

Cure Characteristics of Carbon Black-Filled Rubber Compounds Composed of NR, SBR, and BR

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NR, SBR, BR로 이루어진 고무배합물의 고무조성비에 따른 가황 특성

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ABSTRACT: Cure characteristics of carbon black-filled rubber compounds with different rubber composition were studied using a rheometer. The carbon black-filled rubber compounds with single, binary, and ternary rubber compositions of natural rubber (NR), styrene-butadiene rubber (SBR), and butadiene rubber (BR) were used. Delta-torques of the NR/BR- and SBR/BR-based compounds with a high BR content were higher than those of the single rubber-based compounds. For ternary rubber-based compounds, the delta-torques of the compounds were lower when the difference in the rubber content ratios was small than when it was big. Scorch and optimum cure times of the rubber compounds became shorter by increasing the content of NR in the compounds while those became longer by increasing the SBR content. Cure rates of the rubber compounds increased with a decrease of the SBR content in the rubber compounds. Reversion ratios decreased with an increase of the SBR content in the rubber compounds.

요약: 고무 조성비가 다른 카본블랙으로 보강된 고무 배합물의 가황 특성을 연구하였다. 한 가지 고무로 이루어진 고무 배합물, 두 가지 고무로 이루어진 고무 배합물, 그리고 세 가지 고무로 이루어진 고무 배합물을 실험 대상으로 삼았다. NR/BR과 SBR/BR 배합물 중에서 BR의 함량이 높은 것의 델타 토크는 단일 고무 배합물의 경우보다 높다. 삼중 고무 배합물의 델타 토크의 경우에는 세가지 고무의 함량비가 유사할수록 델타 토크가 낮아졌다. 스코치 시간과 적정 가황 시간은 NR이 증가할수록 빨라졌고 SBR이 증가할수록 느려졌다. 가황 속도는 SBR 함량이 증가할수록 느려졌다. 가교 역전(reversion) 현상은 SBR 함량이 증가할수록 감소하였다.

Keywords : rubber compounds, cure characteristics, NR, SBR, BR.

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I. Introduction

In general, rubber compounds are cross-linked by sulfur vulcanization,¹⁻³ peroxide curing,⁴ or resole curing.⁵ The sulfur vulcanization is the most popular method in a tyre industry. Degree and type of crosslink of a rubber vulcanizate determine physical properties of the vulcanizate such as modulus, hardness, resilience, elongation at break, heat build-up, and so forth. By increasing degree of crosslinking, modulus, hardness, resilience, and abrasion resistance are increased while elongation at break, heat build-up, and stress relaxation are decreased. By increasing in proportion of di- and polysulfides, stress relaxation, tensile strength, and resilience are increased while fatigue failure and thermal aging resistance are decreased. The vulcanization process produces several different crosslink structures including mono-, di-, and polysulfidic linkages. It is well established that the network structure varies with the time and temperature of vulcanization. Polysulfidic linkages are changed into mono- or disulfidic linkage as the vulcanization is proceeding. Reversion is speculated to occur when the desulfurization reaction is faster than the crosslinking reaction. Reversion occurs well in NR compounds.^{6,7}

A typical cure curve is divided into three regions of scorch delay, crosslinking, and reversion periods.⁸ The first region is the scorch delay period or induction period, in which the majority of the accelerator chemistry takes place. The second period is the crosslinking period, in which the initial

network structures are formed and the intermediated accelerators are consumed. The final stage is the overcure or reversion period, during which network maturation and resulting property deterioration occurs. Accelerated sulfur formulations are the most common vulcanization systems used in commercial and industrial applications. Because of this, there is a large body of ongoing work into both the fundamental and applied aspects of accelerated sulfur vulcanization.

Cure characteristics of a rubber compound depends on many factors of kind and content of rubber, filler, and curing agents. Cure characteristics and vulcanizate properties of rubber blends with binary rubber compositions were studied by several groups.^{9,10} Bhowmick and De⁹ studied the effects of cure temperatures of 150 and 180°C and cure systems of conventional and efficient vulcanization (EV) systems on cure characteristics and physical properties of rubber blends with a binary rubber base. Joseph and coworkers¹⁰ studied cure characteristics of 50/50 NR/SBR blend depending on cure system. Given the economic and technical uncertainties associated with synthesizing new polymeric materials, the utilization of polymer mixtures to achieve a desired combination of properties has obvious attraction. Blends of elastomers¹¹⁻¹⁴ are employed in rubber products for a variety of reasons which include improved physical properties, increased service life, easier processing, and reduced product cost.

