Mechanical and wear characteristics of epoxy composites filled with industrial wastes: A comparative study

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Abstract: Use of industrial wastes, such as slag and sludge particles, as filler in polymers is not very common in the field of composite research. Therefore in this paper, a comparison of mechanical characteristics of epoxy based composites filled with LD sludge, BF slag and LD slag (wastes generated in iron and steel industries) were presented. A comparative study among these composites in regard to their dry sliding wear characteristics under similar test conditions was also included. Composites with different weight proportions (0, 5, 10, 15 and 20 wt.%) of LD sludge were fabricated by solution casting technique. Mechanical properties were evaluated as per ASTM test standards and sliding wear test was performed following a design of experiment approach based on Taguchi's orthogonal array. The test results for epoxy-LD sludge composites were compared with those of epoxy-BF slag and epoxy-LD slag composites reported by previous investigators. The comparison reveals that epoxy filled with LD sludge exhibits superior mechanical and wear characteristics among the three types of composites considered in this study.

Keywords: Epoxy composites; Characterization; Sliding wear; Industrial wastes

1. Introduction

Significant quantities of slag and sludge are generated as byproduct or waste material every day from steel industries. During the production of steel, 2–4 tonnes of wastes are being generated per tonne of steel produced. They generally have significant amounts of valuable metals and materials. It is normally possible to regain some values by chemical or physical processing techniques, such as magnetic separation, crushing, flotation, grinding, leaching or roasting [1]. Transforming these solid wastes from one form to another, to be reused either by the same production unit or by different industrial installation, is very much essential not only for conserving metals and mineral resources, but also for protecting the environment.

The different solid wastes in the form of sludge and slags that are generated in huge quantity from steel plants are Linz-Donawitz sludge (LDS), blast furnace slag (BF slag) and Linz-Donawitz slag (LD slag). The composition of these solid wastes differ extensively depending on the source of generation but generally consists of some reusable materials, such as carbon, iron, calcium, phosphorous, sulfur, etc., which can be recovered and recycled in a judicious manner. Various efforts have been made on the utilization of these steel industry wastes in the past. The BF slag is generated in a blast furnace, where combustion is intensified by a blast of air, especially a furnace for smelting iron by blowing air through a hot mixture of ore, coke and flux. It contains mainly inorganic constituents such as SiO_2, CaO, Fe_2O_3, MgO, Al_2O_3 etc. The fine solid particles recovered after wet cleaning of the gas emerging from LD converters in the sludge form are termed as LD sludge. It mainly contains FeO, Fe_2O_3 and CaO along with small quantities of MgO, SiO_2, Al_2O_3, P and MnO. Huge quantities of slags from steel plants are produced through LD converter or basic oxygen furnace route of steel making. The main components present in LD slag are CaO, Fe, and SiO_2.

As an advanced engineering material, polymer composites are used in many low load bearing applications, where high wear resistance is required. The wear resistance of neat epoxy can generally be enhanced by introducing a secondary phase(s) into the matrix material [2–6]. There have been various reports of applications of polymers and their composites in dry sliding wear situations in the literature [7-8]. Although available references suggest a large number of materials being used as fillers in polymers [9], utilization of solid industrial wastes for this purpose has been rare. Only very few studies on the use of industrial wastes like red mud, fly ash etc. in polymer composites have been reported so far [10-15]. Due to the presence of hard phases, the solid wastes generated from steel industry can also be used as filler material in polymer matrix to enhance hardness and tribological properties of the composite [16-18]. In view of this, in the present work a comparative study is presented for dry sliding wear response of epoxy-based composites filled with LDS, BF slag and LD slag under similar test conditions.

2. Materials and Methods

2.1 Composite fabrication

In the present work, epoxy LY-556 which belongs to the epoxide family was used as the matrix material. Epoxy LY-556 is a low-temperature curing resin, and it was mixed with hardener HY-951 in the ratio of 10:1. LD sludge collected from Rourkela Steel Plant (Rourkela, India), was used as the filler material in this investigation. These sludge particles were sieved to obtain an average particle size in the range of 70–100 μm. This particulate filler was thoroughly mixed with the epoxy resin (LY556) in different weight proportions (0, 5, 10, 15 and 20 wt. %). The dough was then slowly poured into the mould of different shapes, coated beforehand with silicone-releasing agent. These were left to cure for 24 h after which the moulds were broken and specimens were released. Then samples of desired shapes were cut to conduct tensile, flexural, micro-hardness and sliding wear tests.

