

Investigation of the effects of ore abrasivity index on ball wear in wet ball milling operations with lab scale tests

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Abstract: The operational costs of a mineral processing plant are largely dominated by energy consumption and the use of consumable materials during the grinding operations. Industrial mills come in various types and sizes, with grinding media such as balls and rods that differ in hardness and properties. Ore characteristics, such as hardness and abrasiveness, influence the wear of these consumables. The selection of appropriate grinding media based on ore abrasivity is therefore critical. This study investigates the wear of grinding media during wet grinding in ball mills made from cast iron at ETİ Bakır Co.'s Samsun plant. A laboratory-scale ball mill and the LCPC abrasivity test were used to assess grinding media wear. Samples from various ores were collected from the company's mines. The relationship between media wear and ore characteristics was analyzed using multi-linear regression frameworks incorporating the LCPC and Bond Wi tests. The study evaluated the effects of different ore types on grinding media wear and determined the relationship between ore abrasiveness and ball wear. Finally, a dimensionless ball wear index model was developed to relate ore characterization parameters to grinding media wear under controlled laboratory conditions.

Keywords: grinding, abrasivity, lab-scale ball mill, LCPC abrasivity test

1. Introduction

In mineral processing plants, grinding operations account for some of the highest operating costs (Radziszewski, 2002; Matsanga et al., 2023). In these comminution operations, grinding media consumption accounts for a large portion of the total operating expenditure (Bond, 1961). Ball wear is a complex phenomenon resulting from the interaction between the mineralogical and physical properties of the ore, ball metallurgy, and operational parameters (Radziszewski, 2002). According to Jankovic (2003), the combined effects of mechanisms in the grinding environment, such as abrasion, impact, and corrosion, must be better understood to predict grinding media wear accurately under dynamic operational conditions.

To characterize ball wear in the mill, it is necessary to have information on the ore's abrasiveness and grindability. The Bond abrasion index (A_i) has been used for many years to measure ore abrasiveness. However, parameters such as the amount and size of material introduced, as measured by the Bond abrasion index, make this standard test difficult to apply. As highlighted by Peres et al. (2018), the LCPC (Laboratoire Central des Ponts et Chaussées) test emerges as a significant alternative to the Bond abrasion index, requiring less material and a finer particle size. In their study of copper sulfide ores, the LCPC index (LAC, g/Mg) was shown to determine abrasiveness effectively and to correlate strongly with the Bond A_i . These advantages make the LCPC test a promising tool for rapid ore characterization. This approach supports the development of the ball wear index model, which is the primary objective of this study.

However, studies integrating LCPC abrasivity data directly with laboratory-scale grinding media wear measurements remain limited. For these reasons, a laboratory study integrating LCPC test data with the actual wear behaviour observed in the controlled grinding environments highlights a gap in the mineral processing literature.

Therefore, the main objective of this study is to investigate the relationship between ore abrasivity determined by the LCPC test and grinding media wear measured by marked ball wear tests conducted in a laboratory-scale ball mill. In addition, a predictive dimensionless ball wear index model is proposed to evaluate the influence of ore characteristics on grinding media wear as a rapid laboratory screening tool.

2. Materials and methods

2.1. Grinding media specifications and metallurgical characterization

The grinding balls evaluated in this study were sourced from ETİ Bakır Co. ball production plant located at the Samsun smelting and electrolysis plant. Steel balls with diameters of 20, 25, 30, and 40 mm were used in the experiments. Table 1 shows the chemical composition of the steel balls.

Table 1. Chemical compositions of steel balls

Ball Diameter	%C	%Mn	%Si	%Cr	%Cu
20	0.65	0.75	0.25	0.20	0.20
25	0.65	0.75	0.25	0.20	0.20
30	0.65	0.75	0.25	0.20	0.20
40	0.70	0.85	0.30	0.40	0.40

The steel balls used in this study were produced by cooling standard commercial round steel billets after hot cutting and forging. They were used to monitor the performance of the balls manufactured in-house.

The copper detected in the chemical analyses of the balls stems from trace (tramp) elements originating in the raw materials used to produce the externally sourced billets. Low copper content in the balls slightly increases micro-corrosion resistance in wet grinding applications (Iwasaki et al., 1985).

