Wear Characteristics of Styrene Butadiene Rubber/Natural Rubber Blends with Varying Carbon Blacks by DIN Abrader and Mining Rock Surfaces

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Received 1 December 2007; accepted 7 July 2008
DOI 10.1002/app.29128

ABSTRACT: In this study, nine rubber compounds were produced by varying the proportions of natural rubber (NR), styrene butadiene rubber (SBR), and four different carbon blacks. Tensile and tear properties are enhanced by the addition of intermediate super abrasion furnace (ISAF) N231, and modulus increases for the compounds containing N234 carbon blacks. The wear behavior of the prepared rubber vulcanizates against various rocks, such as, granite, shale, schist, sandstone, coal, and concrete, at 4.4 N normal load and 0.8 m/s relative sliding speed were studied in a specially fabricated experimental setup. The DIN abrasion testing results show good abrasion resistant properties of 70 phr NR and 30 phr SBR with N231 grade ISAF type carbon black. Also, moderate abrasion resistance is found in rubber compound containing 80 phr NR and 20 phr SBR with N234 grade ISAF type of carbon black. Out of the various rock types, the schist and sandstone are observed to be highly abrasive against the prepared rubber compounds. The microscopic examination of the abraded rubber surfaces has indicated the formation of longitudinal grooves against harder rocks and transverse ridges against softer rocks. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 111: 348–357, 2009

Key words: elastomers; fillers; mechanical properties; wear; DIN abrasion; rocks

INTRODUCTION

Tires used in mining vehicles are very costly and need regular maintenance, as it is impossible to accept its replacement expense within very short term. The rugged working conditions in mining industries reduce the life span of tires on account of cuts, contamination, abrasion, wear, speed fluctuations, etc. There are several types of damage that occur in the dump-truck tire, such as tread detachment, sidewall cuts, impact ruptures, bead damage, etc. For transportation of minerals from one place to another, the wear and abrasion must be filled by changing of tire compounds. The simplest form of wear, which is particularly important in the friction of rigid materials, is abrasive wear and this had also been observed previously[1–4] as the wear governed by the abrasion of the surface layer of materials by the sharp edges of hard projections from the rough surface of the abradant. An increase in the abrasion resistance of rubber products can be achieved by studying the mechanism of wear of rubber under different operating conditions. The mechanism of wear provides a link between the abrasion resistance of rubber and its mechanical properties, which will predict the life of a product in service and also develop the method of testing abrasion.

The wear of rubber is a complex phenomenon and dependent on a combination of processes such as mechanical, mechanochemical, thermochemical, etc. Schallamach[5] and later, Grosch and Schallamach[6] reviewed abrasion of rubber and tire wear. Schallamach[5] suggested that the saw teeth were bent back and abraded from thin underside until torn off. Champ et al.[7] and Thomas[8] suggested that abrasion takes place through a cyclic process of cumulative growth of cracks and tearing. As regards to physical ideas on the nature of abrasion, Kragelskii and Nepomnyashchil[9] and Schallamach[10] were the first to examine the simple case of the failure of rubber by the action of a hard projection moving over its surface. It has been observed[10] that during intense abrasion in sliding contact, a high temperature is developed, and consequently the abrasion resistance of the rubber depends, to a large extent, on its resistance to high temperature and heat. During abrasion, ridge formation takes place on the rubber surface, which is indicative of the mechanism of wear.[11] The coefficient of friction can also be expressed as a

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Contract grant sponsor: Coal India Limited, Kolkata.

Journal of Applied Polymer Science, Vol. 111, 348–357 (2009)

function of the elastic and hysterics properties of rubber and of the configuration of the abrading surface.[9,12] Of the various types of wear, the prominent wear observed in rubber and rubber products are the fatigue wear, abrasive wear, and wear by means of roll formation.[13] Hence the aim falls in developing products and improving their service conditions, so that abrasion wear and wear through roll formation cannot occur. Bhowmick[14] observed that ridges were formed by coalescence of particles. Southern and Thomas[15] described the mechanism of pattern formation, and Medalia et al.[16] discussed the same for tank track pads during abrasion on asphalt roads.

Investigations by Viswanath et al.[17] and Rymuza[18] show that the wear dynamics of polymer–polymer and polymer–metal systems are determined by the properties of the polymer such as surface energy, modulus of elasticity, specific heat, thermal conductivity, and various operating conditions. Ratner,[19] Lewis,[20] Rhee,[21] Lancaster,[22] Atkinson,[23] and others have developed various forms of equations and relationships for the wear of polymers. All these models have expressed variables such as load/pressure, speed, sliding length, sliding duration, and also include properties such as hardness of the counter face, asperities height, shear strength of the polymer, etc. Schallamach[24] explained the linear relation of wear to pressure by abrasive wear. There were many contradictions to this theory.[25] Ratner[26] has demonstrated that increase in the material's elasticity and decrease in the roughness of the hard surface promotes the formation of cross bands. Some Russian workers referred the frictional wear by roll formation.[27–30]

To overcome all these problems, in this investigation, nine sets of rubber compounds in varying compositions of styrene butadiene rubber (SBR) and natural rubber (NR) in addition with different filler particles were prepared. These rubber compounds were examined in a specially fabricated experimental setup for evaluating their wear resistance properties when abraded against various rock types. The parameters such as influence of composition of rubber vulcanizates on wear characteristics and the mechanism of wear of these compounds against different rocks are reported.