In the present work, cure characteristics of carbon black-filled rubber compounds with

different rubber bases were studied using a rheometer. Cure characteristics of the rubber compounds with single, binary, and ternary rubber bases of natural rubber (NR), styrene-butadiene rubber (SBR), and butadiene rubber (BR) were compared.

II. Experimental

Carbon black-filled rubber compounds with single, binary, and ternary rubber compositions were prepared. Tables 1, 2, and 3 give formulations of the single rubber-based, binary rubber-based, and ternary rubber-based compounds of NR, SBR, and BR, respectively. Three single rubber-based compounds, twelve binary rubber-based compounds, and thirteen ternary rubber-based compounds were prepared. Three binary rubber bases of NR/SBR, NR/BR, and SBR/BR with the content ratios of 20/80, 40/60, 60/40, and 80/20 were used. For the ternary rubber-based compounds, the content ratios of the rubbers were NR/ SBR/BR = 1/1/1, 1/1/2, 1/2/1, 2/1/1, 1/1/0.5, 1/0.5/1, 0.5/1/1, 1/1/5, 1/5/1, 5/1/1, 1/1/0.2, 1/0.2/1, and 0.2/1/1. Among the three

Table 1. Formulations (phr) and cure characteristics of carbon black-filled rubber compounds with single rubber base.

Compound No.	S1	S2	S3
SMR 20	100.0	0.0	0.0
SBR 1500	0.0	100.0	0.0
BR 01	0.0	0.0	100.0
N330	50.0	50.0	50.0
ZnO	4.0	4.0	4.0
Stearic acid	2.0	2.0	2.0
Wax	2.0	2.0	2.0
HPPD	3.0	3.0	3.0
TBBS	2.0	2.0	2.0
Sulfur	1.2	1.2	1.2
Cure characteristics at 160°C			
T_{min} (N·m)	0.28	0.29	0.44
T_{max} (N·m)	2.29	2.19	2.57
t_5 (min)	1.58	3.62	2.40
t_{95} (min)	5.87	13.42	7.45
t_{min} (min)	0.48	0.38	0.58
t_{max} (min)	11.18	21.92	11.17
Cure rate (N·m/min)	1.33	0.44	0.89
Reversion ratio at $2t_{max}$ (%)	7.3	3.2	9.2

rubbers, the content ratios of two rubbers were the same and that of only the other one was different (variable rubber). The

Table 2. Formulations (phr) of carbon black-filled rubber compounds with binary rubber base.

Compound No.	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
SMR 20	80.0	60.0	40.0	20.0	80.0	60.0	40.0	20.0	0.0	0.0	0.0	0.0
SBR 1500	20.0	40.0	60.0	80.0	0.0	0.0	0.0	0.0	80.0	60.0	40.0	20.0
BR 01	0.0	0.0	0.0	0.0	20.0	40.0	60.0	80.0	20.0	40.0	60.0	80.0
N330	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
ZnO	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Stearic acid	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Wax	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
HPPD	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
TBBS	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sulfur	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Table 3. Formulations (phr) of carbon black-filled rubber compounds with ternary rubber base.

Compound No.	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
SMR 20	33.4	25.0	25.0	50.0	40.0	40.0	20.0	14.0	14.0	72.0	45.5	45.5	9.0
SBR 1500	33.3	25.0	50.0	25.0	40.0	20.0	40.0	14.0	72.0	14.0	45.5	9.0	45.0
BR 01	33.3	50.0	25.0	25.0	20.0	40.0	40.0	72.0	14.0	14.0	9.0	45.5	45.0
N330	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
ZnO	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Stearic acid	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Wax	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
HPPD	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
TBBS	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sulfur	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

content ratios of the variable rubber are 0.09, 0.20, 0.33, 0.50, and 0.72. In order to compare cure characteristics of the rubber compounds depending on only rubber base, contents of curing agents of stearic acid, zinc oxide, sulfur, and cure accelerator were fixed for all the compounds. Cure characteristics were obtained using a Flexsys rheometer (MDR 2000) at a frequency of 100 cycles/min and 1.5 arc at 160°C.

III. Results and Discussion

Scorch time (t_s), optimum cure time (t_{95}), cure rate (slope at t_{40}), maximum and minimum torques (T_{max} and T_{min}), delta-torque ($T_{max} - T_{min}$), and reversion are typical parameters describing cure characteristics of rubber compounds. The scorch time denotes a starting point of vulcanizing reaction. The slope at t_{40} was used as the cure rate. The delta-torque is the difference between the maximum and minimum torques ($T_{max} - T_{min}$). Reversion ratio was determined by dividing the difference between the maximum torque and the torque at $2t_{max}$ by the delta-torque. The t_{max} means the time at the maximum

torque.

