ISSN 1392-1134/ eISSN 2345-0371
Agricultural Engineering, Research Papers, 2019, Vol. 51, 1 – 9

TRENDS IN TRIBOLOGICAL RESEARCHES OF DIFFERENT RUBBERS USED IN ENGINEERING

Abhijit Mukhopadhyay
Associate Professor, Mechanical Engineering Department, Jadavpur University, Kolkata, India

Abstract: Rubber is an important elastomer used in engineering and several other applications where friction and wear are involved. In this juncture of hours several newer developments of rubber composites are going on in different parts of globe along with several modifications in their properties. This necessitates the tribological studies of this dominant elastomer. However, rubber tribology is a very complex problem owing to its viscoelastic property and there are hardly any models which can predict closely the tribological characteristics of a particular type of rubber under a particular work environment. Thus, individual researches and development of test rigs are important for the property prediction. This paper is intended for an overview of recent trends in rubber modifications and tribological researches around the globe. The paper also highlights the experimental studies of an indigenous EPDM rubber tribology done by the author. The conclusions are made accordingly.
Keywords: EPDM rubber, wear, friction.

Received 2019-09-18, accepted 2019-12-27

Introduction

Use of different kinds of rubber in engineering, domestic, sports and several other applications are worth mentioning. However, it must be admitted that the use of rubber is gaining importance in the recent time due to various property enhancements through novel reinforcement techniques. This has initiated several need based researches in this field for the past few decades. Amongst various types of synthetic rubbers Ethylene Propylene Diene Monomer, ‘EPDM’, is the fastest growing elastomer since its inception in 1963. Study of friction and wear of EPDM rubber is of great practical importance in the context of conveyor belts, wiper blades, door and window seals in automobiles, bungee jump chord application and many more. They are subjected to wear and tear due to pressure, vibration, friction and exposure to extreme conditions of atmosphere [1–4, 8, 18 and references there in].

Movement in the forward direction can only be achieved by the property friction, but during a motion, friction is responsible for some permanent losses like energy dissipation, mass loss, movement loss, heat generation and so on. Therefore, friction is the process where both the positive and negative effects are prominent. In certain situations, a large frictional force is not only desirable but an essential minimum; on the contrary, in some other situations small friction force is required [5].

It has been mentioned earlier that there are several applications of different kinds of rubber. However, majority of them includes but not limited to automotive industries, conveyor belts, electric cable covers and footwear. Understanding friction and wear mechanisms as well as flow behaviour of rubber material is essential for accurate modelling and evaluation of tribological properties. However, knowledge on the tribological behaviour of viscoelastic materials like rubber is limited in spite of several research works in this area till date. Friction, wear and flow behaviour of rubber is very complex due to the viscoelasticity and depends on the variation of a single parameter of the rubber composition. Beside the laboratory test conditions like temperature, humidity, normal load, rolling speed of the reference wheel, abrasive grit size and so on, the viscoelastic behaviour of the particular material as well as the type of test rigs also play a dominant role in the friction, wear and flow characters of the said material. A general conclusion regarding a rubber material and tribological characteristics can hardly be validated [2, 6]. Assessment of such parameters for each individual rubber composition is thus necessary. This is the motivating factor of conducting individual research regarding the friction, wear and flow characteristics of any rubber, particularly for indigenously developed rubber. Such characteristics of an indigenous EPDM rubber, used widely in automobile industries, have been studied experimentally by the present author and reported accordingly [7, 8, 10, 11, 18].

Experimental Researches

Forward motion during walking is a result of tribological interactions between the shoe/footwear and the floor materials. Hence, understanding the friction and wear of concerned mating pairs and their adequate design is very important to prevent slip and fall accidents. D.Stamenkovic et al. [5] had conducted research work in this area and presented some overviews of the existing standards in this regard. Major attention in their study has been given on the measurement of static frictional force between footwear samples and floor materials. Static frictional force can be measured just immediately before the initiation of the forward sliding motion and in the very next moment this force falls under kinetic frictional force.

It has been stated in a research report by Health and Safety Executive, UK that approximately 11000 workers had serious injury due to slip in UK during 2007. There are several standards of expressing slip resistance of flooring materials and footwear. However, due to very complex interactions and involvement of different factors it is hardly possible to predict the actual data. This necessitates continual tribological researches on different footwear and flooring materials combinations. D.Stamenkovic´ et al. have selected new flat rubber, new rubber with relief, worn rubber and leather as sole material against laminate plate, matt ceramic tiles and gloss ceramic tiles as the flooring materials. Tribological studies had been conducted in dry, wet and soap lubricated conditions considering different mating combinations of the materials. Their observations reveal that static friction coefficient values are random and unpredictable and no unique decisions could be taken. Hence, it is a potential area of further researches considering various other mating combinations and environmental conditions along with the development of measuring systems and suitable test rigs.

