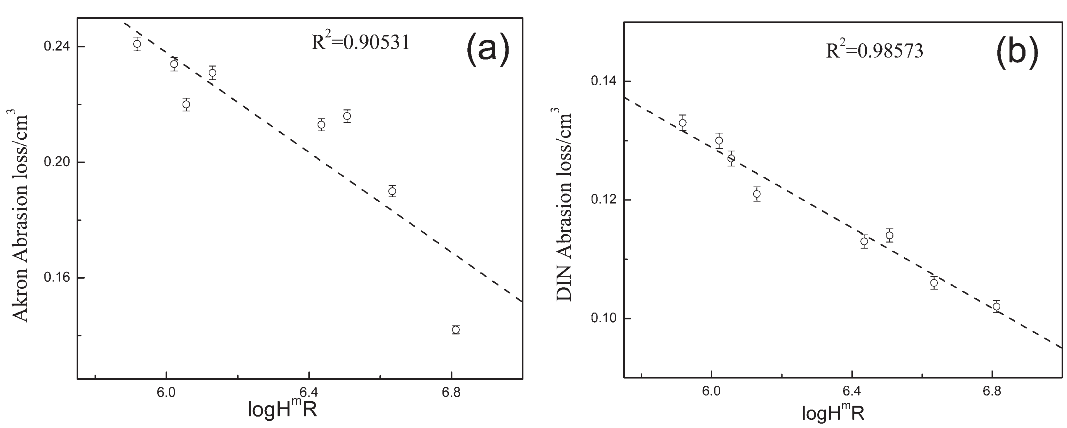
As observed from Figure 3, the m value increased with the content of SBR improved. The improvement of m value indicated that the tensile strain was larger, the crack grew faster after cracks had occurred, namely the dynamic fatigue process and fatigue life being decreased with the increase of SBR content for pre-cut samples.

The Relationships Between H^{m}R and Abrasion Loss of NR/SBR Vulcanizates. The relationships between hardness–resilience product [$\log(H^4R)$] and abrasion loss (Akron and DIN) of NR/SBR vulcanizates were shown in Figure 4(a,b), respectively.



(a) Akron (b) DIN

Figure 4. Effects of $\log(H^4R)$ on the abrasion loss of NR/SBR vulcanizates.



(a) Akron (b) DIN

Figure 5. Effects of $\log(H^mR)$ on the abrasion loss of NR/SBR vulcanizates.

Table V. The Recipes of SBR/BR Compounds

	Composites (phr)							
Ingredients	1	2	3	4	5	6	7	8
SBR (1502)	100	80	70	60	40	30	20	0
BR (9000)	0	20	30	40	60	70	80	100
Carbon black(N330)	50	50	50	50	50	50	50	50
Sulfur	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
MBTS	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
CBS	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3
Zinc oxide	5	5	5	5	5	5	5	5
Stearic acid	3	3	3	3	3	3	3	3
Wax	1	1	1	1	1	1	1	1
Antidegradants 4010	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Antidegradants D	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

MBTS: 2,2′-dibenzothiazoledisulfde; CBS: *N*-cyclohexyl-2-benzothiazole-sulfenamide.

Table VI. The Physio-Mechanical Properties of SBR/BR Vulcanizates

	Compound no.							
Properties	1	2	3	4	5	6	7	8
Tensile strength (MPa)	23.7	21.3	19.8	18.6	17.6	15.2	15.4	13.0
100% modulus (MPa)	2.26	2.31	2.39	2.27	2.46	2.56	2.21	2.25
300% modulus (MPa)	9.01	8.81	9.09	8.22	8.62	8.87	7.06	7.64
Tear strength (kN/m)	60.7	53.4	58.5	53.4	52.3	49.8	49.3	50.3
Hardness (Shore A)	70	68	69	68	69	69	67	68
Resilience (%)	43	46	48	49	51	52	54	58
Akron abrasion (cm^3)	0.175	0.171	0.167	0.136	0.121	0.092	0.058	0.034
DIN abrasion (cm^3)	0.102	0.092	0.086	0.088	0.071	0.067	0.063	0.039