Experimental results were summarized in Figures 1 - 10. Figures 1, 3, 5, 7, and 9 give variations of the cure characteristics of the binary rubber-based compounds (Compounds B1 - B12) as a function of the content ratio of rubber. Figures 2, 4, 6, 8, and 10 give variations of the cure characteristics of the ternary rubber-based compounds (Compounds T1 - T13) as a function of the content ratio of the variable rubber. The Compounds T11, T5, T1, T2, and T8 have the constant content ratio of NR and SBR and the BR is variable. The variable rubber content ratios are 0.09, 0.20, 0.33, 0.50, and 0.72, respectively. The Compounds T12, T6, T1, T3, and T9 have the constant content ratio of NR and BR and the SBR is variable. The Compounds T13, T7, T1, T4, and T10 have the constant content ratio of SBR and BR and the NR is variable.

1. Cure Characteristics of Single Rubber-Based Compounds

Cure characteristics of the carbon black-filled rubber compounds with a single rubber

base of NR, SBR, and BR are listed in Table 1. The t_5 and t_{95} of the NR compound are shorter than those of the SBR and BR compounds. Especially, the t_5 and t_{95} of the NR compound are much shorter than for the SBR compound by over twice. The t_{max} of the SBR compound is longer than those of the NR and BR compounds by about twice, while the cure rate of the SBR compound is slower than those of the NR and BR compounds by over twice. The cure rate of the NR compound is faster than those of the BR compound. This can be explained by the number of crosslinking sites. The sulfur crosslinking reaction occurs between allylic carbon.¹⁵ NR (polyisoprene) has three allylic carbon atoms per repeat unit ($-\text{CH}_2\text{C}(\text{CH}_3)=\text{CHCH}_2-$), while BR has two allylic carbon atoms per repeat unit ($-\text{CH}_2\text{CH}=\text{CHCH}_2-$). SBR has less allylic carbon atoms per repeat unit than BR, since SBR is a copolymer of styrene and butadiene, and styrene does not have any allylic carbon atoms. SBR used in this study has styrene content of 23.5 wt%. The reversion resistance of the SBR compound is much stronger than those of the NR and BR compounds. The reversion ratio of the SBR compound is smaller than those of the NR and BR ones by over twice.

2. Delta-Torque

Figures 1 and 2 give variations of the delta-torque of the binary and ternary rubber-based compounds with the rubber content ratio. For the binary rubber-based compounds, the delta-torques of the NR/BR compounds are higher than those of the

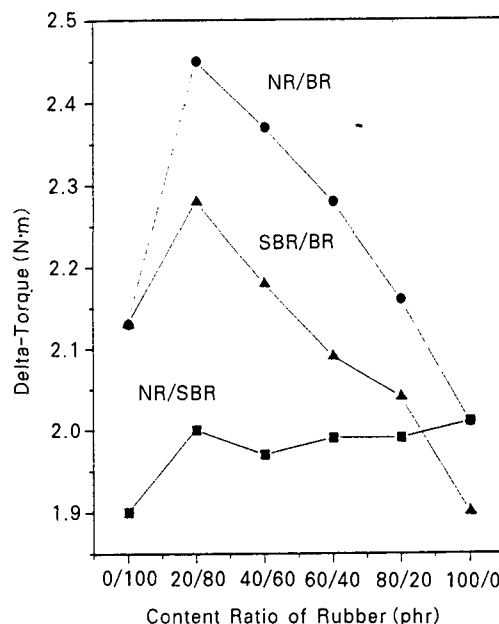


Fig. 1. Variation of the delta-torque of binary rubber-based compounds as a function of the rubber composition. Rectangles, circles, and triangles stand for NR/SBR, NR/BR, and SBR/BR compounds, respectively.

NR/BR and SBR/BR compounds. The delta-torques of the NR/BR blend compounds are higher than those of the BR single compound as well as that of the NR single compound. The delta-torques of the SBR/BR blend compounds with the content ratios of 20/80 and 40/60 are higher than those of the BR single compound as well as that of the SBR single compound. The delta-torques of the NR/BR and SBR/BR compounds with a high BR content are higher than those of the single rubber compound. This may be because cure synergy has occurred, i. e., co-curing produces higher states-of-cure in both phases. The delta-torques of the NR/BR