D.M.Bielinski et al. of Poland [19] had stated about some rubber modifications in their review work on current trends in rubber tribology. A ceramicazable silicon rubber composite, a dispersion type of materials, is suitably used as electric cable covers. Due to the formation of ceramic shield on the external surface heat dissipation is minimized and the cables are protected from fire up to the melting point of the inner copper wire. Ion bombardment, through an ion beam focused on the rubber surface, energizes rubber to release hydrogen and further modification of rubber takes place. They have also demonstrated the influence of ageing on micro hardness of rubber nanocomposites. Needless to be mentioned that thermal cycle or ozone are mainly responsible for rubber surface ageing and this phenomenon is particularly important in aerospace and transportation application. Surface sensitivity analysis like micro hardness test gives a firsthand impression about ageing which then initiate further detailed study and preventive measures.

It has already been mentioned that major use of rubber is involved in automotive industries. Modern vehicles are associated with increased speed, loads and engine power. Disc pads are required to with stand high and stable friction coefficient and the wear rate should also be low. Benzoxazine resins are used as a better alternative of commonly used thermosetting binders and reduce micro voids in the structure. Disadvantages like brittleness and short shelf life are also rectified. Amine terminated butadiene acrylonitrile copolymer (ATBN) modification of rubber has also been reported. In their recent studies, C.Jubsilp et al. have experimented on the effect ATBN modifications on polybenzoxazine. Along with the overall improvement of thermal and mechanical properties, the tribological properties of this copolymer are also enhanced compared to those of the purepolybenzoxazine. The coefficient of friction is reported as about 0.32 with the ATBN contents in the range of 1–5% [20]. Kumar S et al. have initiated a study at IIT Dhanbad to observe the tribological behaviours and optimize the weight percentage of SBR rubber, used as an organic binder, along with other components in the break pad material. The targeted composite padding material will have grey cast iron as its mating pair. Another important elastomer ethylene propylene diene monomer (EPDM) has wide application in automotive industries as seals in different parts. Flow behavior, friction and wear characteristics under different experimental conditions of an indigenous EPDM rubber have been studied extensively by the present author and results have been published accordingly [7, 8, 10, 11, 18]. Experimental procedures have been accomplished utilizing the instruments like Instron, Abrasive wear tester, Multi tribo-tester, SEM/EDAX etc.

Tribological properties of water lubricated rubber after modification by MoS_2 nanoparticles have been studied by Dong C et al. in China. They have studied the worn surface morphology due to frictional vibration and noise in under water application. Submarine includes rubber stern tube bearings, an important part of the propulsion system. Due to poor lubrication and operating factors (like low speed, frequent starting and stopping, heavy load etc.) in this particular part severe stick-slip induced vibration and noise may be generated which ultimately pose a severe threat to the submarine. In their studies, Dong C et al. have modified Nitrile Butadiene Rubber (NBR) with flaky as well as spherical MoS_2 nanoparticles and the developed composites have been slid against $ZCuSn_{10}Zn_2$, which is used as stern shaft material, under water lubricated condition [21]. Needles to be mentioned that molybdenum disulphide (MoS_2) is a good solid lubricant and used as an additive.

Sivaraos et al. in Malaysia have conducted one need based and interesting work of recycling waste tire rubber. Addressing the burning global issue of environment and waste minimization, they have utilized the waste rubber tires as the reinforcing material. 0% to 40% of such powder had been reinforced with polypropylene matrix and the developed composites had been tested for friction and wear characteristics using pin-on-disc tribometer. The composite shows an enhanced coefficient of friction over pure polypropylene [22].

Various industrial applications are associated with very small cycle vibrational amplitude for long time, known as fretting. During fretting, heat generation at mating surfaces leads to oxidation corrosion while stress concentration yields surface cracks. Cracks are gradually enlarged leading to wear. Thus fretting is a serious concern for engineering applications. D.K.Baek et al. of USA took up a research work on friction and wear studies of rubber coating during fretting. The fretting experiments had been performed with thin rubber coated surface against steel counterpart. The tribological data had also been compared with the fretting test results between steel to steel surfaces. Parameters like load, displacement amplitude and oscillating velocity had been considered at different levels in the study [23].

Researchers from Austria, South Korea and Germany jointly conducted theoretical as well as experimental studies on rubber friction on ice at different conditions of ice surface roughness [24]. This is an important real life application area because icy road surfaces (particularly during winter in cold countries) and automobile tires combination may lead to fatal failures due to friction and wear. Thus, the understanding is need based and important too.