MATERIALS AND METHODS

Materials

The SBR used was Krylene HS 260, No. 5 of 1948 grade of Bayer AG. Its styrene content is 23.5 ± 1.0, specific gravity is 0.94, and Mooney viscosity at 100°C is 50 ± 5.

Natural rubber (NR-RMA1X) was supplied by the Rubber Board, Kottayam, Kerala. Zinc oxide, stearic acid, and antioxidant (HQ) was supplied by Bayer (India) Ltd. Standard rubber grade aromatic oil, *N*-cyclohexyl-2-benzothiazyl sulfonamide (CBS) was procured from the local market. Carbon black was purchased from the Birla carbon.

Cure characteristics of rubber compound

The cure characteristics of the rubber compound were studied with the help of a Monsanto oscillating disc rheometer (ODR-100 s), which complies with ASTM D 2084 at 150°C. From the graphs, the optimum cure time and scorch time could be determined.

Mechanical characterization (tensile and tear) of rubber compound

Vulcanized slabs were prepared by compression molding, and the dumbbell-shaped specimens were punched out from a molded sheet by using ASTM Die C. The tests were done by means of a universal tensile testing machine (Hounsfield H10KS) under ambient condition (25 ± 2°C), following the ASTM D 412-99 and ASTM D 624-99. The moduli at 300% elongation, tensile strength, tear strength, and elongation at break (%) were measured at room temperature. The initial length of the specimens was 25 mm, and the speed of the jaw separation was 500 mm/min.

Five samples were tested for each set of conditions at the same elongation rate. The values of the tensile strength, modulus at 100% elongation, 200% elongation, and elongation at break were averaged. The relative error was below 5%. The shore A hardness was measured.

Preparation of vulcanized rubber

The compounding formulation for the SBR rubber and natural rubber blends with its various ingredients were mixed in a two roll mill at a friction ratio of 1 : 2 following standard mixing sequence. The cure characteristics of the rubber compound were studied with the help of Monsanto ODR-100 s at 150°C. From the graphs, the optimum cure times were determined.

DIN abrasion test

DIN abrasion test was done by the DIN abrasion tester for determining the abrasion resistance of compounds of vulcanized rubber recommended by the Indian Standards Institution vide IS:3400 (Part 3)-1987.

The experimental setup

The experimental setup as shown in Figure 1 is designed to rotate a circular rubber-coated

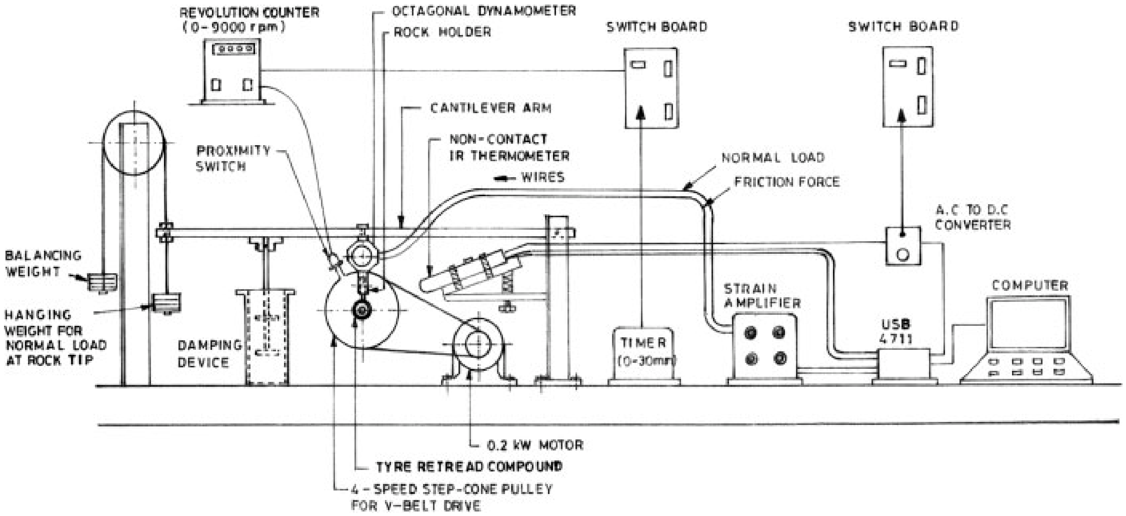

Figure 1 Schematic diagram of the total arrangements in the experimental setup.

aluminum disc against a rigidly held rock sample under variable applied normal load and sliding speeds. The rotation of the rubber disc was provided through a single-phase 0.2 kW electric motor, and a four-speed step-cone pulley was so adjusted as to provide four different speeds of the bigger pulley shaft. The rock sample holder was connected to a long cantilever arm through an octagonal ring-type dynamometer. For a simultaneous measurement of frictional and normal forces developed at the rubber-rock interface during dynamic contact process, this octagonal dynamometer was fabricated with least cross-sensitivity and it enables the measurement of one force independent of the other. Three circular discs suspended from the cantilever beam were kept immersed inside an oil-filled container for damping the vibration generated due to stick-slip phenomenon in frictional sliding process. In this setup, instrumentation was provided to control the duration of contact by a timer and to measure the number revolution of the rubber disc using a proximity switch. Normal load was applied at the rubber rock interface by hanging weights at the free end of the cantilever beam. The actual normal load acting at rock–rubber interface could be obtained from a calibration chart that was prepared with the help of measured load cell readings at the tip of rock sample corresponding to different hanging weights.