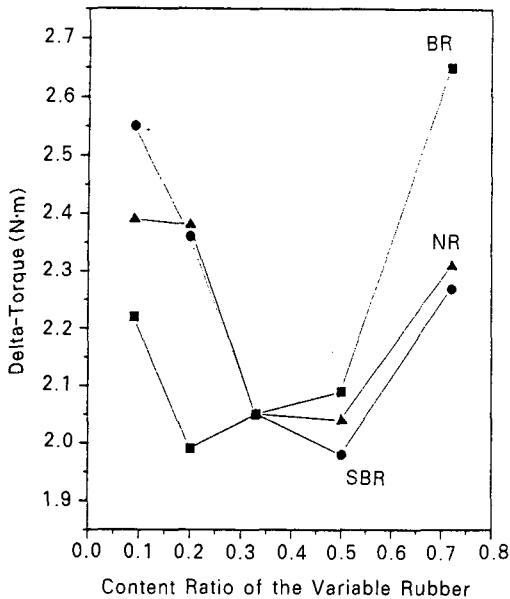


Fig. 2. Variation of the delta-torque of ternary rubber-based compounds as a function of the variable rubber content ratio. Rectangles, circles, and triangles stand for the constant content ratios of NR/SBR (variable BR), NR/BR (variable SBR), and SBR/BR (variable NR), respectively.

and SBR/BR compounds decrease continuously by decreasing the BR content. The delta-torques of the NR/SBR biblend compounds are similar to that of the NR single compound rather than that of the SBR single compound.

For the ternary rubber-based compounds, the delta-torque variations of the compounds with the variable rubber content ratio show local minima as shown in Figure 2. The delta-torque of the compounds with the variable BR increases from 1.99 to 2.65 N·m by increasing the variable rubber content ratio from 0.09 to 0.72. The delta-torques of

the compounds with the constant content ratio of NR/BR and SBR/BR decrease from 2.55 to 1.98 and from 2.39 to 1.96 N·m, respectively, by increasing the respective variable rubber content ratios from 0.09 to 0.50.

The delta-torques of the triblend compounds are lower when the difference in the rubber content ratios is small (Compounds T1 - T7) than when it is big (Compounds T8 - T13). The delta-torques of the NR/SBR biblend compounds are lower than those of the ternary rubber-based compounds with a low BR content (Compounds T9, T10, T11). This phenomenon is also observed in the SBR/BR and NR/BR biblend compounds compared to the triblend compounds with a low NR (Compounds T8, T9, T13) and with a low SBR (Compounds T8, T10, T12) contents, respectively. Thus, it can lead to a conclusion that the delta-torques of the biblend compounds are higher than those of the triblend ones with a small amount of the third rubber.

3. Scorch Time

Figures 3 and 4 give variations of the scorch time (t_s) of the binary and ternary rubber-based compounds with the rubber content ratio. For the binary rubber-based compounds, the t_s of the NR/SBR and NR/BR compounds, on the whole, become faster by increasing the NR content. The t_s of the NR/SBR compounds are between those of the NR and SBR single compounds. The t_s of the NR/BR compounds are also between those of the NR and BR single compounds,

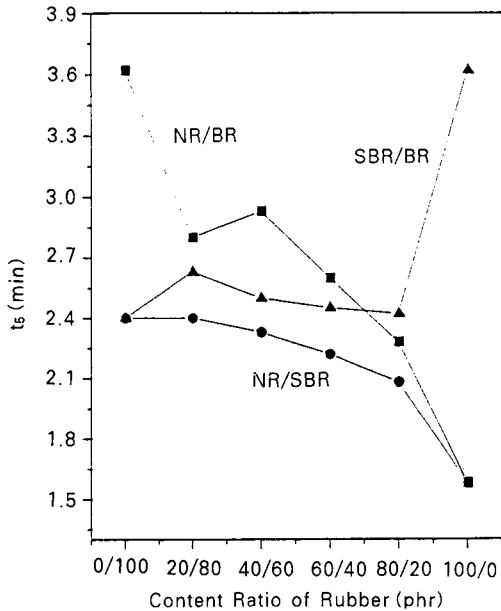


Fig. 3. Variation of the scorch time (t_s) of binary rubber-based compounds as a function of the rubber composition. Rectangles, circles, and triangles stand for NR/SBR, NR/BR, and SBR/BR compounds, respectively.

however, they are closer to that of the BR single compound rather than that of the NR one. The t_s of the SBR/BR compounds are between those of the SBR and BR single compounds, but it decreases slightly by increasing the SBR content from 20 to 80 phr. The t_s of the SBR/BR compounds are much closer to that of the BR single compound than that of the SBR one.