Differences in chemical composition observed across different ball diameters comprehensively balance abrasion resistance. Carbon (C) provides the essential high-hardness martensitic structure required to resist mechanical mass loss (Radziszewski, 2002). Manganese and chromium, meanwhile, play a critical role in hardening. As ball size increases, the cooling rate is slower than that of smaller-diameter balls; therefore, high manganese and chromium contents compensate for thermal lag, resulting in a homogeneous hardness profile and preventing premature degradation in the ball cores (Meulendyke and Purdue, 1989).

Compared with reference values reported in the literature, the balls used in this study fall into the standard medium- to high-carbon, low-alloy steel category. The carbon content falls within the 0.50%–1.00% range specified in the literature to achieve a high martensitic structure without causing brittleness (Radziszewski, 2002). Similarly, the manganese and chromium contents are consistent with the industrial low-alloy steel ranges reported by Meulendyke and Purdue (1989) and Aldrich (2013) to ensure core and surface hardening. Finally, the low copper content is consistent with steel production standards (Iwasaki et al., 1985).

2.2. Ore samples and characterization

To evaluate the wear performance of the balls in different geological formations, three different ore samples were obtained from the Adıyaman Koçali copper mine, the Artvin Murgul copper mine, and the Samsun smelting and electrolysis plant, all of which are under the ownership of ETİ Bakır Co. The representative sample taken from the Adıyaman Koçali copper mine is a feed sample of the ore processing plant, while the sample taken from the Artvin Murgul region is a silica sample. Additionally, the sample obtained from the Samsun plant is a copper slag sample.

These three ore samples were analysed in the ETİ Copper R&D Center laboratory. Cu, Fe, and Zn analyses were performed using the aqua regia digestion and ICP-OES methods; %SiO₂ analyses were performed using the gravimetric dissolution method; and S analyses were performed using the tube furnace roasting method. Table 2 presents the results.

To complement the elemental assays, mineralogical characterization was performed on each ore sample using X-ray diffraction (XRD) and mineral liberation analysis (MLA). For MLA, samples were prepared by casting 2 g of material into 30 mm diameter molds, followed by a three-stage sanding

process and diamond suspension polishing. The prepared bakelite was coated with carbon for mineralogical analysis. Mineralogical examinations were performed using a Thermo Fisher Scientific Apreo 2C scanning electron microscope (SEM). The Mineral Liberation Analysis (MLA) software in the pertinent microscope was utilized for modal mineralogy analysis.

Table 2. Chemical composition of the investigated ore samples (wt.%)

Ore	%Cu	%Fe	%Zn	%S	%SiO ₂
Adiyaman/Koçali	3.41	30.14	0.95	29.20	12.68
Samsun	1.55	37.10	3.69	0.59	35.19
Artvin/Murgul	0.57	2.82	0.08	2.78	83.36

Table 3. XRD phase composition of the investigated ore samples (wt.%)

Ore	Dominant phase	wt%	Secondary phases (wt%)
Adiyaman/Koçali	Pyrite (FeS ₂)	83.4	Quartz (8.8), Chalcopyrite (7.6), Sphalerite (0.2)
Samsun	Fayalite ((Fe,Mg) ₂ SiO ₄)	84.9	Magnesioferrite (7.5), Cuprospinel (3.2), Filipstadite (4.3)
Artvin/Murgul	Quartz (SiO ₂)	100.0	—

MLA modal mineralogy analysis corroborated the XRD results presented in Table 3: quartz was confirmed as the dominant phase in the Murgul silica sample (64.1 wt%), while pyrite dominated the Adiyaman/Koçali feed sample (63.3–72.8 wt% across size fractions). The Samsun copper slag was characterized separately via SEM-EDS elemental mapping rather than MLA because of its non-crystalline matrix; this analysis confirmed Fe, O, and Si as the dominant elements (41.0%, 37.8%, and 15.5%, respectively), consistent with the fayalite-spinel assemblage identified by XRD.