The noncontact temperature measuring arrangement

The noncontact infrared temperature probe made by METRAVI used with a test instrument capable of measuring DC volts in the millivolt range (220 mV/400 mV/2 V/4 V/6 V range) such as a digital multimeter. The probe has a temperature range of 30–550°C (−22 to 1022°F), with a basic accuracy of 2% of reading, and an output of 1 mV dc per °C or °F.

The probe is rigidly attached to the static frame of the setup and kept pointed at a portion of the rotating rubber wheel close to the rock–rubber interface. The data acquisition system connected to the setup can thus be set to record the temperature rise of the rubber sample during its frictional contact with different rocks dynamically at a rate as low as five readings per second.

Data acquisition system and the software

The Advantech USB-4711 is a powerful data acquisition (DAS) module for the USB port. It features a unique circuit design and complete functions and control. In the tailor-made software, named "MiDAS," the device from the list and the number of channels should be at first selected, by which the software will work. Then, the range of voltages corresponding to the ranges of normal and frictional forces will be assigned to the software. Pressing the

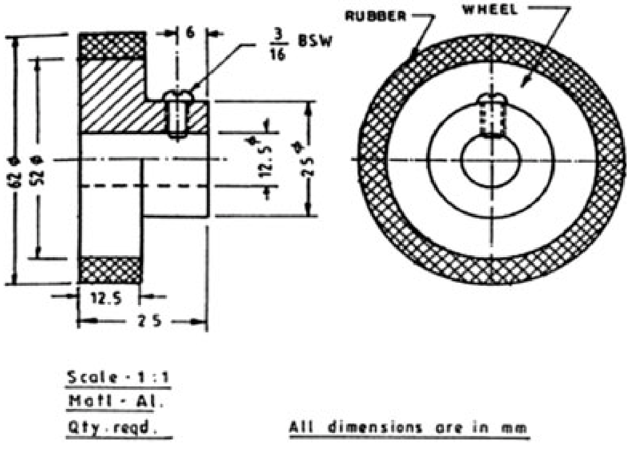

Figure 2 Sectional view of the rubber-coated aluminum disc.

TABLE I
Formulation of the Rubber Compound

Ingredients		A	B	C	D	E	F	G	H	I
		Content in phr[a]								
Natural rubber (NR)		80	80	80	90	90	90	70	70	70
Styrene butadiene rubber (SBR)		20	20	20	10	10	10	30	30	30
Carbon blacks	1. SAF[b] (N110)	20	–	–	20	–	–	20	–	–
	2. SRF[c] (N774)	20	–	–	20	–	–	20	–	–
	3. ISAF[d] (N234)	–	40	–	–	40	–	–	40	–
	4. ISAF[d] (N231)	–	–	40	–	–	40	–	–	40
Stearic acid		2	2	2	2	2	2	2	2	2
Antioxidant (HQ)[e]		1	1	1	1	1	1	1	1	1
Accelerator (CBS)[f]		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Zinc oxide		5	5	5	5	5	5	5	5	5
Process oil–Elasto 710		2	2	2	2	2	2	2	2	2
Sulfur		1	1	1	1	1	1	1	1	1

Sample codes: A–I

[a] phr, parts per hundred parts of rubber.
[b] SAF, super abrasion furnace.
[c] SRF, semi-reinforcing furnace.
[d] ISAF, intermediate super abrasion furnace
[e] HQ, hydroquinone.
[f] CBS, *N*-cyclohexyl-2-benzothiazyl sulfenamide.

"Run" button, the value in temperature bar in degree Celsius, value in horizontal force bar in Newton and value in vertical force bar in Newton will be automatically displayed in the computer monitor. Also number of revolutions of the rubber disc, data acquisition rate, and time of running will be displayed by the software. After the desired rpm or time is completed, "Stop" button should be pressed to stop the data acquisition by the software and pressing the "Save" button, the result will be automatically saved in an excel file with desired file name including date and time of the experiment.

From the experimental data, the volume loss of the rubber and dynamic coefficient of friction of the rock–rubber interaction can be calculated. Different graphs showing the variation of normal force, frictional force, and interface temperature with time can also be plotted.

Preparation of rubber specimen for abrasion test

The rubber specimens were prepared by molding with a circular aluminum disc of 44 mm diameter, 12.5 mm thickness in a press at 150°C to its optimum cure time, obtained from the Monsanto ODR-100 s. The hub of the aluminum disc has a collar of 12.5-mm thickness with a central hole of 12.5-mm diameter. The disc can be mounted on the step-cone pulley shaft by means of a 3/16″ BSW set screw. The outer diameter of the circular rubber disc is 62 mm, and the other dimensional are shown in the Figure 2.