2.2 Characterization

The tensile tests were carried out on flat specimens as per ASTM D 638 M91. The dimensions of the specimens used to carry out the test were 150 mm × 20 mm × 3 mm and a uniaxial load was applied through both ends of the specimen. In the present research work, tensile and flexural tests were carried out in the universal testing machine Instron 1195 at a crosshead speed of 10 mm/min and the results were used to calculate the strength of the composite. The tests were repeated five times and the mean value was reported as the tensile and flexural strength of that specimen respectively. A Vaiseshika micro-hardness tester is used to measure the micro-hardness of the composite samples. A right pyramid form of diamond indenter with a square base having an angle of 136° between the opposite faces was forced into the material under a load of 50g. The two diagonals X and Y of the indentation left on the surface of the material after removal of the load were measured and their arithmetic mean L was calculated. Vickers hardness was then calculated by using the relation:

$$H_v = 0.1889 \frac{F}{L^2} \tag{1}$$

2.3 Test apparatus

Wear tests were carried out as per ASTM G 99 using a pin-on-disc type friction and wear monitoring test rig. The counter body is a disc made of hardened ground steel (hardness 72 HRC, surface roughness 0.6 µmR_a). The specimen was held stationary while the disc rotates. A series of tests were conducted with five sliding velocities of 63, 125,190, 250 and 315 cm/s each under five different normal loads of 5, 10, 15, 20 and 25 N. The material loss from the composite surface was measured using a precision electronic balance with accuracy ±0.01 mg and the specific wear rate (mm^3/N-m) is expressed on a volume loss basis as:

$$W_s = \frac{\Delta \mathrm{m}}{\rho\, \mathrm{t}} \times V_s F_n \qquad (2)$$

where, Δ m is the mass loss of the composite in the test duration (g), ρ is the density of the composite (g/mm^3), t is the test duration (s), V_s is the sliding velocity (cm/s), and F_n is the average normal load (N).

To conduct sliding wear test, four major factors sliding velocity, normal load, sliding distance and filler content have been considered, each at five levels according to Taguchi's L_{25} orthogonal array as shown in Table 1.

Table 1. Control factors and their selected levels for dry sliding wear tests.

Control factors	Levels					
	I	II	III	IV	V	Units
Sliding velocity (A)	63	125	190	250	315	cm/sec
Normal load (B)	5	10	15	20	25	N
Sliding distance (C)	500	1000	1500	2000	2500	m
LDS content (D)	0	5	10	15	20	wt. %

3. Results and discussion

3.1 Tensile, Flexural and Micro-Hardness Test Results

The tensile strength of the epoxy-LD sludge composites was evaluated and the test results for various compositions of composites are presented in figure 1. It was found out that with increase in the filler content, tensile strength of the composite gradually decreased. Figure 1 also represents the variation of tensile strength of epoxy-BF slag and epoxy-LD slag composites with filler content as reported previously by many authors [16-17]. It has been observed that out of all the three fillers, epoxy-LD sludge composites have higher strength in tension.

In the present work, the flexural strength values of the epoxy-LD sludge composites were evaluated and presented in figure 2 along with the flexural strength values of epoxy-BF slag and epoxy-LD slag composites [16-17]. A gradual decrease in flexural strength was recorded for all the three classes of composites and this decrement was found to be proportional to the filler content. From figure 2 it was also observed that flexural strength of the epoxy-LD sludge composites showed better result than the other two types of composites.

The micro-hardness values of the epoxy matrix composites filled with different wt. % of LD sludge, were obtained and compared with BF slag and LD slag [16-17] and are presented in figure 3. It was evident that with addition of filler, micro-hardness of the composite had improved. With an addition of 5 wt.% of LD sludge in the neat epoxy, the micro-hardness of the neat epoxy increased from 0.085 to 0.12 GPa. The micro-hardness value further increased to 0.181, 0.232 and 0.273 GPa with the addition of 10, 15 and 20 wt. % of LD sludge to the neat epoxy, respectively. The micro-hardness values of epoxy-LD sludge composites were found to be higher than the other two classes of composites, filled with BF slag and LD slag, at same filler content. There can be two reasons for the decline in the strength of these particulate-filled composites. One possibility is that the chemical reaction at the interface between LD sludge particles and the matrix may be too weak to transfer the tensile stress; the other is that the irregular-shaped LD sludge particles act as stress raisers in the polymer matrix.

