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Wear and friction of composites of an epoxy with boron containing wastes

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Abstract

Polymer surface coatings provide superior adhesion to substrates, some flexibility and corrosion resistance. On the other hand, 400,000 ton of boron wastes are generated each year. We have developed polymer composites based on epoxy resins containing up to 50 wt. % of boron wastes and determined their pin-on-disk dynamic friction, wear, Shore D hardness and surface roughness. The hardness and wear resistance increase with increasing boron waste concentration. An equation, with parameters dependent on the load, relating wear rate to hardness is provided. Dynamic friction increases with increasing surface roughness, as represented by the equation. Further, dynamic friction is an increasing function of the wear rate. Micrographs of pure epoxy without fillers shows traces after pin-on-disk testing, with tears, breaks and cracks. For the composites, we observe simpler and relatively homogeneous surfaces.

Keywords: *boron-containing waste, epoxy composites, abrasive wear, dynamic friction, shore hardness, roughness.*

1. Introduction

The largest boron deposits are found in Turkey with a worldwide share of 72% in terms of B_2O_3 content. During the obtaining of boron minerals such as tincalconite ($Na_2O{\cdot}2B_2O_3{\cdot}5H_2O$), ulexite ($Na_2O{\cdot}2CaO{\cdot}5B_2O_3{\cdot}16H_2O$) and colemanite ($2CaO{\cdot}3B_2O_3{\cdot}5H_2O$), about 400,000 tons of different types of boron wastes are formed and rejected in tailing dams per year[1]. A few studies are carried out on evaluation of boron wastes. Kavas et al.[1] investigated the production of artificial lightweight aggregates (LWA) by using four boron-containing wastes (BW), named as Sieve (SBW), Dewatering (DBW), Thickener (TBW) and Mixture (MBW) waste, from Kırka Boron plant in Turkey. They reported that SBW and DBW boron-containing wastes combined with a clay mixture and quartz sand can be used for the manufacturing of LWA. Kurama et al.[2] used a dewatering sieve waste (TSW) of Etibor Kırka Borax company (Turkey) in order to develop an experimental terracotta floor tile body composition in combination with a feldspathic waste provided from a local sanitaryware plant and a ball clay. The results indicated a prospect for using the TSW as a raw material in mixtures with both clay and sanitaryware waste for the production of a terracotta floor tile body. The utilization of boron-containing clay wastes as cement additives was investigated by Özdemir and Öztürk[3]. It was observed that the first clay wastes may be used as cement additives up to 5% or 10%.

On the other hand, polymeric materials are noted for their versatility, high resistance to chemicals, outstanding adhesion to a variety of substrates, toughness, high electrical resistance, durability at high and low temperatures, low shrinkage upon cure, flexibility, and the ease with which they can be poured or cast without forming bubbles[4-6]. Various kinds of polymers and polymer–matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes[7], composites with thermal durability at high temperature[8], etc. The inclusion of such particulate fillers into polymers for commercial applications is primarily aimed at the cost reduction and stiffness improvement.

The wear behavior of polymeric materials has drawn a considerable interest in recent years. Polymers and their composites are being increasingly used in a various applications where resistance to abrasive wear is important[9]. These range from its use as a material (in applications such as machinery parts and biomedical joint replacements) to its use as a glazing material where damage results in loss of optical properties. Polymers are ideal materials for bearing applications due to their general resistance to corrosion, galling and seizure, their tolerance to small misalignments and shock loading and their low coefficients of friction; as glazing materials, their low density and high toughness along with high transparency are desirable properties[10,11]. The acceptability of polymeric materials for abrasive wear conditions largely depends upon its mechanical load carrying capacity and the wear rate. The practical choice of polymeric materials is however not only determined by the mechanical and tribological properties, but also by the price, simplicity of production, processing and the practical limitations in the real application[12,13]. The performance of polymers sliding against hard and smooth counterfaces is determined by the transfer ability and buildup of a polymer film. Efficiency of materials in reducing friction and wear depends on the molecular polymer structure and counterface type. However, only few publications are available on the comparison of the tribological properties of composites under dry sliding and abrasive wear conditions[14-18].