Rock sample preparation

The rocks collected from nearby mines were cored with impregnated diamond coring bit of 22-mm diameter. The concrete core samples and physical properties have been collected from the Hindustan Construction (HCC), NH-6, WB-11, Road Project (Kolaghat, KGP), Vill. Rupnarayanpur, P.O. Jakpur, Dist. Midnapore (W), Pin 721301, W.B. The cylindrical core is cut along a plane normal to the axis. The length of the core sample was kept between 40 to 60 mm for proper grip in the three-screw type clamp of the rock holder.

TABLE II
Properties of Carbon Black

Name	Abbreviation	ASTM designation	Particle size in nm	Tensile strength in MPa	Relative laboratory abrasion	Relative road wear abrasion
Super abrasion furnace	SAF	N110	20–25	25.2	1.35	1.25
Intermediate SAF	ISAF	N231, N234	24–33	23.1	1.25	1.15
Semi-reinforcing furnace	SRF	N774	70–96	14.7	0.48	0.60

TABLE III
Properties of the Rubber Vulcanizates

Parameters	Rubber compounds								
	A	B	C	D	E	F	G	H	I
Scorch time (min)	2	3	3	2	3	4	2	3	3
Optimum cure time (min)	10	8	9	11	8	9	10	8	9
Specific gravity	1.14	1.13	1.14	1.17	1.16	1.17	1.11	1.10	1.11
Hardness (shore A)	65–67	75–77	65–70	44–50	58–62	54–58	77–79	82–84	78–80
Tensile strength (MPa)	14.9	16.2	17.0	13.2	13.1	17.9	15.4	15.5	19.6
Tear strength (N/mm)	29.3	50.4	70.4	28.8	26.1	33.7	30.5	32.48	73.00
Elongation at break (%)	925	871	1084	1054	988	1210	952	875	986
300% modulus (MPa)	2.94	4.8	3.29	2.12	2.71	2.51	4.20	5.07	5.18

Experimental procedure for investigation of wear of rubber

The full arrangement of the experimental setup during wear testing of the rubber sample is shown in Figure 1. At first, rubber disc was fixed tightly to the shaft of the step-cone pulley by the set screw. The smoothly cut rock sample was then clamped in the rock holder. The length of projected portion of the rock sample outside the rock holder was adjusted so as to obtain a reading of 2.5 mm on the dial gauge attached to top surface of the cantilever beam which ensure its horizontality.

Total weight of 250 g was placed on the hanger of the cantilever beam, so as to produce normal load of 4.4 N at the rock–rubber contact, and the test run was conducted for 500 revolutions with sandstone sample placed in the rock holder. The temperature, normal load, and frictional force were recorded on the computer during the wheel rotation. The procedure was repeated on rubber discs of different SBR-NR combination with carbon black variation using other types of rocks as abrader. The mass loss of the rubber samples after 500 revolutions (M_{500}) was measured at room temperature and dynamic coefficient of friction (μ) and abrasion loss (V) were computed.

Studies on abraded surface

Small portions of the tested specimens were cut and gold-coated for examining the nature of abraded surfaces under a scanning electron microscope (JSM-5800 of JEOL; acceleration voltage: 20 kV) at a magnification of 500. The ridge patterns of the worn rubber samples when abraded against different rocks were then compared.

RESULTS AND DISCUSSIONS

Compound formulation

Compounding formulations as shown in Table I were based on blending of the SBR and NR. For vulcanization, the amounts of additives such as sulfur, carbon black, process oil, and CBS were based on 100 g of rubber, and the samples have the code name "A," "B," "C," "D," "E," "F," "G," "H," and "I," respectively.

The physical properties of the different types of carbon black used in this study have been given by the industry and are depicted in Table II.

- N110 gives maximum abrasion resistance, highest reinforcement, and tensile. It is used in off-the-road tire treads, tread rubber, bridge pads, and conveyor belts.
- N231 gives low structure, high abrasion resistance, and used mainly in OTR tires where resistance to tear is important.
- N234 provides superior abrasion resistance versus N220. Excellent wear and extrusion properties typical of improved process high structure blacks. It is used in all elastomers, especially SBR/BR blends for treads and tread rubber.