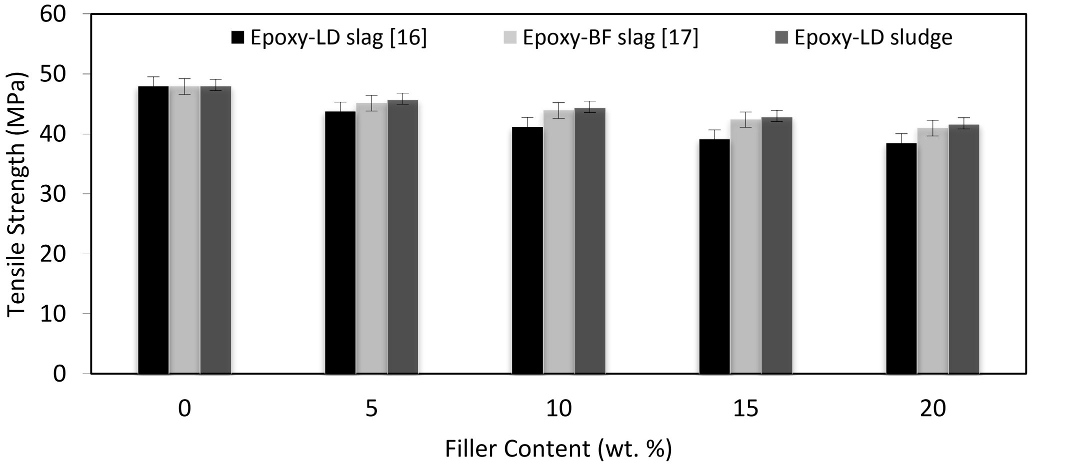

Figure 1. Comparison of tensile strength of LD sludge, BF slag and LD slag filled composites.

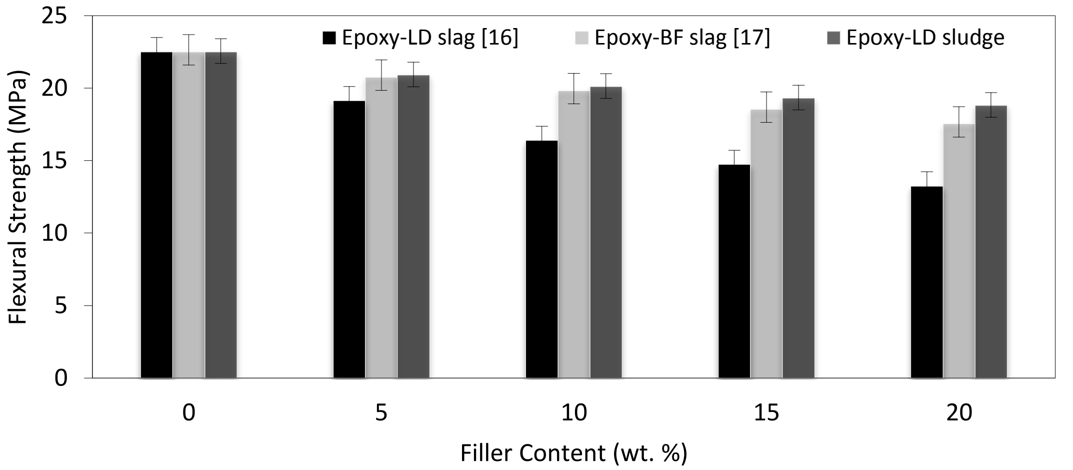

Figure 2. Comparison of flexural strength of LD sludge, BF slag and LD slag filled composites.

3.2 Sliding Wear Test Results

The specific wear rates for composites filled with LD sludge, BF slag and LD slag for all the 25 experiments are presented in table 2. It has been observed that LD sludge filled epoxy composite showed better sliding wear resistance than epoxy-BF slag and epoxy-LD slag composites. A graphical representation of variation in specific wear rate for different test runs are shown in figure 4. It is observed from the figure 4 that for a particular sliding velocity, the specific wear rate decreased with increase in filler addition, irrespective of other two control factors. Hence filler content was found to be the most affecting control factor that controls the specific wear rate of the composites. This decrease in specific wear rate is due to the presence of hard solid particles in the composite, which is also responsible for higher values hardness with increase in filler content.