In general, studies take into account to enhance the wear resistance of polymer materials[19-22]. Epoxy resins are the most commonly used thermoset plastic in polymer matrix composites which do not give off reaction products when they cure and thus have low cure shrinkage[4-6]. They also have good adhesion to other materials, good chemical and environmental resistance, good chemical properties and good insulating properties. We have investigated the influence of boron-containing wastes as a filler on wear and friction characteristics of epoxy composites.

2. Experimental

2.1 Materials and sample preparation

The boron-containing wastes used in the study were provided by the Eti Holding Borax Plant in Kırka/Eskişehir, and were taken from the outlet of dewatering sieve of dissolution units. Its maximum particle size was 500 µm. Chemical component of waste is presented in Table 1.

Commercially available Teknobond 300 epoxy resin along with hardener was used as matrix material in fabrication of different specimens. Epoxy resin has modulus of 3.42 GPa, and possess density of 1100 kg/m^3. For processing, the mix ratio by weight was: 2 parts of the epoxy resin and 1 part of the amine based hardener. The required mixture of resin and hardener (see Table 2 below) were made by mixing them in a beaker by stirring the mixture by a rod, taking care that no air should be entrapped inside the solution. The composites were created at the room temperature.

The required ingredients of resin, hardener and boron waste were mixed thoroughly and the mixture so made was transferred to a mold cavity coated with a separator. Steel moulds in size Ø = 50 mm were used for casting of the specimens. Curing was done at room temperature for approximately 24 h. After curing, the specimens were de-molded. Shore D hardness of the specimens was measured at 8 different locations at the same distance from the surface and averages calculated.

2.2 Tests on polymer composites

Dynamic friction and abrasive wear were determined with a tribometer in a ball-on-disc configuration. WC + Co balls of 2.0 mm diameter from H.C. Starck Ceramics, GmbH, Munich, were used. Experiments were carried out under a dry friction condition at room temperature with applied loads of 5.0, 10.0 and 15.0 N and with the sliding speed of 0.2 m/s at a sliding distance of 125 m. Before and after each wear test, each sample and abrasion element was cleaned with alcohol. After the tests, the wear volumes of the samples were quantified by multiplying cross-sectional areas of wear by the width of the wear track obtained from the device Tribotechnic Rugosimeter, namely

$$\text{Wear rate} = W = \text{Worn volume} / (\text{Applied load x Sliding distance}),\ mm^3/Nm \quad (1)$$

Dynamic friction values as function of the sliding distance were obtained using dedicated software. Surface profiles of the wear tracks on the samples and surface roughness were measured by a Tribotechnic Rugosimeter. All the tests were performed on the three specimens and the averages calculated.

3. Results and Discussion

3.1 Surface roughness

Figure 1 shows the surface roughness values. In samples with high volume waste content, the roughness is lower than in the control pure epoxy specimens, except for 10% boron waste.

3.2 Wear and hardness

Wear rates of our composites are displayed in Figure 2 for the three loads applied as a function of the boron content. As seen in that Figure, wear of composites decreases when increasing the content of boron-containing waste material. The highest wear values are obtained for control series at each loading conditions. The range of wear rates varies from 17x10^{-5} to 2x10^{-5} mm^3/Nm at 5.0 N, from

Table 1. Chemical content of boron wastes.

Oxide	B_2O_3	SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O	Fe_2O_3	Loss of Ignition (LOI)
Content, %	12.09	15.5	1.38	17.7	13.79	0.5	3.34	0.22	34.4

Table 2. Compositions and hardness of the composites.

Mixture code	Epoxy resin*, kg/m^3	Boron waste, kg/m^3	Hardness (H_D)
B0	100	-	32
B10	90	10	38
B20	80	20	47
B30	70	30	59
B40	60	40	74
B50	50	50	98

*Epoxy resin was used with the hardener in the 2:1 ratio.