TABLE IV
Physicomechanical Properties of Rocks and Concrete

Properties	Limestone	Sandstone	Granite	Coal	Shale	Schist	Concrete
Specific gravity	2.33	2.08	2.74	1.15–1.5	2.17	2.3–3.3	2.57
Compressive strength (MPa)	53.78	44.98	169.78	30.69	48.50	40.00	–
Tensile strength (MPa)	5.88	4.97	9.02	1.14	4.63	5.77	5.5
Cohesion (MPa)	10.0	17.0	33.0	2.00	4.00	1.10	–
Static Young's modulus (GPa)	42.5	41.9	93	11.0	12.5	27.0	–
Poisson's ratio (μ)	0.27	0.28	0.33	0.40	0.32	0.22	–
Shore hardness	30.2	41.1	77.0	20.0	36.9	30.1	35.0

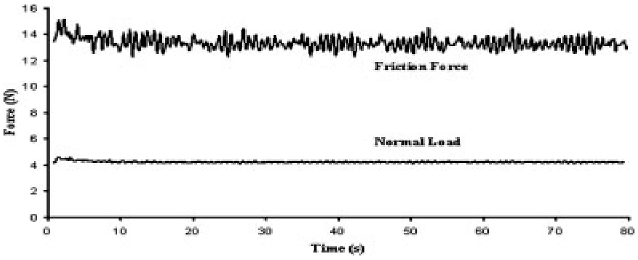

Figure 3 Variation of normal and frictional forces with time during sliding friction of rubber "A" with sandstone.

- N774 moderate reinforcer gives high resilience and excellent dynamic properties, low hysteresis, high loadings obtainable. It is used in tire carcasses and sidewalls, extruded goods, belts, and hose. It is also used in plastics color concentrate.

The physicomechanical properties of the prepared rubber blends have been investigated by Monsanto ODR in Mining Engineering Department, IIT, Kharagpur, and are depicted in Table III. The optimum cure time for A, D, and G rubber sample is higher than other rubber vulcanizates because of the mixing of N110 + N774 carbon black with SBR and NR. Tensile strength, modulus, elongation at break, and tear strength for all the compounds are shown in Table III. The tensile and tear strength of the compounds containing carbon black ISAF N231 in the system is higher, which may be due to the outstanding reactivity of the carbon black acting as filler, and increases the mechanical properties of the samples. This trend is seen throughout the system. In case of modulus at 300%, the compounds containing carbon black ISAF N234 shows superior properties. Overall mechanical properties are enhanced by the use of ISAF N231 and N234 carbon blacks with rubber vulcanizates.

Physicomechanical properties of rock

All the physicomechanical properties, which were considered to be influencing the wear of rubber in some way or the other, as well as those properties

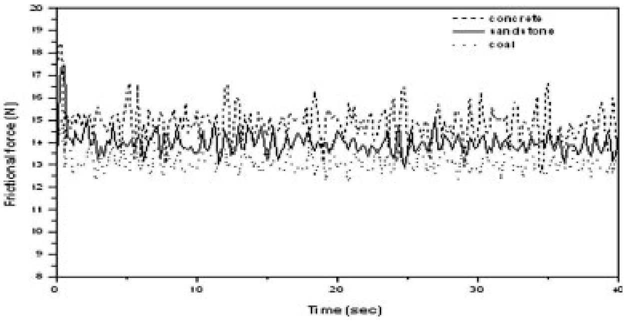

Figure 4 Frictional force versus time of the rubber compound "A" with varying rock types.

TABLE V
Dynamic Coefficient of Friction μ at 4.4 N Normal Load

S. No.	Rocks	Mean and standard deviation of μ for different rubber compounds								
		A	B	C	D	E	F	G	H	I
1.	Coal	2.97 ± 0.10	3.06 ± 0.18	3.09 ± 0.17	3.15 ± 0.08	3.15 ± 0.08	3.00 ± 0.10	3.22 ± 0.17	3.23 ± 0.11	3.27 ± 0.15
2.	Concrete	3.32 ± 0.20	3.36 ± 0.16	3.80 ± 0.17	3.86 ± 0.17	3.96 ± 0.16	4.08 ± 0.20	4.24 ± 0.19	3.73 ± 0.82	3.00 ± 0.09
3.	Granite	3.45 ± 0.15	3.68 ± 0.09	4.09 ± 0.17	4.05 ± 0.15	3.32 ± 0.29	3.47 ± 0.15	3.89 ± 0.22	3.59 ± 1.73	4.35 ± 0.29
4.	Sandstone	3.16 ± 0.11	3.32 ± 0.13	3.46 ± 0.12	3.82 ± 0.12	3.98 ± 0.15	4.41 ± 0.21	4.52 ± 0.40	4.66 ± 0.34	4.22 ± 0.37
5.	Schist	3.34 ± 0.15	3.44 ± 0.81	2.07 ± 2.12	4.45 ± 0.23	5.01 ± 0.30	4.77 ± 0.87	5.31 ± 0.33	5.37 ± 0.34	5.19 ± 1.93
6.	Shale	3.12 ± 0.12	3.57 ± 0.18	3.84 ± 0.16	3.78 ± 0.19	3.82 ± 0.67	3.80 ± 0.15	4.30 ± 0.15	5.52 ± 0.16	5.03 ± 0.25