For the ternary rubber-based compounds, the t_s variations of the compounds with the variable rubber content ratio show local maxima as shown in Figure 4. The t_s of the compounds with the variable SBR increases from 2.42 to 3.33 min by increasing the

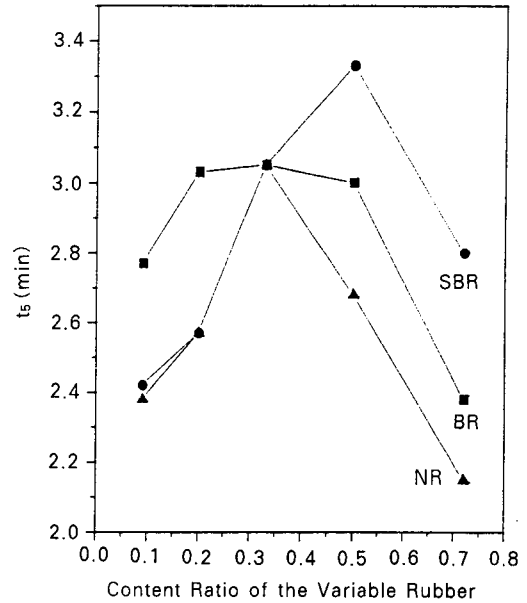


Fig. 4. Variation of the scorch time (t_s) of ternary rubber-based compounds as a function of the variable rubber content ratio. Rectangles, circles, and triangles stand for the constant content ratios of NR/SBR (variable BR), NR/BR (variable SBR), and SBR/BR (variable NR), respectively.

variable rubber content ratio from 0.09 to 0.50. The t_s of the compounds with the constant content ratio of NR/SBR and SBR/BR increase by increasing the variable rubber content ratios from 0.09 to 0.33 and then decrease from 3.05 to 2.38 and 2.15 min, respectively, by increasing the variable rubber content ratios from 0.33 to 0.72.

Of the ternary rubber-based compounds, the t_s of the compound T10 is the fastest. This is because the compound T10 has the most content of NR. The compounds with a high SBR content have slower scorch time than those with a high NR or BR content.

The t_5 of the compounds become faster with an increase of the NR content in the compounds. This implies that the scorch time mainly depends on the NR content in the compounds. This may be due to the short scorch time of the NR compound.

4. Optimum Cure Time

Figures 5 and 6 give variations of the optimum cure time (t_{95}) of the binary and ternary rubber-based compounds with the rubber content ratio. For the biblend compounds, the t_{95} of the NR/SBR and NR/BR compounds become faster by increasing the NR content. The t_{95} of the SBR/BR

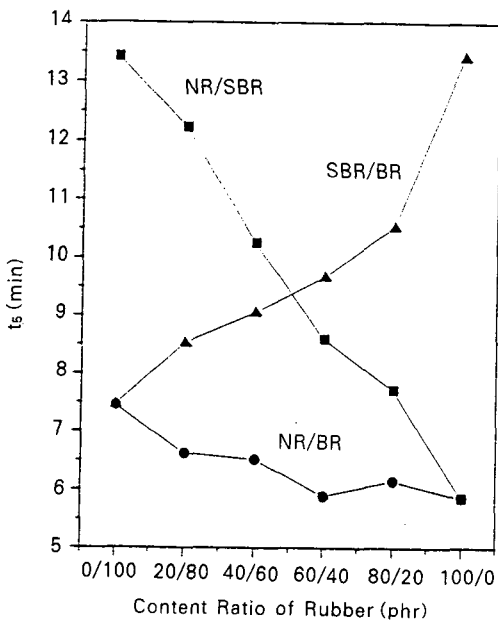


Fig. 5. Variation of the optimum cure time (t_{95}) of binary rubber-based compounds as a function of the rubber composition. Rectangles, circles, and triangles stand for NR/SBR, NR/BR, and SBR/BR compounds, respectively.

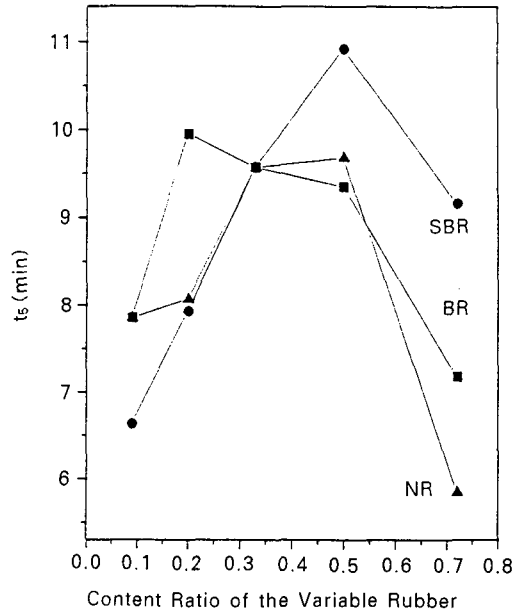


Fig. 6. Variation of the optimum cure time (t_{95}) of ternary rubber-based compounds as a function of the variable rubber content ratio. Rectangles, circles, and triangles stand for the constant content ratios of NR/SBR (variable BR), NR/BR (variable SBR), and SBR/BR (variable NR), respectively.