$21x10^{-5}$ to $3x10^{-5}$ mm^3/Nm at 10.0 N, from $27x10^{-5}$ to $3.5x10^{-5}$ mm^3/Nm at 15.0 N, depending on waste content. In other words, there is approximately 7.7 times enhancement in wear resistance of polymer composites at 15 N caused by the waste presence, with higher waste concentrations producing larger effects. Thus, the addition of the waste material makes the epoxy material harder and also changes the character of the surface. Wear strength is higher at higher waste concentrations due to more homogeneous distribution of filler particles since they enhance the resistance to abrasion. At the same time, when load values are considered, the wear rate for all specimens increases with load for all waste material ratios. The wear rate increases with an increase of load from 5 to 15 N due to increase of abrasion and friction on surface of polymer composite.

A relationship between the wear rate and hardness has been investigated and is shown in Figure 3. For each load, the wear resistance increases with an increase of the hardness. The respective equations are provided in inserts to Figure 3. The coefficient of determination R^2 is very close to 1.0 for each loading condition, the highest for 15.0 N (R^2 = corresponds to the perfect fit).

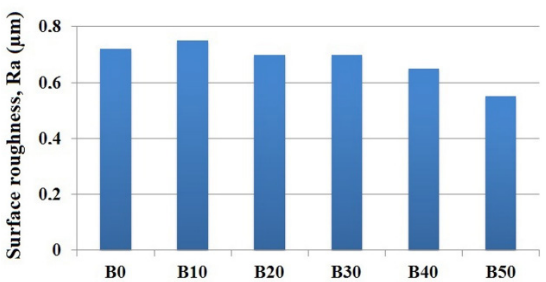

Figure 1. Surface roughness values of epoxy composites with boron waste.

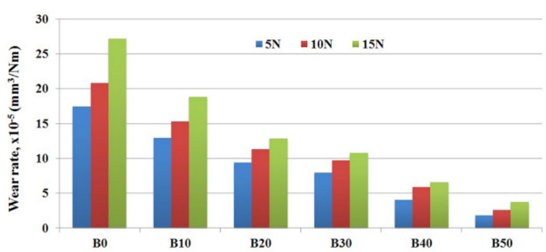

Figure 2. Wear rates of epoxies for various boron waste concentrations.

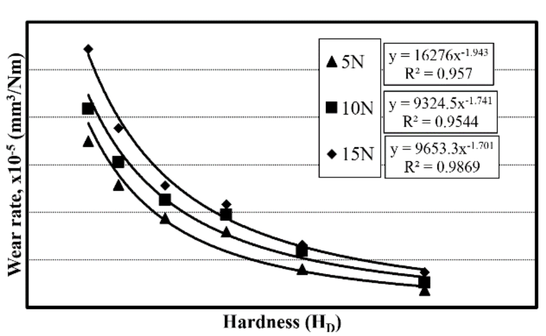

Figure 3. Relationship between hardness and wear rate of the composites in the inserts.

3.3 Friction

Steady state dynamic friction values at different loads are reported in Table 3. The highest dynamic friction is seen in the control samples, namely 0.4. In the composite with 50% waste the friction is equal to 0.21, a reduction to almost one half. As expected, increasing the load increases dynamic friction.

An explanation of friction results can be provided in terms of "bumps" on predominantly polymer composite surface. The bumps model has been advanced before[23] and later confirmed in several cases[24,25]. Without the filler, the nominal contact area is equal to the real contact area. Addition of the filler results in bumps formation; more filler means lower real contact area. Increasing the load makes the bumps slightly less effective in friction lowering.

We have also pursued in Figure 4 the dependence of the dynamic friction values on the surface roughness. There is a clear correlation between these quantities. R^2 values are here reasonably good, the best fit is seen for 15 N.

In turn, we present the relation between dynamic friction and wear rate in Figure 5. A clear correlation emerges in Figure 5:

$$F = 0.164 + 0.0103W \qquad (2)$$

Here F is the dynamic friction; W is the wear rate as before, calculated from Equation 1.

3.4 Microstructure

We observed specimens after ball-on-disk tribometry at 15 N using an optical microscope and SEM; see Figures 6 and 7, respectively. Importantly, waste material particles are uniformly distributed in the epoxy matrix. In Figures 6a and 7a, the cracks and deformations can be clearly seen on the surface of the control (pure epoxy) specimen. The largest track width

Table 3. Dynamic friction values under different conditions.