As mentioned earlier that there are many fold applications of rubber. One such application is in the field of sports. Table tennis racket is one example where several researchers are going on. Varenberg et al. had researched on the performance of table tennis racket's rubber covering surface against the sliding of the ball considering three factors like friction, stickiness and grip [25]. In such determination they had utilized a homemade tribometer which includes mainly two units- driving and measuring units.

Rubber bearing applications have been studied by A.E.Martinelli [30]. The study of friction, wear and lubrication that means tribology, is also important in case of viscoelastic materials like rubber. The importance of tribological studies had been stated long time back by Peter Jost [29]. Researchers have also demonstrated the way of finding out coefficient of friction [27, 28].

The author of the present paper has studied the abrasive wear of EPDM rubber of three different hardness values namely 55 Å, 70 Å and 85 Å. Carbon black has been added in different proportions (parts per hundred) to vary the hardness. The samples have been prepared in the laboratory of National Engineering Ltd. (Rubber) of Kolkata, mixing the ingredients EPDM gum, ZnO, stearic acid, PEG 400, FEF 550, P oil, sulphur, HBS, TMT etc. The actual proportions can't be disclosed due to the privacy policy of the company. The ingredients, as mentioned, have been mixed thoroughly in a laboratory inter mix (K4/2A–MK3; Alfred Herbert) and curative have been added in a two-roll laboratory mill (φ330×φ150) at room temperature. Molding of the samples have been done as per IS: 3400 (part–X)–1977 following the rheometric analysis. Molding has been done in a steam heated hydraulic press (Hydromech and Pneumatics pvt. Ltd., India) [7 and references there in].

Studies for abrasive wear and wear by roll formation have been carried out by the present author utilizing a two-body abrasion tester 'TR–605' (Ducom) as per ASTM D 6037 (Test method B) and/or ISO 8251 [9, 10] for abrasive wear test and a multi tribo-tester 'TR–25' (DUCOM) for the wear by roll formation in the laboratories of Jadavpur University, Kolkata. The tribotester is supported with

‘Winducom 2006’ software for the analysis of various tribo parameters. Block-on-roller configuration of the said tester has been utilized for the experimental purpose. Samples have been slid against EN–8 stainless steel roller of 50 mm diameter and hardness of 52 HRC [11].

Results And Discussions

In this section brief discussion on some important findings, not all, are presented. Majority of them are on EPDM rubber tribology as conducted by the present author. The intention of the discussion is to shed light on the main area of interest and how different rubber behaves in such characterization.

Different flow characteristics of EPDM rubber have been shown in Table 1. Percentage hysteresis gives a very important property ‘damping’ of rubber, has been noticed to be maximum in EPDM 70 and water combination whereas minimum in EPDM 55 and grease combination. No trend has been noticed in any set of experiments for this parameter. The loss factors are ‘low loss’ type (less than ‘1’) for all combinations of EPDM and lubricants. Considering all the dimensions, it may be stated that

Table 1. Different flow characteristics of EPDM rubber during compression.

Flow Parameters	Compression Condition														
	Dry			Fixed Contact			Talc			Water			Grease		
	55	70	85	55	70	85	55	70	85	55	70	85	55	70	85
Load at 50% deflection (KN)	2.7	4.1	16.6	1.8	3.2	13	2.7	3.9	16	2	3	12	1.7	2.5	–
True stress at 50% deflection	2.1	3.2	10	1.3	2.4	9.9	2.1	3.2	12	1.5	2.3	9.3	1.3	2.6	–
True stress at a true strain of 0.7	2.2	3.5	12.5	9.9	2.4	1.3	2.1	3	12.3	1.5	2.3	8.8	1.3	1.9	–
% Hysteresis	33.6	77.3	20.9	21.2	60.8	38.6	23.9	75.9	25.5	36.5	81	43	19.4	71.6	–
Loss Factor	0.3	0.8	0.2	0.2	0.5	0.4	0.2	0.8	0.3	0.4	0.9	0.4	0.1	0.4	–

EPDM 70 and water combination is better for hysteresis requirement, EPDM 55 and grease combination is suitable for low loss factor and EPDM 55 with water combination is better from minimum strain energy point of view. The selection of a particular EPDM – lubricant pair depends on the specific requirement and should be done judiciously.

The nature of all the experimental hysteresis curves shows a perfect banana shape which is theoretically correct. One set of such curve, for EPDM 85 Å has been shown in figure 1.