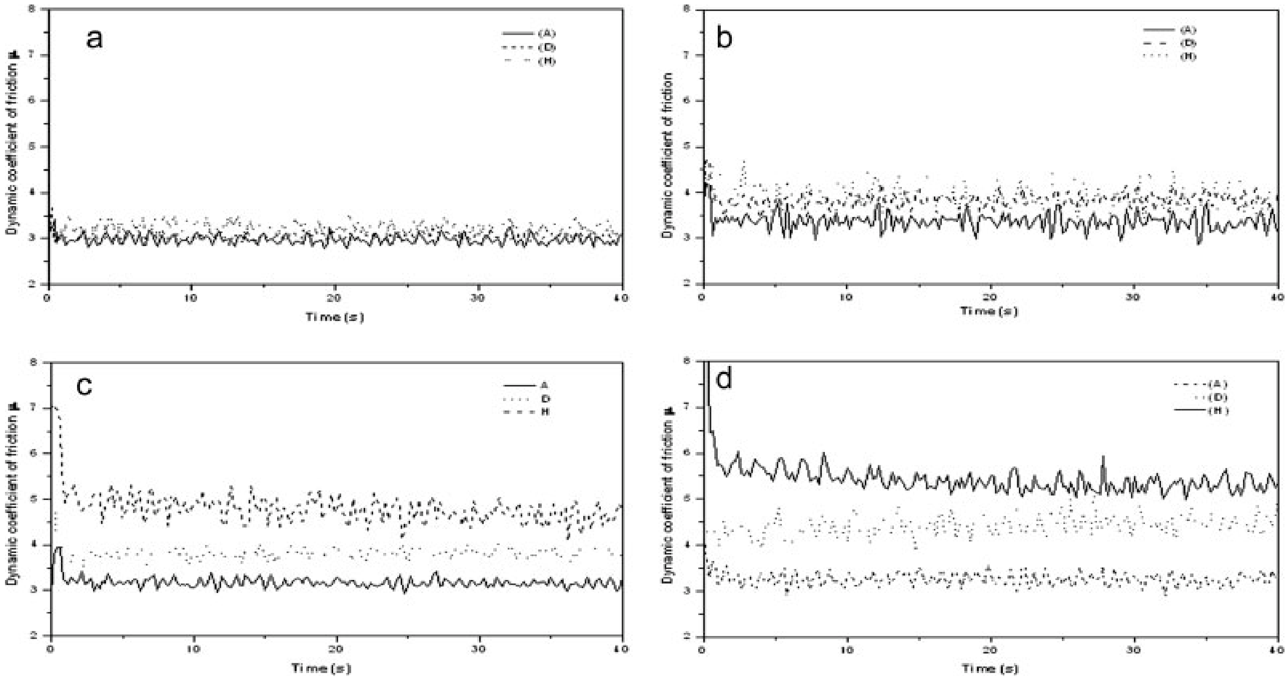

Figure 5 Dynamic coefficient of friction of the rubber compounds with varying rocks: (a) coal, (b) concrete, (c) sandstone, and (d) schist.

essential for characterizing the rocks, were determined by the Universal Testing Machine (UTM) of 50 tonne capacity, in Mining Engineering Department, IIT, Kharagpur, as per the norms recommended by International Society of Rock Mechanics (ISRM) and American Society of Testing Materials (ASTM). Values of different physical properties of rocks and concrete are given in Table IV. Concrete sample has been taken not to confine the study in the mining area as well as to elaborate it for the general purpose.

Rock–rubber abrasion results

The dynamic nature of the variation in normal and frictional forces is depicted in Figure 3. The amplitude of variation in normal force is smaller due to the damping effect in vertical direction produced by the oil dash pot deployed for the purpose. The variation of the frictional force over a mean value clearly indicates the nature of stick-slip process during sliding friction.

As shown in Figure 4, the frictional force for rubber “A” is higher in case of its abrasion against concrete, followed by sandstone, and the lowest value of frictional force is observed in coal. Although both concrete and sandstone are of nearly similar hardness and strength, the roughness of concrete surface is more, thereby causing generation of higher magnitude of frictional force. Coal is a softer rock and gets abraded along with rubber during the frictional contact. A layer of abraded coal surface is created at the

TABLE VI
Temperature Ranges of Different Rubber Samples During Abrasion Against Rocks

	Temperature ranges (°C) up to 500 revolutions at 4.4 N normal load					
Sample code	Sandstone	Concrete	Granite	Schist	Shale	Coal
A	29–123	30–123	29–113	30–135	30–97	30–160
B	28–132	29–129	28–117	30–104	29–72	28–136
C	29–151	28–94	29–121	30–138	28–76	29–126
D	30–158	30–102	28–93	29–156	28–89	29–154
E	28–143	29–106	28–84	30–123	29–83	30–147
F	29–126	30–103	29–123	28–143	30–135	28–161
G	30–122	28–83	29–94	30–127	28–134	30–89
H	30–116	29–83	29–85	30–103	28–89	30–75
I	30–140	29–138	28–88	30–86	28–94	30–82

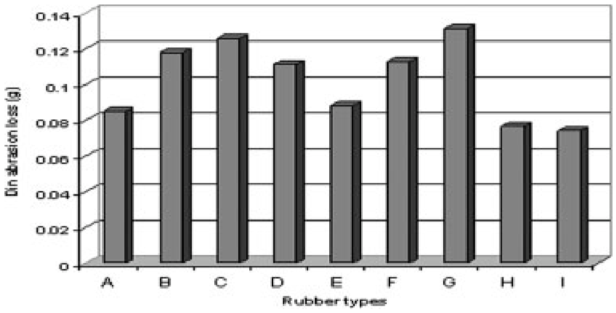

Figure 6 DIN abrasion values of different compounds.