Mixture code	5.0 N	10.0 N	15.0 N
B0	0.37	0.39	0.40
B10	0.28	0.33	0.36
B20	0.26	0.30	0.32
B30	0.21	0.27	0.30
B40	0.19	0.22	0.24
B50	0.16	0.19	0.21

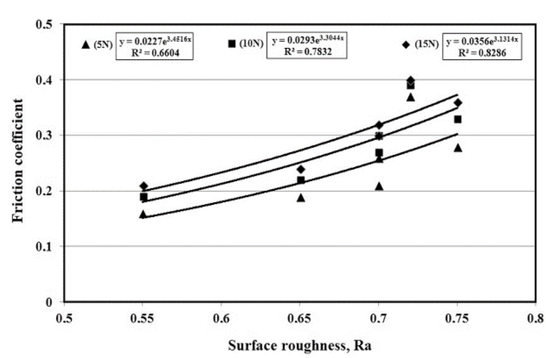

Figure 4. Relationship between dynamic friction and surface roughness.

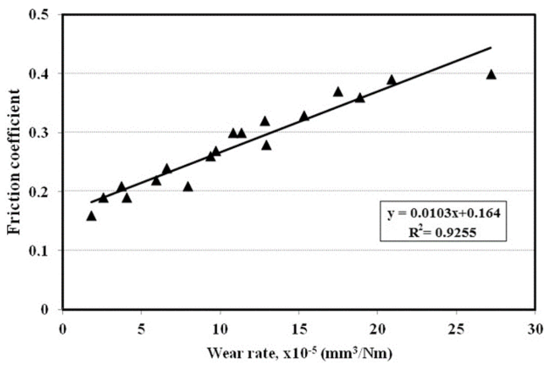

Figure 5. Relationship between dynamic friction and wear rate.

is also observed for pure epoxy, possibly due to small air bubbles in the mixtures during the hardening. Needless to say, the microscopy results confirm the findings reported above, particularly in Figure 2.

We have seen in Table 2 that more waste as the filler increases the hardness. The filler also increases the wear resistance, as seen in Figure 3. These facts are reflected in Figures 6 and 7. Figure 6 shows us how the pin moves across ‘borders’ between the phases; the arrows illustrate such movements.

Pure epoxy without fillers shows traces with tears, breaks and cracks. For the composites we see simpler and relatively homogeneous surfaces.