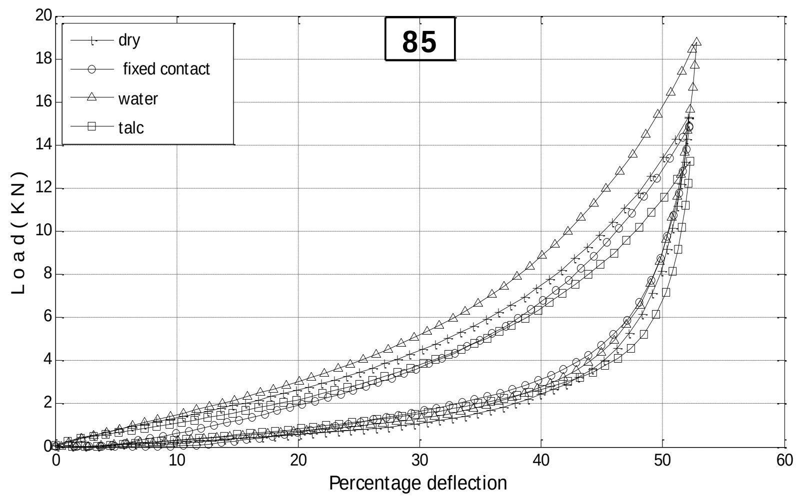
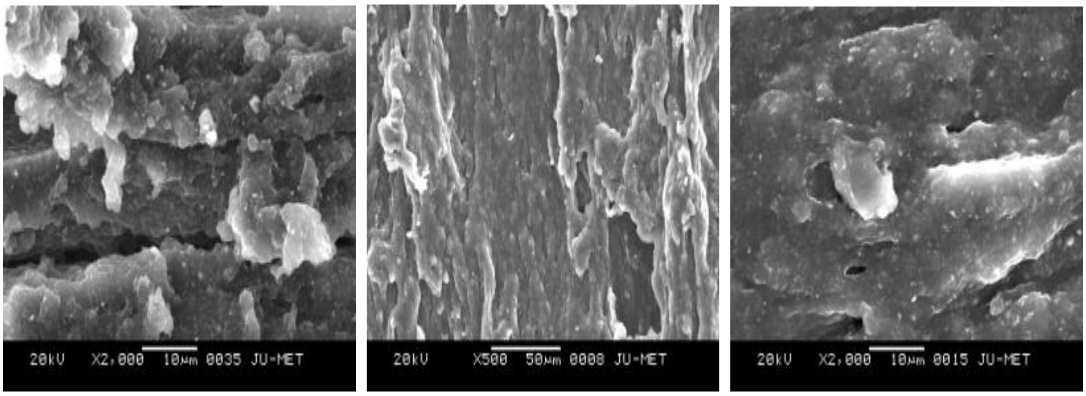


Figure 1. Hysteresis curves of EPDM 85 Å under different conditions of lubrications.

Two body abrasions take place when the cutting points are embedded on the counter surface. Abrasion wear of EPDM rubber against emery papers of different grit size results in gouges, scratches and scoring marks in the laboratory experiments. During two body abrasion process some asperities produce ploughing and the rest cutting. Abrasion is considered to be influenced by hysteresis of rubber, frictional force and strength of rubber against rupture. Some SEM photographs of worn surfaces due to abrasive wear have been furnished in figure 2.



a) b) c)

Figure 2. SEM images of worn surfaces showing (a) surface crack (b) separation of rubber agglomerates and groove formation (c) pitting and smaller particles detachment.

In figure 3, SEM images of NBR rubber modified with flaky as well as spherical nanoparticles of MoS_2 and the X–ray diffraction patterns of all three composites have been shown. Results reveal that spherical MoS_2 nanoparticles enhance mechanical and tribological properties and reduce frictional noise, critical velocity. On the other hand, flaky MoS_2 nanoparticles reduce COF but poor in enhancing mechanical, that is, damping capacity and wear resistance property.

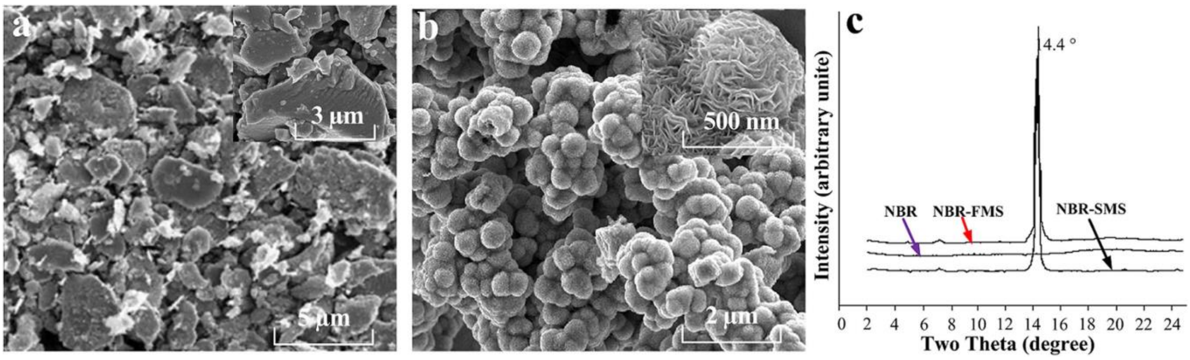


Figure 3. SEM images of modification of NBR rubber with flaky and spherical MoS_2 nanoparticles and XRD patterns [courtesy: 21].