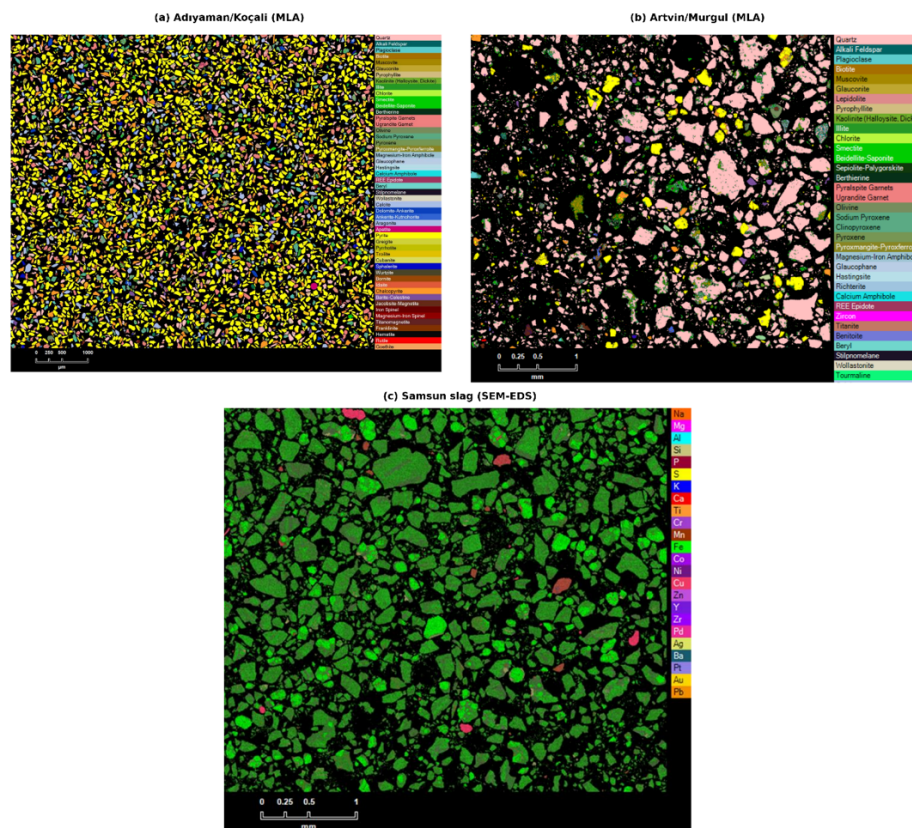


Fig. 1. Mineral liberation analysis (MLA) maps of (a) Adiyaman/Koçali and (b) Artvin/Murgul samples showing grain-scale mineral distribution (pink/salmon: quartz; yellow: pyrite), and (c) SEM-EDS elemental map of the Samsun copper slag (green: Fe; red: Cu), reflecting its non-crystalline matrix unsuitable for standard MLA phase mapping

Table 4. Modal mineralogy (MLA) of Adıyaman/Koçali and Artvin/Murgul samples (wt.%)

Mineral	Adıyaman/Koçali (+106 μm)	Artvin/Murgul
Pyrite	63.27	12.66
Quartz	4.90	64.14
Chalcopyrite	8.34	2.15
Pyrrhotite Garnets	8.16	—
Calcite	2.98	—
Smectite	0.48	4.42
Beryl	—	3.46
Muscovite	—	2.24
Other	11.87	10.93

The Samsun copper slag was not analyzed by MLA due to its non-crystalline matrix; it was instead characterized by SEM-EDS elemental mapping

2.3. Grinding tests

2.3.1. Bond work index test

The Bond Work Index (W_i) tests were performed in accordance with the standard procedure defined by Bond (1961). A standard Bond ball mill measuring 30.5 cm x 30.5 cm was operated at 70 rpm with a charge of 285 steel balls. All test runs were conducted in a dry grinding state under a simulated 250% circulating load using a 106 μm closing screen size. Grinding cycles were repeated until a steady state was achieved. The W_i values (kWh/Mg) were then calculated using the standard Bond equation.