As observed from Figure 4, there were no obvious linear relationship between $\log(H^4R)$ and abrasion loss of NR/SBR vulcanizates, no matter Akron or DIN abrasion. However, when the exponent of hardness was changed from four to dynamic fatigue fracture parameters (m), the linear relationship became very good, especially for DIN abrasion, as shown in Figure 5(a,b). These results indicated that the hardness–resilience product defined as H^mR was more reasonable than H^4R.

The Relationships Between H^mR and Abrasion Loss of SBR/BR Vulcanizates

The recipes of SBR/BR compounds were shown in Table V, and only the ratio of SBR and BR being changed due to the similar curing rate of SBR and BR compounds.

The Physio-Mechanical Properties of SBR/BR Vulcanizates. The physio-mechanical properties of SBR/BR vulcanizates according to Table V were shown in Table VI.

As observed from Table VI, the tensile and tear strength decreased with the increase of BR content. With the increase of BR content, the resilience increased obviously, while the hardness changed little. The DIN and Akron abrasion resistance improved with the increase of BR content because of the better abrasion resistance of BR compounds than that of SBR.

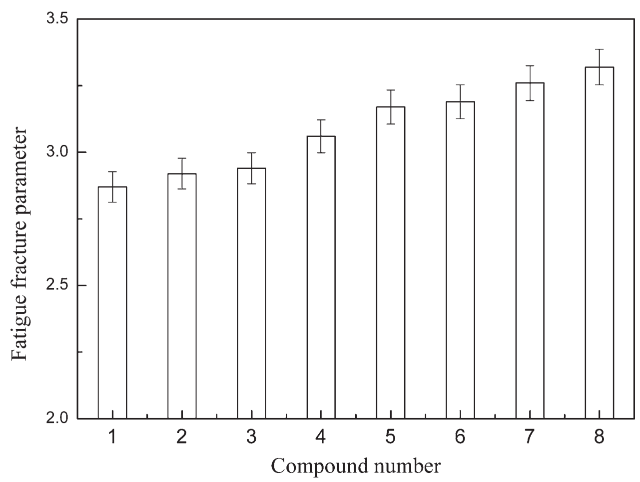
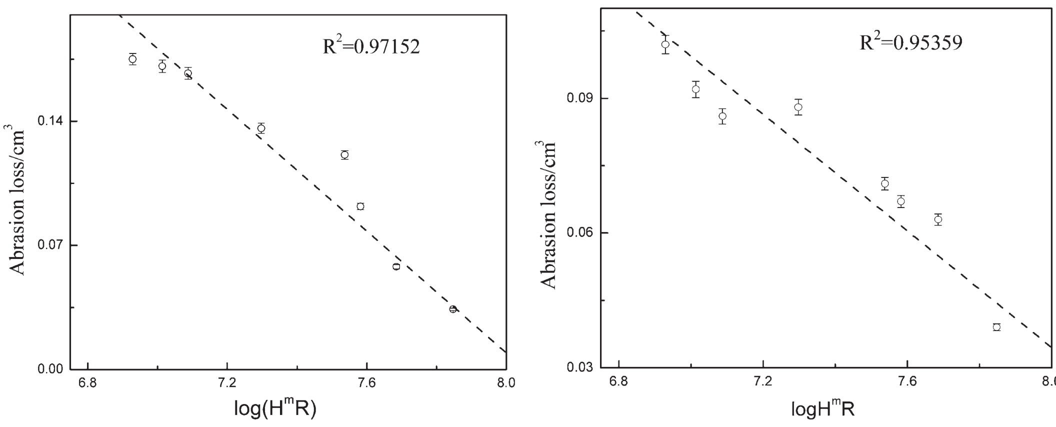


Figure 6. The dynamic fatigue fracture parameters of SBR/BR vulcanizates.