Comparative curves of coefficient of friction vs. sliding distance of different composites of waste rubber reinforced polypropylene have been depicted in figure 4. The curves have directly been generated from the data acquisition software of the tribometer. The curves reveal how the increased weight percentages of waste rubber powder enhance the COF over the virgin material. This is not only the property enhancement but also the alternative way of waste minimization.

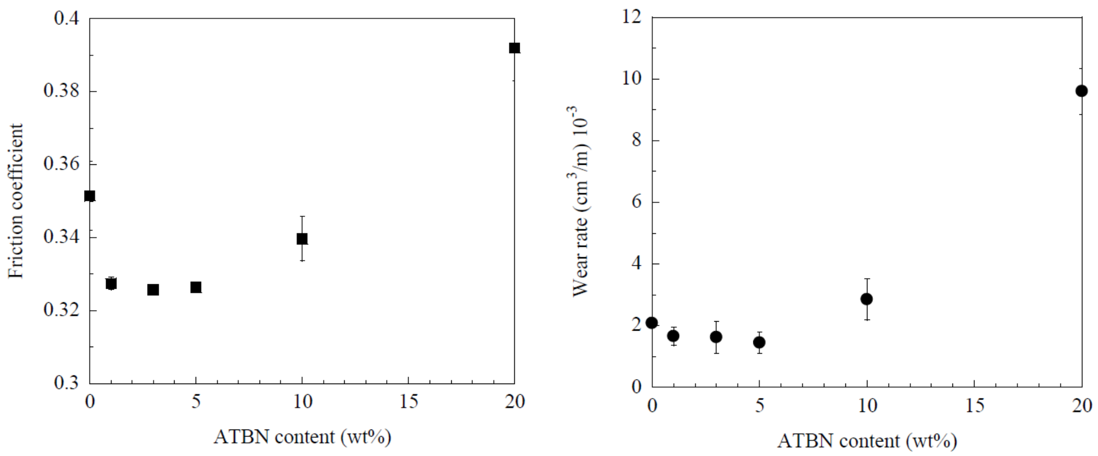


Figure 4. COF and Wear rate of ATBN modified Polybenzoxazine [Courtesy: 20].

The copolymers of polybenzoxazine modified with ATBN show enhancement in the friction coefficient and wear resistance compared to those of the virgin polybenzoxazine. The coefficients of friction for the ATBN–modified polybenzoxazine copolymers are about 0.32 with the ATBN contents in a range of 1–5 wt% as depicted in figure 4. Figure 5 reveals the rubber coating life as a function of number of cycles against different load during fretting wear. The friction coefficient of the rubber coating increases with the number of cycles as the rubber wears out. From figure 5, the friction coefficient with 2 N load starts from 0.09 (approximately) and reaches up to 0.15 after about 3600 cycles. When the load is higher, the friction coefficient varies rapidly. For example, the friction coefficient with 25 N load is about 0.05 at the beginning and reaches at 0.15 just after 100 cycles.

Figure 6 (a) indicates the comparative charts of coefficient of friction as a function of time of EPDM 55, 70 and 85 at a rotational speed of 50 min^{-1}. These curves have been generated by 'Winducom 2006' software. It is evident from figure 6 (a) that the experimental data have strongly fluctuated from a high to low value, that is, at any instantaneous time the coefficient of friction has two values and the total curve appears as a patch. This is due to stick slip effect. However, for a better comparison, the average values of friction have been considered and the results have been depicted in figure 6 (b) – (e) for other rotational speeds of 75, 100, 125 and 150 min^{-1} respectively.