2.3.2. LCPC abrasiveness index test

LCPC abrasiveness index (LAC , g/Mg) tests were conducted in accordance with the AFNOR P18-579 standard. Each test was performed under controlled laboratory conditions, and careful weighing procedures were applied to minimize experimental error. 50×25×5 mm metal plates with a Rockwell B hardness of 60-75 were used in the LCPC tests. 500 g samples were ground for 5 min in each test. Metal plates were weighed before and after the tests. Weight loss from metal plates was noted, and the abrasiveness index of ores was calculated in terms of g/Mg. After the test, the ground ore was screened to 1.6 mm, and the breakability coefficient (LBC , %) was calculated (Thuro et al., 2006).

2.3.3. Marked ball wear test

In marked ball wear tests (MBWT), the Ünal Engineering and Machinery Industry laboratory-scale ball mill (internal diameter 178 mm; length 356 mm) was used. The ball charge was kept constant at 40%, and pulp density was maintained at 66% solids by weight during the grinding tests. The initial ball charge distribution specified in Table 5 was prepared strictly according to the equipment manufacturers (Ünal Engineering and Machinery Industry) recommended charge specifications for this specific mill geometry to maintain optimum grinding efficiency. A total of 15.85 kg of balls were loaded, and 25% by weight of each size fraction was marked. A total of 40 marked balls were used in the tests. Of these, 8 balls each of 20, 25 and 30 mm, and 16 balls of 40 mm were marked. MBWT was planned for 100 hours of total grinding time, time intervals are 1 hour at first five hours, after fifth hour time intervals are 5 hours to the twentieth hour, after twentieth hour test the time intervals are 20 hours for the end of the test. The balls were weighed before the test began. The marked balls were weighed at regular time intervals, and the cumulative weight loss was determined (Çolak, 2018).

2.4. Statistical evaluations

Statistical analyses were performed to develop a predictive model for ball wear based on laboratory test data. A ball wear index model was presented using multiple linear regression based on ANOVA (Analysis of Variance) to determine the statistical significance of each independent variable and its

respective interactions. The coefficients of the independent variables were estimated using ordinary least squares (OLS) to minimize the sum of squared residuals and to ensure the unbiased nature of the regression estimators.

Table 5. Grinding media charge and marked ball distribution used in MBWT

Ball diameter (mm)	Number	Marked number
40	31	8
30	31	8
25	32	8
20	64	16

3. Results and discussion

3.1. LCPC and Bond Work Index

The tests showed a linear relationship between the LCPC abrasiveness index and ball wear. The highest LCPC abrasiveness index was obtained for the Samsun ore, whereas the highest ball wear was observed for the Artvin/Murgul silica ore. Although the Samsun ore exhibited higher *LAC* values, the elevated wear associated with the Artvin/Murgul ore is attributed to its high silica content and mineralogical characteristics. Table 6 shows the LCPC test results and Bond Work Index results.

Table 6. LCPC abrasivity index and Bond work index results

Ore	LAC (g/Mg)	LBC (%)	Wi (kWh/Mg)
Adıyaman/Koçali	280	67.16	12.80
Samsun	1940	42.70	15.00
Artvin/Murgul	1080	24.23	20.00

The test results showed that the Samsun slag sample exhibited the highest wear in short-term wear tests. The Bond work index test revealed that the Artvin/Murgul silica sample was the most resistant ore to grinding. These findings provide a foundation for understanding the abrasive performance of ores on grinding balls during long-term grinding operations.

3.2. MBWT

The MBWT results indicate that ball diameter is an effective parameter for ball wear. The wear rate of 40 mm balls differed from that of 20 mm balls, which can be attributed to the increasing surface area-to-volume ratio as ball diameter decreases, exposing proportionally more surface to abrasive contact per unit mass (Matsanga et al., 2023). Table 7 shows the MBWT results.

Table 7. MBWT results

Ore	Time (h)	Feed (Mg)	Mass Loss (g/Mg) 40Ø	Mass Loss (g/Mg) 30Ø	Mass Loss (g/Mg) 25Ø	Mass Loss (g/Mg) 20Ø
Adıyaman/Koçali	100	0.40	16.83	9.62	6.28	4.43
Samsun	100	0.38	10.64	6.85	3.97	2.93
Artvin/Murgul	100	0.29	26.76	15.38	9.86	6.40

Throughout the 100-hour cumulative grinding process, the Artvin/Murgul silica ore showed the highest physical abrasion, while the Samsun slag exhibited the lowest, despite its higher LCPC abrasiveness index. For all three ores, the specific mass loss of 40 mm balls was, on average, about 3.9 times higher than that of 20 mm balls (ranging from 3.6 to 4.2 across the ore types), indicating that the ball-size effect follows a similar trend regardless of ore type. This consistency suggests that, in addition to ore mineralogy, the wear differential between ball sizes is also governed by mechanical factors intrinsic to the charge motion within the mill.