friction interface, which often leads to lower magnitude of frictional force. During longer duration of frictional contact, a sticky tarry layer at the interface is generated, which sometimes leads to relatively higher magnitude of frictional force. Table V shows the dynamic coefficient of friction μ for different rock–rubber combinations under 4.4 N normal loads and at 0.8 m/s of relative sliding speed. In general, the rubber compounds "H," "I," and followed by "G" have produced higher values of μ for all types of rocks. Lower values of μ have been observed in rubber compounds "A." The μ values in other rubber compounds fall in the intermediate zone. The Compounds "H" and "I" containing carbon blacks N231 and N234 along with increased amount of SBR in NR have probably lead to a tougher rubber that can produce high friction during wear. The rubber compound "A" produces a lesser friction because of the variation in carbon black (N110 and N774) and lower content of SBR in NR. Regarding the variation in rock types during abrasion against different rubber compounds, the schist rock has produced highest μ values, whereas coal has produced the lowest μ values. A thin oily layer between the coal and rubber surface was visible at the time of abrasion. It is interesting to note that the wear in this study is directly influenced by the coefficient of friction. Higher the coefficient of friction, higher is the wear. Figure 5 shows the dynamic variation of μ values for "A," "D," and "H" type of rubber compounds, when abraded against four different types of rocks.

Temperature generation at rock–rubber interface

Table VI shows the range of temperature generated during friction of rocks with different rubber compounds. In general, the temperature generation has been found to be higher in case of the rubber compounds containing N231 type ISAF carbon black.

The temperature generation during friction in rubber compound "A" is slightly lower, which may be attributed to the presence of SRF N774 type of carbon black. The highest temperature was observed when rubbers are abraded against coal surfaces, whereas the lowest temperature could be noticed for shale. For other rocks, the temperature generation was found to be in the moderate range.

Mass loss of rubber compounds

Figure 6 refers to the DIN abrasion test result in terms of mass loss of rubber compounds. Compounds H and I show higher abrasion resistance mainly due to the presence of 30 phr of SBR in NR. The Compound A also exhibited good abrasion resistance, which also has 20 phr SBR blended with NR.

Figure 7 shows the abrasion loss of different rubber compounds when abraded against various rocks. Out of all types of rocks, the schist has been identified as the major abrader for almost all types of rubber compounds excepting the I type. The rubber compound I is found to be the toughest rubber against all rock types under this study. Coal being the softest rock causes least abrasion to all types of rubber compounds. Sandstone is another rock that

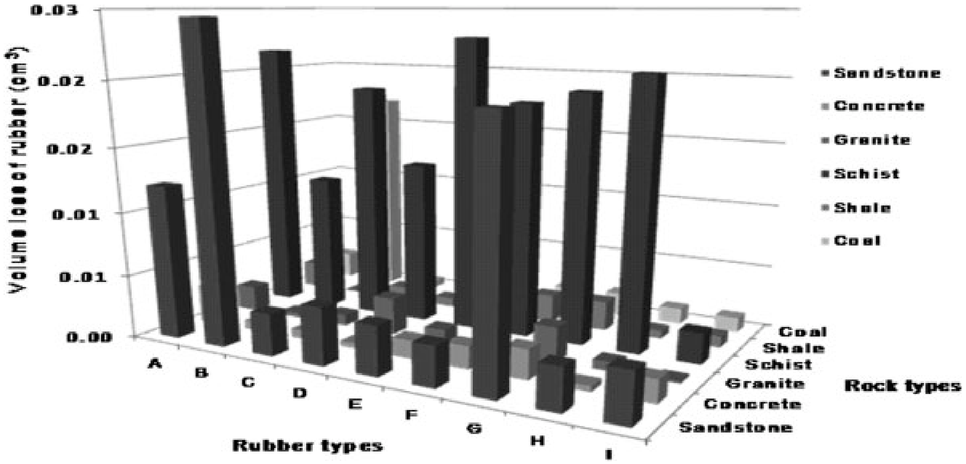

Figure 7 Volume loss of rubber compounds with different rock types.

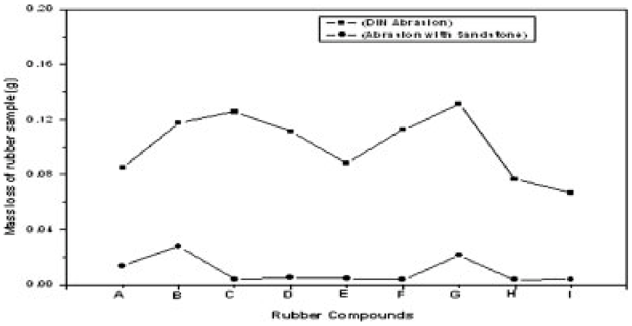

Figure 8 Comparison of mass losses of rubber "I" in DIN abrader against sandstone.

has abraded almost all the rubber compounds extensively and may be considered as an important rock for rock–rubber abrasion studies. A comparison between the DIN abrasion loss and the mass loss of rubbers against sandstone has been shown in Figure 8, which indicates a fairly good correlation between the two.