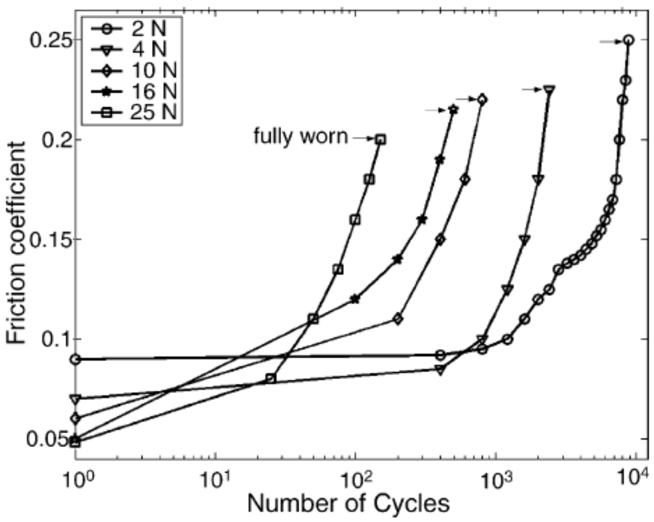


Figure 5. COF of rubber layer against number of cycles during fretting [Courtesy: 23].

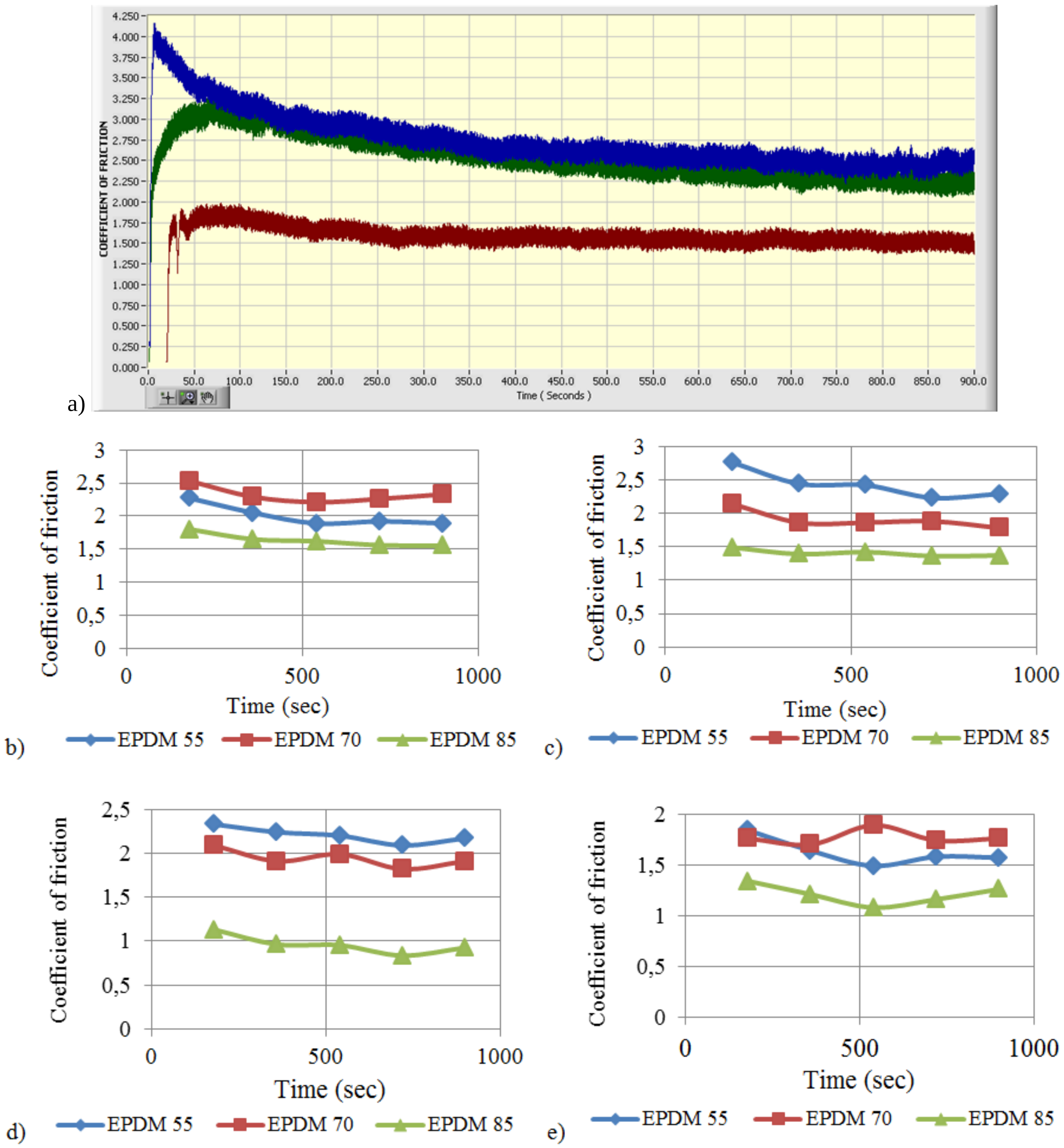


Figure 6. Coefficient of friction as a function of time (a) at 50 min^{-1} [Green: EPDM 55; Blue: EPDM 70; Maroon: EPDM 85] (b) at 75 min^{-1} (c) at 100 min^{-1} (d) at 125 min^{-1} and (e) at 150 min^{-1}.