compounds increases with an increase of the SBR content. The t_{95} of the SBR/BR biblend compounds are between those of the SBR and BR single compounds, and are closer to the BR single compound rather than the SBR one. Difference in the t_{95} of the NR/BR compounds with the different rubber content ratio is much smaller than those of the NR/SBR and SBR/BR ones. This is because the difference of the t_{95} of the single rubber-based compounds of NR and BR is small by 1.58 min.

For the triblend compounds, the t_{95} variations of the compounds with the variable

rubber content ratio show local maxima as shown in Figure 6 as similar to the t_5 variations. The t_{95} of the compounds with the constant content ratio of NR/BR and SBR/BR increase from 6.63 to 10.92 min and from 7.85 to 9.68 min, respectively, by increasing the respective variable rubber content ratios from 0.09 to 0.50. The t_{95} of the compounds with the constant content ratio of NR/SBR decreases from 9.95 to 7.18 min by increasing the variable rubber content ratio from 0.20 to 0.72.

5. Cure Rate

Slopes at t_{40} were used as the cure rates. Figures 7 and 8 give variations of the cure rates of the binary and ternary rubber-based compounds with the rubber content ratio. The cure rates of the compounds decrease by increasing the SBR content in the compounds. This implies that the cure rate mainly depends on the SBR content in the compounds. This may be due to the very slow cure rate of the SBR compound. The cure rate of the SBR single compound is much slower than for the NR and BR ones by above twice as shown in Table 1.

For the binary rubber-based compounds, the cure rates of the NR/SBR and NR/BR compounds become faster by increasing the NR content. The cure rates of the NR/BR blend compounds are much closer to the NR single compound than the BR one. The cure rates of the NR/BR compounds are faster than that of the BR single compound by over 40%. The cure rates of the NR/SBR blend compounds are closer to the SBR

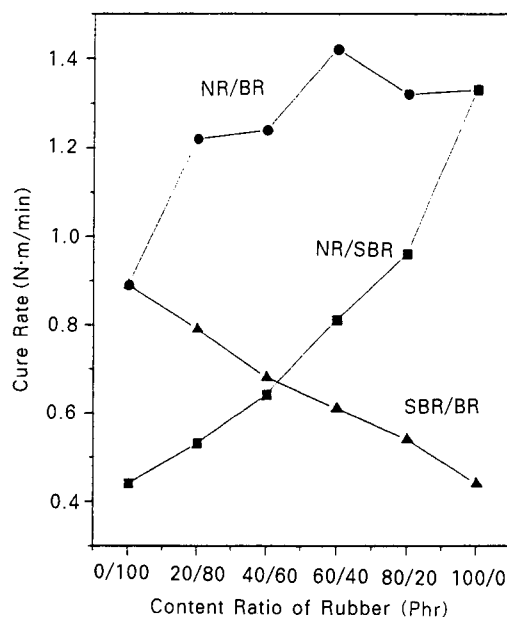


Fig. 7. Variation of the cure rate of binary rubber-based compounds as a function of the rubber composition. Rectangles, circles, and triangles stand for NR/SBR, NR/BR, and SBR/BR compounds, respectively.

single compound than the NR one. The cure rate of the SBR/BR compound decreases linearly with an increase of the SBR content.

For the ternary rubber-based compounds, the cure rate variations of the compounds with the variable rubber content ratio also show local minima as shown in Figure 8. The cure rate of the compounds with the constant content ratio of NR/SBR increases from 0.72 to 1.08 N·m/min by increasing the variable rubber content ratio from 0.20 to 0.72. The cure rate of the compounds with the constant content ratio of SBR/BR also increases from 0.76 to 1.33 N·m/min by increasing the variable rubber content ratio from 0.33 to