(a) Akron (b) DIN

Figure 7. Effects of log($H^m R$) on the abrasion loss of SBR/BR vulcanizates.

The Dynamic Fatigue Fracture Parameters of SBR/BR Vulcanizates. The dynamic fatigue fracture parameters (m) of SBR/BR vulcanizates obtained from *S–N* curves was shown in Figure 6.

The m value increased with the content of BR improved as shown in Figure 6, which indicated that the dynamic fatigue life decreased with the increase of BR content for pre-cut samples.

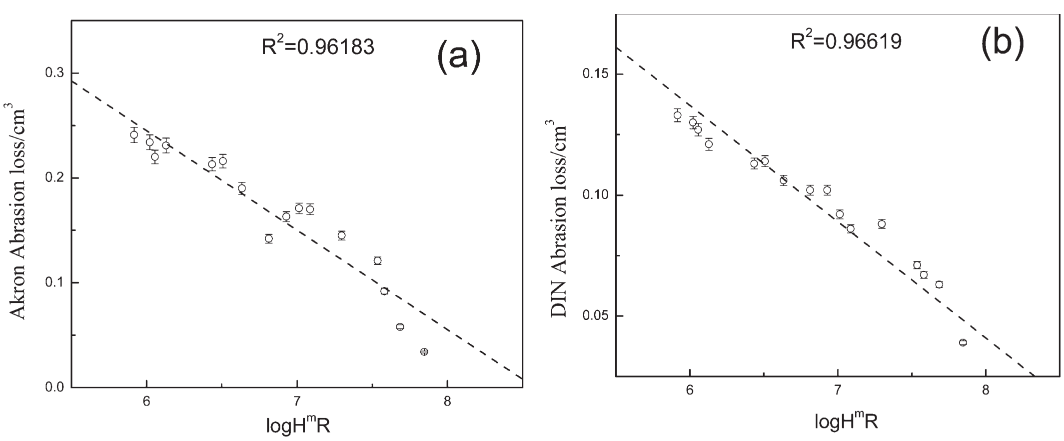
The Relationships Between H^mR and Abrasion Loss of SBR/BR Vulcanizates. The relationships between hardness–resilience product [log($H^m R$)] and abrasion loss (Akron and DIN) of SBR/BR vulcanizates were shown in Figure 7(a,b), respectively.

As observed from Figure 7, both Akron and DIN abrasion loss also had good linear relationship with log($H^m R$). To verify the universality of this relationship, for both NR/SBR and SBR/BR systems, when all the data were put together, the fitting curves of abrasion loss versus log($H^m R$) are shown in Figure 8(a,b) for Akron and DIN abrasion, respectively.

From Figure 8, it can be observed that, for both Akron and DIN abrasion, the abrasion loss had good linear relationships with its log($H^m R$) when the data for NR/SBR system and SBR/BR system were put together. These results indicated that the linear relationship between abrasion loss and log($H^m R$) had some universality.

CONCLUSIONS

The synergistic effects of hardness (H), resilience (R), and dynamic fatigue fracture parameters (m) on the Akron and DIN abrasion properties of NR/SBR and SBR/BR vulcanizates were investigated. The results showed that the linear relationships between log($H^4 R$) and abrasion loss only suited for SBR vulcanizates, but not suited for NR and BR vulcanizates. However, for NR/SBR system with different SBR content, compared with log($H^4 R$), when the exponent of hardness was changed from four to dynamic fatigue fracture parameters (m), the linear relationship became very good, no matter for Akron or DIN abrasion. This good linear relationship also appeared in SBR/BR system with different BR content. Furthermore, for both systems, when all the data were put together, the abrasion loss also had good linear relationships with its log($H^m R$) no matter Akron or DIN abrasion, which indicated that this linear relationship had some universality.



(a) Akron (b) DIN

Figure 8. Effects of hardness-resilience product on the abrasion loss for both NR/SBR and SBR/BR compounds.

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