Weight loss data of the specimens before and after the tribo-testing has been made as a measure of wear. The values have been furnished in Table 2 and corresponding comparative graphs have been depicted in figure 7 respectively.

Table 2. Weight loss of the samples after 900 sec at different rotational speeds.

min^{-1} of roller	Weight Loss (gm) ($\Delta w = w_1 - w_2$)		
	EPDM 55	EPDM 70	EPDM 85
50	0.003	0.001	0.003
75	0.003	0.006	0.003
100	0.003	0.004	0.002
125	0.004	0.003	0.002
150	0.007	0.004	0.002

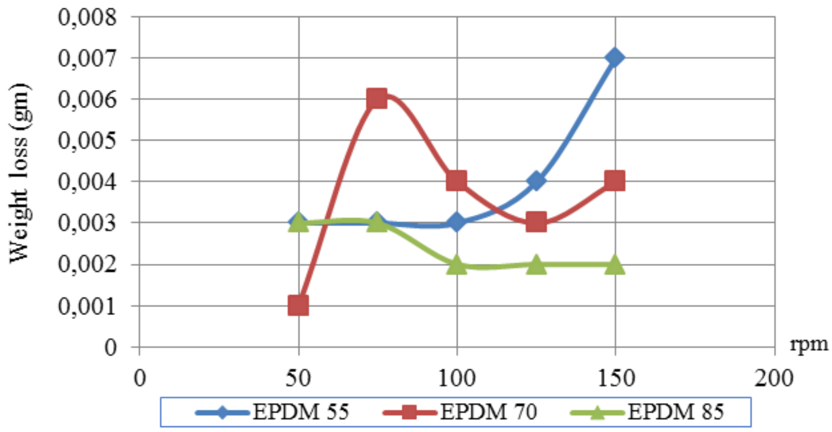


Figure 7. Comparative curves of weight loss at different rotational speeds.

It has been revealed from the figure 7 that EPDM 55 undergoes a maximum loss of 0.007 gm at a speed of 150 min^{-1} and minimum of 0.003 at speeds 50 min^{-1}, 75 min^{-1} and 125 min^{-1} respectively. EPDM 70 undergoes a maximum loss of 0.006 gm at a speed of 75 min^{-1} and minimum at 50 min^{-1}. Weight losses are gradually coming down at speeds of 100 min^{-1} and 125 min^{-1}. Similarly EPDM 85, comparatively harder counterpart, faces a maximum weight loss of 0.003gm only at a speed of 50 min^{-1}. The loss is minimum at speeds 100 min^{-1}, 125 min^{-1} and 150 min^{-1} with a value of 0.002 gm only.

Conclusions

Various researches are going on around the globe to enhance the tribological properties of different kinds of rubbers for engineering as well as other applications, including domestic and sports. In this literature attempts have been made to highlight some of the important and need based works. Some experimental results of an indigenously developed EPDM rubber have been furnished based on laboratory experimentations conducted by the author of the present paper. However, the area is too broad and complex. No unique conclusion can also be made on the tribological properties for any viscoelastic material like rubber in particular. Hence, the tests for individual rubber must have to be carried out based on the case specific application. The reference along with the cross references thereto will help the readers to open new dimension of rubber researches.

References

[1] Ismail H., Ishiaku U. S., Lu E. S., Md. Ishak Z. A. The fatigue and hysteresis behavior of filled epoxidized natural rubber compounds. Int. J. of Polymeric Materials 39 (1998) 45–57.

[2] Karger-Kocsis J., Mousa A., Major Z., Bekesi N. Dry friction and sliding wear of EPDM rubber against steel as a function of carbon black content. Wear 264 (2008) 359–67.

[3] El-Tayeb N. S. M., Nasir Md. R. Effect of soft carbon black on tribology of deproteinised and polyisoprene rubbers. Wear 262 (2007) 350–61.

[4] Felhos D., Karger-Kocsis J. Tribological testing of peroxide-cured EPDM rubbers with different carbon black contents under dry sliding conditions against steel. Tribology International 412 (2008) 404–15.

[5] Stamencovic´ D., Nikolic´ M., Milosevic´ M., Banic´ M., Miltenovic´ A., Mijajlovic´ M. Tribological aspect of rubber based parts used in engineering. Tribology in Industry 36, 1 (2014) 9–16.

[6] Xu D., Karger-Kocsis J., Schlarb A. K. Rolling wear of EPDM and SBR rubbers as a function of carbon black contents: correlation with microhardness. Journal of Material Science 43 (2008) 4330–4339.