In a tumbling ball mill, wear is not solely a function of ball–ore contact; ball–ball interactions also contribute to media consumption, since larger balls carry higher kinetic energy and generate different collision-energy distributions within the charge than smaller balls, which can influence the effective grinding action experienced by each size fraction (Cleary, 1998; Powell et al., 2011). This inter-ball contact effect, combined with the classical abrasive contact mechanics described by Archard (1953) – where wear volume is proportional to the real contact area, applied load, and sliding distance – helps explain why the wear differential between size fractions remained proportionally stable across ores with very different abrasivity and breakability characteristics.

3.3. Regression analysis and Ball Wear Index (BWI) modelling

3.3.1. Phase 1: Combined grinding energy and LCPC framework

In the first stage of statistical modelling, a prediction model was developed by defining the LCPC Abrasivity Coefficient (LAC , g/Mg), the Bond Work Index (W_i , kWh/Mg), and the nominal ball diameters (d , mm) as independent variables. To capture the wear kinetics observed in the 100-hour MBWT test, a multiplicative power-law regression structure was used.

Before calculating the BWI, a raw equation was first developed using the ordinary least squares method to estimate the raw wear rates obtained from the experiments in g/Mg. Eq. 1 presents the initial regression analysis.

$$W = 14.613 \times (D^{1.9884} \times LAC^{0.8830} \times W_i^{-4.7717}) \quad (1)$$

where W represents the absolute predicted ball wear rate (g/Mg). Table 8 details the parameters of this initial regression analysis, reflecting the raw statistical power before normalization.

Table 8. First regression analysis parameters (Raw Model)

R^2	Adjusted R^2	Significance F	Intercept Coefficient	LAC Exponent	W_i Exponent	Diameter Exponent
0.9932	0.9905	5.36x10 ⁻⁹	2.6819	0.8830	-4.7717	1.9884

To transform this raw empirical output into a standardized, universally applicable industrial screening tool, a systematic normalization procedure was developed. A reference point has been established to normalize the data. The highest abrasion value from the MBWT tests was used as this reference point. In other words, the amount of abrasion caused by the Murgul silica ore using 40 mm balls was established as the reference point.

The Dimensionless Ball Wear Index (BWI) is mathematically defined as the ratio of the estimated raw wear value to this reference point:

$$BWI = \frac{W_{raw}}{W_{max}} = \frac{(14.613 \times (D^{1.9884} \times LAC^{0.8830} \times W_i^{-4.7717}))}{26.76} \quad (2)$$

The normalized BWI formula is given in Eq. 3:

$$BWI = 0.546 \times (D^{1.9884} \times LAC^{0.8830} \times W_i^{-4.7717}) \quad (3)$$

It should be noted that Eq. 3 is an empirical regression relationship rather than a dimensionally homogeneous physical law; similar to Bond's (1961) classical work index equation, $W = 10 \cdot W_i \cdot (1/\sqrt{P_{80}} - 1/\sqrt{F_{80}})$, which likewise combines variables of different physical units (W_i in kWh/Mg; P_{80} , F_{80} in μm) through an empirically derived constant, the fractional exponents on D , LAC , and W_i in the present model were obtained purely from statistical fitting of the experimental data rather than from first-principles unit conversion. Consequently, the equation is valid only when D is expressed in mm, LAC in g/Mg, and W_i in kWh/Mg, consistent with the experimental dataset, and the resulting BWI is dimensionless in the sense that it is normalized to the reference wear value (W_{max}) rather than being dimensionally derived in the strict physical sense.

According to the line fit plot from the regression based on the bond index, there is a strong correlation in the data. The estimated values of the independent variables are nearly perfectly consistent. Line fit plots are shown below in Fig. 2.