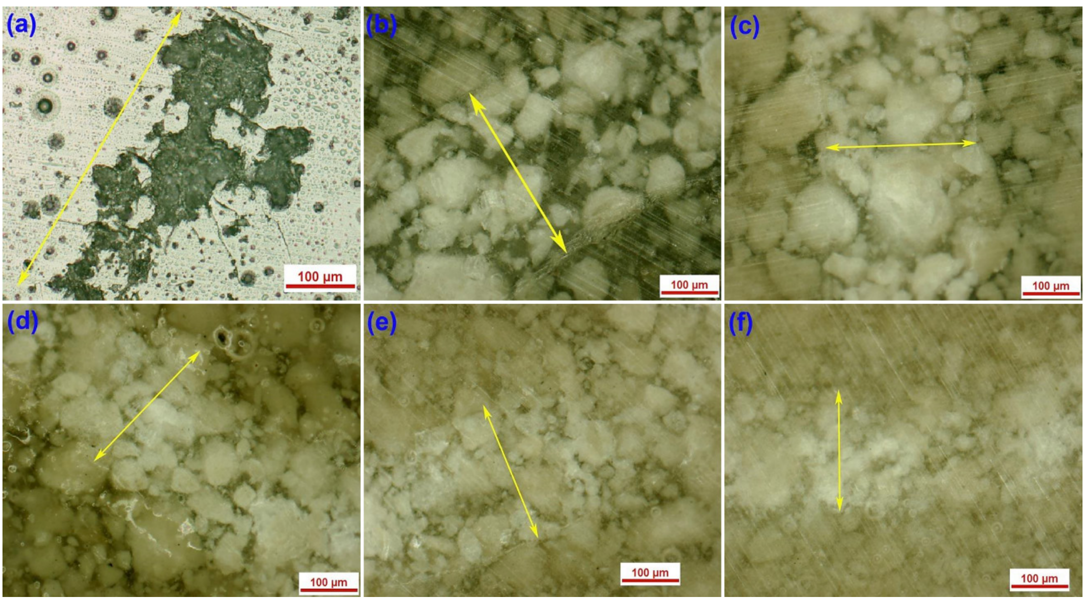

Figure 6. Microstructures of epoxy composites after tribometry for various boron waste concentrations: (a) for pure epoxy, (b) for 10% waste, (c) for 20% waste, (d) for 30% waste, (e) for 40% and (f) for 50% waste.

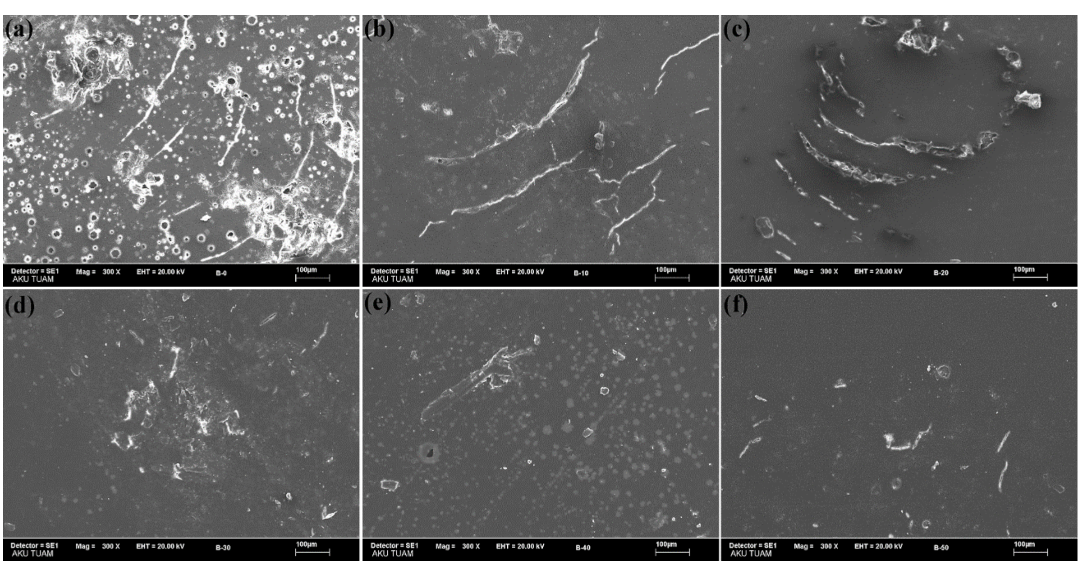

Figure 7. The wear SEMicrographs of epoxy composites after tribometry for various boron waste concentrations: (a) for pure epoxy, (b) for 10% waste, (c) for 20% waste, (d) for 30% waste, (e) for 40% and (f) for 50% waste.

4. Conclusions

We report above wear and friction characteristics of epoxy based polymer composites as well as the role of boron-containing waste additives on properties. Several conclusions are derived:

- The hardness values of samples are increased three times by using boron-containing waste material when compared to pure epoxy.
- The surface roughness values are similar to each other in samples with or without waste material content; the lowest roughness is seen for 50 wt. % waste.
- Dynamic friction decreases with increasing waste concentration while it increases slightly with increasing load.
- Wear resistance is higher in high waste material composites, apparently due to more homogeneous distribution of filler particles with high resistance to abrasion. The wear rate for the 50 wt. % boron waste composite is 7.7 times smaller than for the pure epoxy.
- A good was relationship between hardness versus wear rate; coefficient of friction versus roughness; and coefficient of friction versus wear rate is obtained, respectively, for epoxy based and waste material blended polymer composites.
- Microstructure observations show that the waste material particles are uniformly distributed in the epoxy matrix. While the deformations such as tears, breaks and cracks are observed in pure epoxy specimens, there is only trace on the waste material containing samples after the tribometry tests.

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