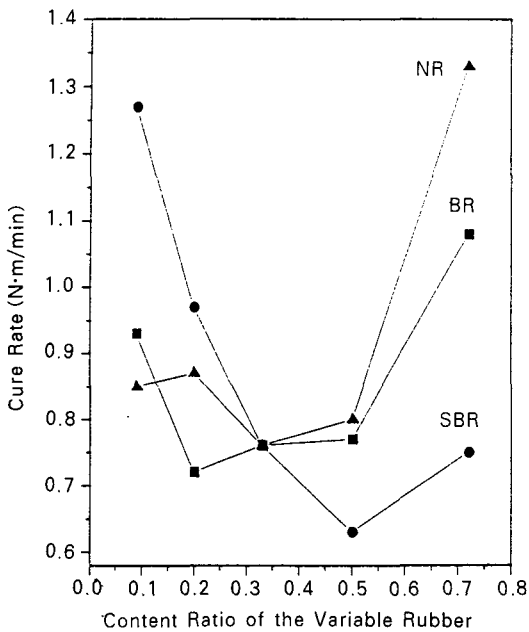


Fig. 8. Variation of the cure rate of ternary rubber-based compounds as a function of the variable rubber content ratio. Rectangles, circles, and triangles stand for the constant content ratios of NR/SBR (variable BR), NR/BR (variable SBR), and SBR/BR (variable NR), respectively.

0.72. The cure rate of the compounds with the constant content ratio of NR/BR decreases from 1.27 to 0.63 N·m/min by increasing the variable rubber content ratio from 0.09 to 0.50.

6. Reversion Ratio

In this study, the reversion ratios at $2t_{max}$ of the compounds were compared. Figures 9 and 10 give variations of the reversion ratios of the binary and ternary rubber-based compounds with the rubber content ratio. The reversion ratios of the compounds decrease

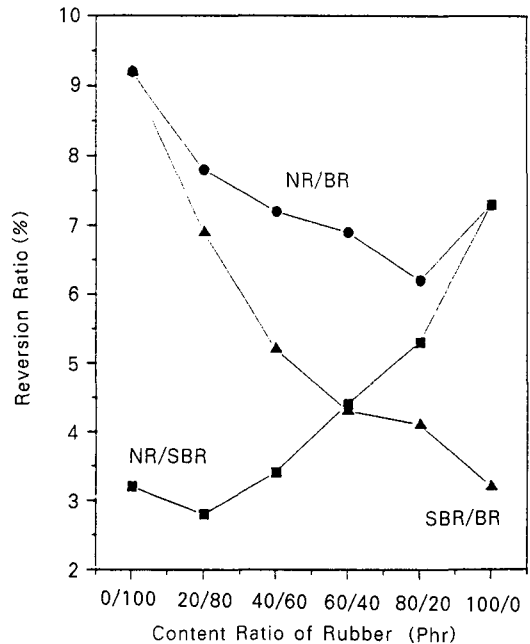


Fig. 9. Variation of the reversion ratio at $2t_{max}$ of binary rubber-based compounds as a function of the rubber composition. Rectangles, circles, and triangles stand for NR/SBR, NR/BR, and SBR/BR compounds, respectively.

by increasing the SBR content in the compounds. This implies that the reversion ratio mainly depends on the SBR content in the compounds. This may be due to the strong reversion resistance of the SBR compound.

For the binary rubber-based compounds, the reversion ratios of the NR/BR and SBR/BR compounds decrease by decreasing the BR content. The reversion ratio of the NR/SBR compounds increases by increasing the NR content. The reversion resistance of the NR/SBR and SBR/BR compounds becomes stronger with an increase of the SBR content. The reversion ratio of the 20/80 NR/SBR

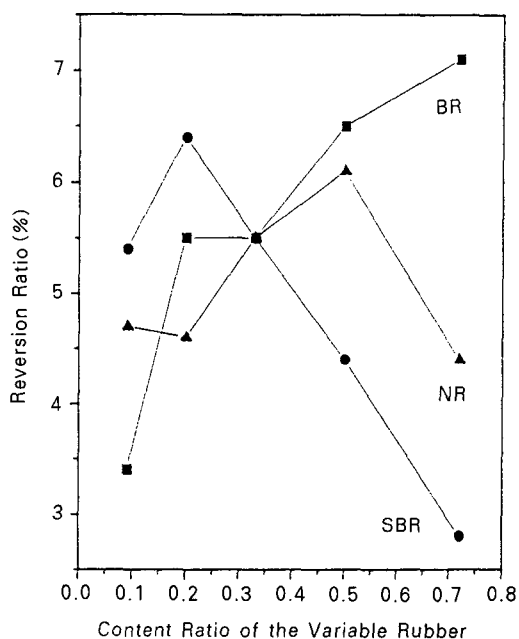


Fig. 10. Variation of the reversion ratio at $2t_{max}$ of ternary rubber-based compounds as a function of the variable rubber content ratio. Rectangles, circles, and triangles stand for the constant content ratios of NR/SBR (variable BR), NR/BR (variable SBR), and SBR/BR (variable NR), respectively.