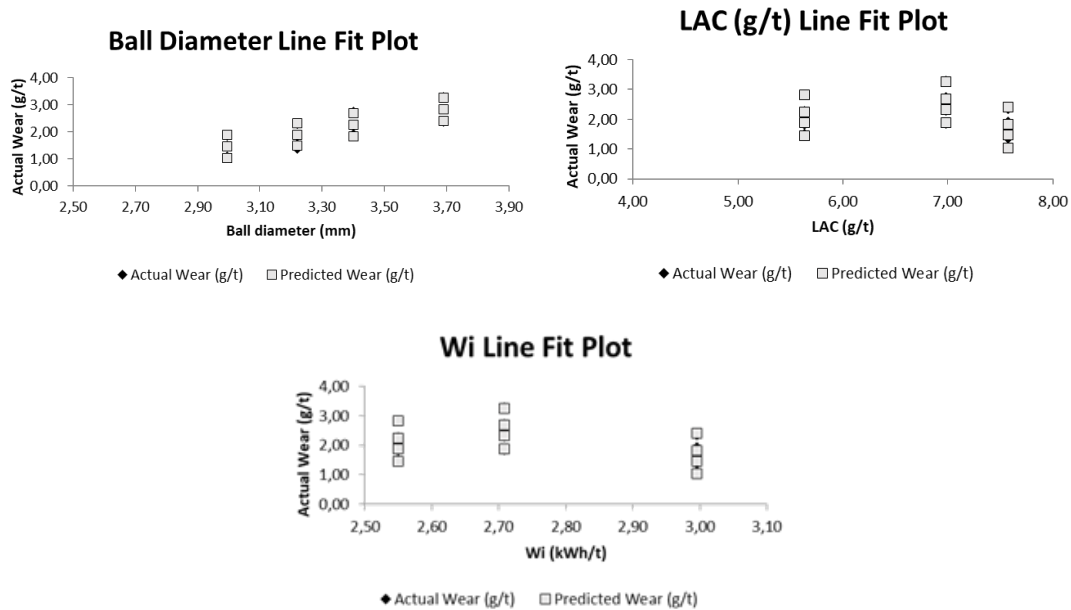


Fig. 2. Line fit plots showing the relationship between ball wear and independent variables: ball diameter, LCPC abrasivity index (LAC), and Bond work index (W_i)

Residual plot analysis was used to examine the prediction errors of the Bond work index-based regression. Upon examining the graph, it was evident that the residuals were distributed around the origin on the x-axis. The fact that all data remained within the range of plus or minus 0.1 proves the reliability of the regression. Fig. 3 shows the residual plots for the independent variables.

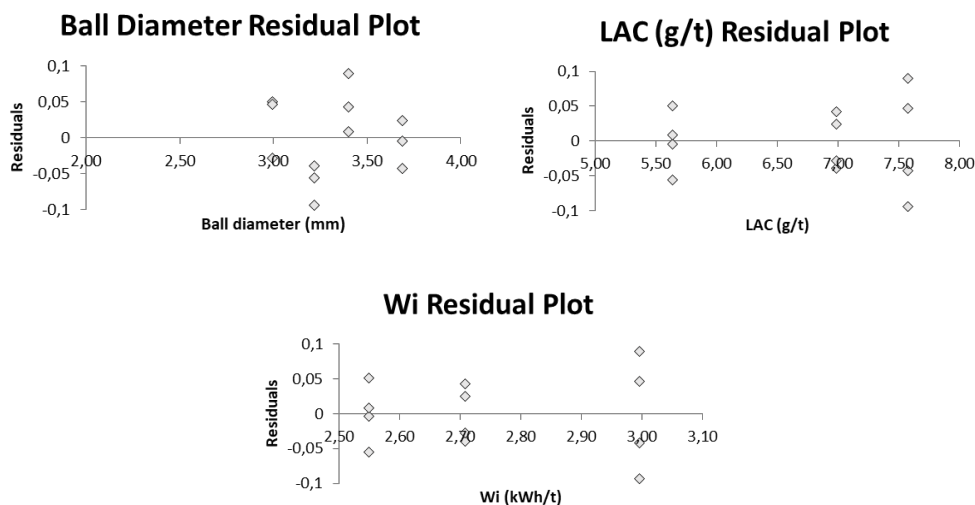


Fig. 3. Residual plots showing the distribution of prediction errors for the independent variables used in the regression analysis: Ball diameter (mm), LAC (%), and W_i (kWh/Mg)

The data distribution was evaluated using a normal probability graph and bond-based regression analysis. Upon examination of the graph, the data points show a linear trend. This slope indicates that the residuals are normally distributed and that extreme values did not drive the R^2 value for the study. Fig. 4 shows the normal probability plot.