Microscopic examination of abraded rubber surface

Figure 9(a–d) shows the pictographs of the abraded surfaces rubber compound I by different rocks. As observed in Figure 9(a), both abrasive furrow and uneven ditches from tearing of rubber are typical in the case of schist rock, which has the ability to tear apart almost all type of rubber compounds under consideration. Sandstone rock [Fig. 9(b)] has created only abrasive furrow in the rubber surface and therefore it can also produce devastating wear in the rubber compounds. The softer rocks like shale and coal, as shown in Figure 9(c,d), only produce transverse ridge patterns during wear. Since, the samples have higher coefficient of friction, the abrasion of those rubber vulcanizates by the rock surface is less, which may be further responsible for the higher ridge spacing.

CONCLUSIONS

The overall results indicate that, out of nine SBR/NR blends with different types of carbon black, the Compounds H and I containing 70 phr NR and 30 phr SBR has ability to resist wear against most of the hard rocks. The coefficient of friction has also been found to be higher in the same rubber compounds. Out of different rocks, schist and sandstone has been found to cause high μ values against the toughest rubber. The same rock has also been responsible for causing devastating wear to the tougher rubber compounds. The temperature generation in rubber compounds during their frictional contact with different rocks is found to be higher in rubber compounds containing N231 grade ISAF carbon black. Also, friction of rubbers against coal has been found to be producing much higher temperature at friction interface probably due to some thermochemical reaction between abraded coal and rubber surface. From the examination of the abraded surface, it may be inferred that abrasive wear due to

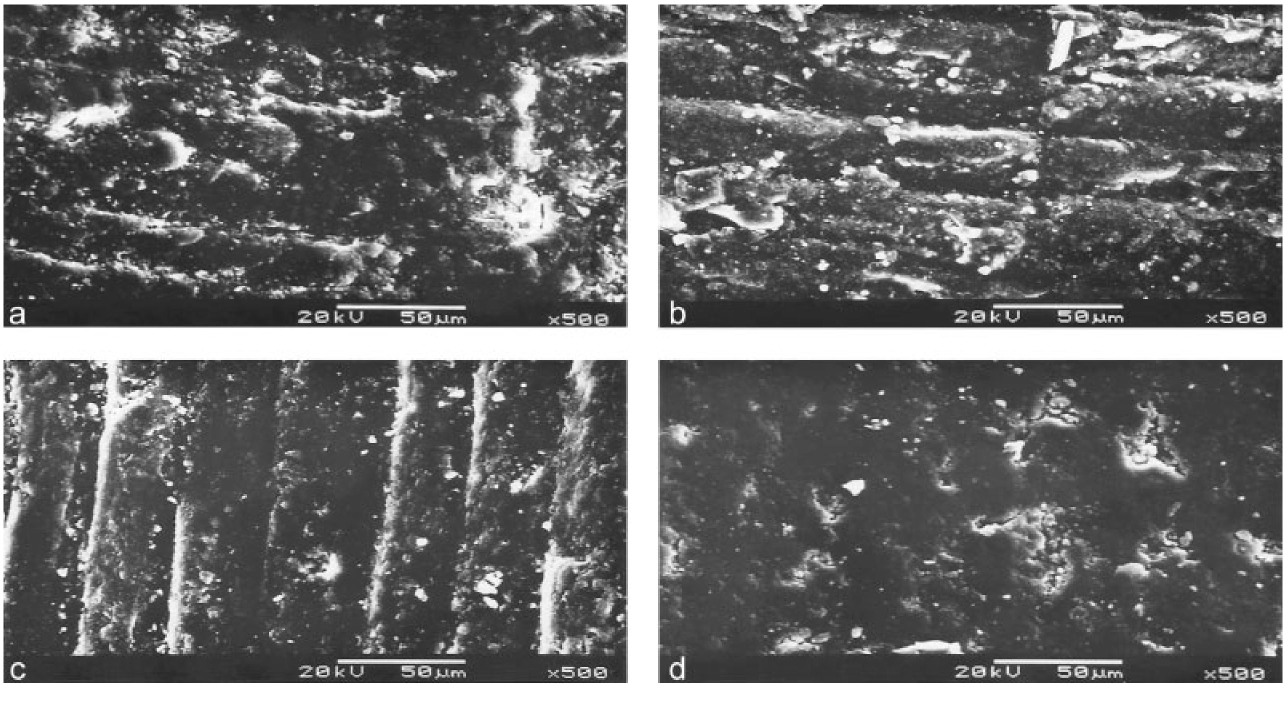

Figure 9 SEM photographs of some abraded rubber samples when abraded against (a) schist, (b) sandstone, (c) shale, and (d) coal.

longitudinal furrows are responsible for high abrasion loss of rubber compounds against sandstone and schist. Transverse ridge patterns have been very well developed against shale, whereas against coal, these ridges are weak and hidden under the layer of the worn out coal particles strongly adhering to the rubber surface.

The authors thank all members of the R and D project and laboratory personnel of Materials Science Centre and Central Research Facility at IIT, Kharagpur.

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