[7] Mukhopadhyay A. Some tribological characterization of ‘EPDM’ rubber. Tribology in Industry 36, 2 (2014) 109–116.

[8] Mukhopadhyay A. Effect of some lubricants on the flow characteristics of ‘EPDM’ rubber under compressive load. The 6th Int. Conf. BALTTRIB'2011, Aleksandras Stulginskis university, 26–27.11.2011, Kaunas, Lithuania. 2015. 162–169.

[9] Handbook of 'Two Body Abrasion Tester: TR–605', Ducom Instruments, available at http://www.ducom.fm.alibaba.com/product/134860210–102932571/Two Body Abrasion Tester Tester.html
[10] Mukhopadhyay A. SEM/EDAX studies of pattern abrasion of 'EPDM' rubber surfaces under selected parametric combinations of two-body abrasion in controlled laboratory conditions. Journal of Material Science & Engineering – A 3, 1 (2013) 31–40.
[11] Mukhopadhyay A. SEM study of worn surface morphology of an indigenous EPDM rubber. Polymer Testing (Elsevier) 52 (2016) 167–173.
[12] SEM/EDAX Analysis, available at http://www.ML06\1\ANALYSISWITHSEM_EDS.PMD060317
[13] Kalpakjian S. and Schmid Steven R. Manufacturing Processes for Engineering Materials (4th Edition). Pearson Education. UK. 2009
[14] Dieter G. E. Mechanical Metallurgy (SI metric edition). McGraw-Hill. US. 1988
[15] Hasan S., Jahan R. Flow behavior of plasticine used in physical modelling of metal forming processes. Tribology International 33 (2000) 523–29.
[16] Martinelli Barton A. E. Rubber bearings for precession positioning systems. Master of Mechanical Engineering Degree Thesis. MIT. US. 2005. 1–252.
[17] Ludema Kenneth C. Friction, Wear, Lubrication: A text book in tribology. CRC press. US. 1996
[18] Mukhopadhyay A. Flow behaviour of 'EPDM' rubber during dry compression. International Journal of Manufacturing Science and Production 14, 2 (2014) 115–123.
[19] Bielinski D. M., Kleczewska J., Anyszka R., Jagielski J., Pedzich Z. Current trends in rubber engineering. Conference paper, available at: https://www.researchgate.net/publication/270588179. 2014. 1–7.
[20] Jubsilp C., Rimdusit S., Takeichi T. Effect of rubber contents on tribological and thermomechanical properties of polybenzoxazine. Applied Mechanics and Materials 576 (2014) 75–79.
[21] Dong C., Yuan C., Wang L., Liu W., Bai X., Yan X. Tribological properties of water lubricated rubber materials after modification by MoS_2 nanoparticles. Scientific Reports 6, 35023 (2016) 1–12.
[22] Sivaraos., Yap T. C., Qumrul., Amran M. A., Anand T. J. S. Izamshah R., Aziz A. A. Friction performance analysis of waste tire rubber powder reinforced polypropylene using pin-on-disc tribometer. Procedia Engineering 68 (2013) 743–749.
[23] Baek D. K., Khonsari M. M. Friction and wear of a rubber coating in fretting. Wear 258 (2005) 898–905.
[24] Lahayne O., Pichler B., Reihsner R., Eberhardsteiner J., Suh J., Kim D., Nam S., Paek H., Lorenz B., Persson B. Rubber friction on ice: experiments and modelling. Tribology Letter 62, 17 (2016) 1–19.
[25] Varenberg M., Varenberg A. Table tennis: preliminary displacement in pimples-out rubber. Tribology Letter 53 (2014) 101–105.
[26] Mandic V., Stefanovic M. Friction Studies Utilizing the Ring-Compression Test – Part I. Proceedings of 8th. International Tribology Conference, Belgrad, Serbia, October 8–10 (2003) 44–51.
[27] Mandic V., Stefanovic M. Friction Studies Utilizing the Ring-Compression Test – Part II. Proceedings of 8th. International Tribology Conference, Belgrad, Serbia, October 8–10 (2003) 52–58.
[28] Khan M.S. Friction, Wear and Mechanical Properties of Electron Beam Modified PTFE-based Rubber Compounds. Ph.D Thesis. Technical University of Dresden, Germany (2009) 1–117.
[29] Jost H.P. Reports, Committee on Tribology. Ministry of Technology and Industry, London (1966).
[30] Martinelli Barton A.E. Rubber Bearings for Precession Positioning Systems. Master of Mechanical Engineering Degree Thesis, Massachusetts Institute of Technology. (2005) 1–252.

Author for contacts: Abhijit Mukhopadhyay
E–mail: m_obiji@yahoo.com