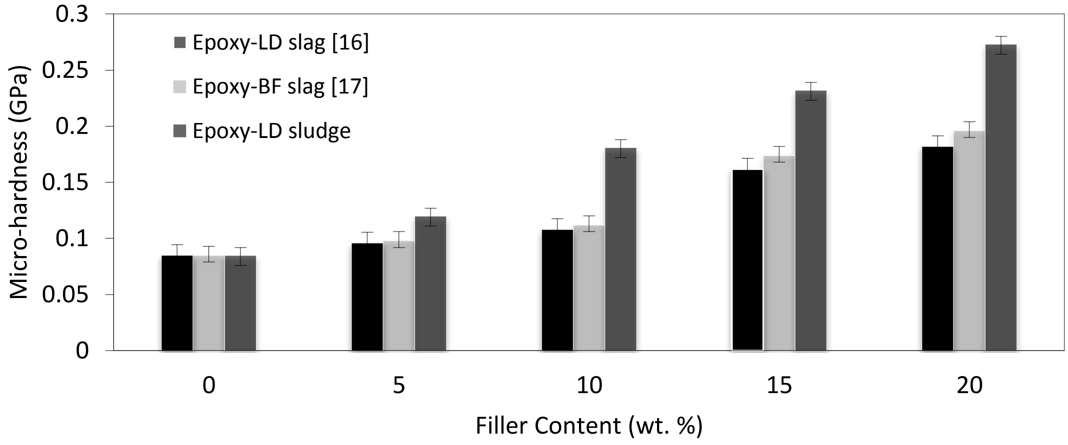

Figure 3. Comparison of micro-hardness of LD sludge, BF slag and LD slag filled composites.

Table 2. The sliding wear test results for LD sludge, BF slag and LD slag filled composites.

Test Run	Sliding Velocity A(cm/sec)	Normal Load B (N)	Sliding Distance C (m)	LDS Content D(wt.%)	Specific Wear Rate ($10^{-9}mm^3$/N-m)		
					LD sludge	BF slag	LD slag
1	63	5	500	0	1.612	1.894	2.098
2	63	10	1000	5	1.325	1.584	1.711
3	63	15	1500	10	0.873	1.609	1.147
4	63	20	2000	15	0.786	0.879	0.919
5	63	25	2500	20	0.688	0.835	0.927
6	125	5	1000	10	1.053	1.167	1.252
7	125	10	1500	15	0.982	1.195	1.293
8	125	15	2000	20	0.788	0.851	0.931
9	125	20	2500	0	1.736	2.107	2.123
10	125	25	500	5	1.442	1.617	1.866
11	190	5	1500	20	0.864	0.949	1.116
12	190	10	2000	0	1.823	2.188	2.221
13	190	15	2500	5	1.518	1.695	1.841
14	190	20	500	10	1.192	1.178	1.565
15	190	25	1000	15	1.118	1.217	1.473
16	250	5	2000	5	1.615	1.827	2.052
17	250	10	2500	10	1.316	1.591	1.559
18	250	15	500	15	1.214	1.483	1.592
19	250	20	1000	20	0.986	1.086	1.288
20	250	25	1500	0	2.012	2.256	2.607
21	315	5	2500	15	1.396	1.664	1.719
22	315	10	500	20	1.117	1.381	1.331
23	315	15	1000	0	2.226	2.514	2.843
24	315	20	1500	5	1.834	2.211	2.385
25	315	25	2500	10	1.528	1.827	1.954

Figure 4 clearly revealed that for similar test conditions, the epoxy-LD sludge composites exhibited minimum wear rate as compared to those obtained for epoxy-BF slag and epoxy-LD slag composites. This may be attributed to the relatively higher value of micro-hardness of epoxy-LD sludge composites.