compound is smaller than that of the SBR single compound. The reversion ratios of the NR/BR compounds with the content ratio of NR/BR = 60/40 and 80/20 are smaller than that of the BR single compound. This phenomenon is not observed in the SBR/BR blend compounds. The reason can not be explained exactly, but it can be considered that this is due to the immiscibility of NR with BR (or SBR). SBR is miscible with BR, while SBR and BR are not miscible with NR.¹⁶ In blend compounds of dissimilar rubbers, crosslink densities of the two phases are

different.¹⁷ Vulcanizing reaction occurs first in the phase with faster cure characteristics and the curatives migrate to the vulcanizing phase from the other phase. Thus, in the blend of dissimilar rubbers, the phase with faster cure characteristics has higher crosslink density than the phase with slower cure characteristics. It can be considered that the unbalanced distribution of curatives between the dissimilar rubber phases causes the abnormal behavior.

For the ternary rubber-based compounds, the reversion ratio of the compounds with the constant content ratio of NR/SBR, on the whole, increases from 3.4 to 7.1% by increasing the BR content ratio from 0.09 to 0.72. The reversion ratio of the compounds with the constant content ratio of NR/BR decreases from 6.4 to 2.8% by increasing the SBR content ratio from 0.20 to 0.72. The reversion ratio of the compounds with the constant content ratio of SBR/BR increases to 6.1% by increasing the NR content ratio to 0.50 and then steeply decreases to 4.4% at the NR content ratio of 0.72. This is not expected because NR does not have a good property for reversion resistance.

IV. Conclusion

Variation of cure characteristics of carbon black-filled rubber compounds was investigated with the rubber composition. The t_5 , t_{40} , t_{95} , cure rate, T_{max} , T_{min} , delta-torque, and reversion ratio were compared. The NR and BR compounds showed fast cure characteristics as compared to the SBR one. However, reversion property of the com-

pound improved by increasing the SBR content in the compound. Delta-torques of the NR/BR- and SBR/BR-based compounds with a high BR content were higher than those of the single rubber-based compounds. For ternary rubber-based compounds, the delta-torques of the compounds were lower when the difference in the rubber content ratios was smaller than when it was big. Cure times of the rubber compounds became shorter by increasing the content of NR in the compounds, while those became longer by increasing the SBR content. Cure rates of the rubber compounds increased with an decrease of the SBR content. Difference in the cure characteristics depending on the rubber composition was explained by the number of the active sites, miscibility of the blends, and co-cure effect.

References

1. N. J. Morrison and M. Porter, *Rubber Chem. Technol.*, **57**, 63 (1984).
2. R. W. Layer, *Rubber Chem. Technol.*, **65**, 211 (1992).
3. M. R. Krejsa and J. L. Koeing, *Rubber Chem. Technol.*, **66**, 3786 (1993).
4. S. K. Chakraborty, A. K. Bhowmick, and S. K. De, *J. Macro. Sci.-Revs. Macro. Chem.*, **C21**, 313 (1981-82).
5. M. van Duin and A. Souphanthong, *Rubber Chem. Technol.*, **68**, 717 (1995).
6. C. H. Chen, J. L. Koeing, J. R. Shelton, and E. A. Colins, *Rubber Chem. Technol.*, **54**, 734 (1981).
7. C. H. Chen, E. A. Collins, J. L. Koeing, and J. R. Shelton, *Rubber Chem. Technol.*, **55**, 1221 (1982).
8. M. R. Krejsa and J. L. Koenig, *Rubber Chem. Technol.*, **66**, 376 (1993).
9. A. K. Bhowmick and S. K. De, *Rubber Chem. Technol.*, **53**, 960 (1980).
10. R. Joseph, K. E. George, and D. J. Francis, *J. Appl. Polym. Sci.*, **35**, 1003 (1988).
11. G. R. Cotton and L. J. Murphy, *Rubber Chem. Technol.*, **61**, 609 (1988).
12. R. Joseph, K. E. George, and D. J. Francis, *J. Appl. Polym. Sci.*, **35**, 1003 (1988).
13. A. Y. Coran, and R. Patel, *Rubber Chem. Technol.*, **53**, 141 (1980).
14. W. M. Hess, P. C. Vegvari, and R. A. Swor, *Rubber Chem. Technol.*, **58**, 350 (1985).
15. A. M. Zaper and J. L. Koenig, *Rubber Chem. Technol.*, **60**, 252 (1987).
16. J. E. Callan, W. M. Hess, and C. E. Scott, *Rubber Chem. Technol.*, **44**, 814 (1971).
17. S. A. Groves, *Rubber Chem. Technol.*, **71**, 958 (1998).