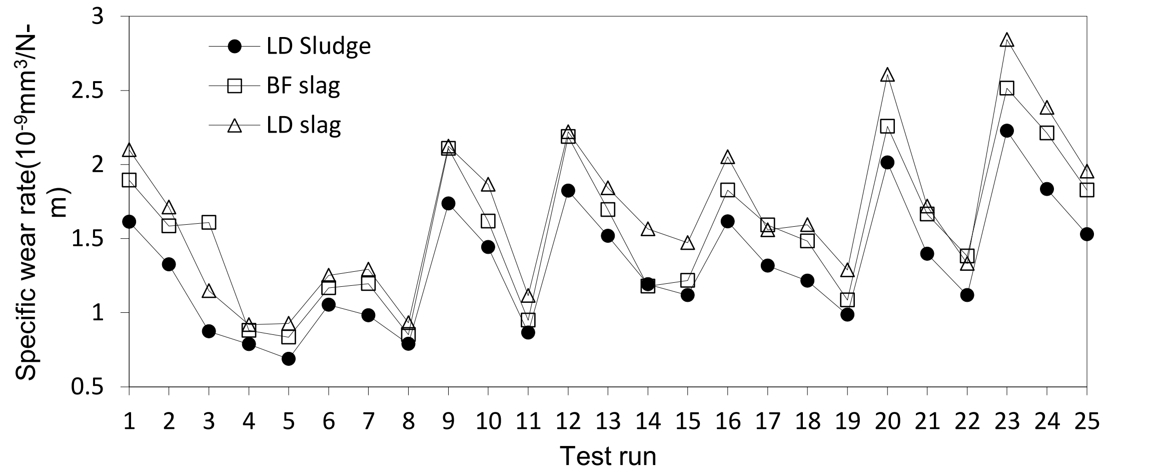

Figure 4. Comparison of specific wear rates of EP-LD sludge, EP-BF slag and EP-LD slag composites for all test runs.

4. Conclusions

i. Successful fabrication of industrial waste filled epoxy matrix composites is possible through solution casting technique.
ii. LD sludge filled composite possesses superior mechanical properties as compared to BF slag and LD slag filled composites.
iii. Dry sliding wear test result revealed that wear resistance of epoxy-LDS composite was higher than other two classes of composite and it increased with increase in filler content.
iv. The analysis also revealed that filler content is the most predominant controlling factor affecting the wear rates of the composites.

References

[1] Das B Prakash S Reddy P S R and V N Misra 2007 *Resources, Conservation and Recycling* **50** 40.
[2] Khruschov M M 1974 *Wear* **28** 69.
[3] Lee G Y, Dharan C K H and Ritchie R O 2002 *Wear* **252** 322.
[4] Harsha A P Tewari U S and Venkatraman B 2003 *Wear* **254** 693.
[5] Ahmed S and Jones F R 1990 *J. Mater. Sci.* **25** 4933.
[6] Basavarajappa S and Ellangovan S 2012 *wear* **296** 491.
[7] Carvalho O Buciumeanu M Madeira S Soares D Silva F S and Miranda G 2015 *Tribology International* **90** 148.
[8] Srinivasa K and Bhagyashekarb M S 2014 *Procedia Engineering* **97** 488.
[9] Katz H S and Mileski J V 1987 “Handbook of fillers for plastics”, A Von Nostrand Reinhold Book International Journal of Plastics Technology.

[10] Patnaik A Satapathy A Mahapatra S S and Dash R R 2009 *J. Reinf. Plast. Compos.* **28** 513.
[11] Mahapatra S S 2010 *Part J: Journal of Engineering Tribology* **224** 157.
[12] Siddhartha V Patnaik A and Bhatt A D 2010 *Part J: Journal of Engineering Tribology* **224** 1103.
[13] Biswas S and Satapathy A 2010 *Waste Manage. Res* **28** 615.
[14] Biswas S and Satapathy A 2009 *Mater. Des* **30** 2841.
[15] Zhang Y Zhang A Zhen Z Lv F Chu P K and Ji J 2011 *J. Compos. Mater* **45** 2811.
[16] Pati P R and Satapathy A 2013 *International Journal on Mechanical Engineering and Robotics* **1** 2321.
[17] Padhi P K and Satapathy A 2013 *Tribology Transactions* **56** 789.
[18] Purohit A and Alok Satapathy 2016 *J. Compos. Mater* **0** 1-13 DOI: 10.1177/0021998316656478.