The linear extension of the data along the correlation line between the actual and predicted wear graphs shown in Fig. 5 demonstrates the model's high predictive power. The results obtained show that, in terms of sensitivity, the proposed LAC -based BWI yields performance comparable to that of a similar grinding-behaviour parameter, without using the Bond work index.

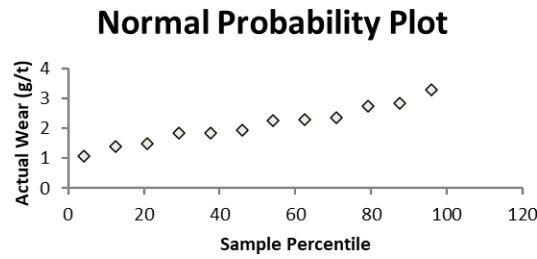


Fig. 4. Normal probability plot

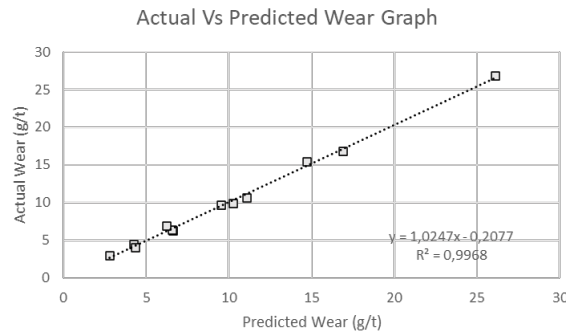


Fig. 5. Comparison between experimentally measured wear values and predicted wear values obtained from the regression model 1

3.3.2. Phase 2: Pure LCPC parametric framework (Rapid Screening Model)

In the second phase of the study, the plan was to evaluate the ore's grinding characterization in the model using a single, low-material laboratory routine. For this reason, the LCPC Abrasiveness Coefficient (*LAC*, g/Mg) and the LCPC Breakability Coefficient (*LBC*, %) along with nominal ball sizes were set as the independent variables.

As in the first stage, the raw wear values were analyzed using the OLS method with the LCPC test parameters. The results obtained from the regression analysis are presented in Eq. 4:

$$W = 11.418 \times (D^{1.9883} \times LAC^{-0.4593} \times LBC^{-1.0350}) \quad (4)$$

where *W* represents the absolute predicted ball wear rate (g/Mg). Table 9 details the parameters of this initial regression analysis, reflecting the raw statistical power before normalization.

Table 9. Second regression analysis parameters (Raw Alternative Model)

R^2	Adjusted R^2	Significance F	Intercept Coefficient	LAC Exponent	LBC Exponent	Diameter Exponent
0.9932	0.9905	5.36×10^{-9}	2.4352	-0.4593	-1.0350	1.9883

Applying the identical normalization protocol to maintain absolute scaling integrity across both frameworks, the raw equation was divided by the empirical upper wear limit of the Murgul silica ore.

$$W = \frac{W_{\text{raw}}}{W_{\text{max}}} = \frac{11.418 \times (D^{1.9883} \times LAC^{-0.4593} \times LBC^{-1.0350})}{26.76} \quad (5)$$

Finalized, dimensionless alternative Ball Wear Index equation represented in Eq. 6:

$$BWI = 0.4267 \times (D^{1.9883} \times LAC^{-0.4593} \times LBC^{-1.0350}) \quad (6)$$

As in Eq. 3, the fractional exponents in Eqs. 4–6 result from empirical curve-fitting rather than dimensional derivation (see the discussion following Eq. 3); accordingly, Eq. 4 is valid only when *D* is

expressed in mm, LAC in g/Mg, and LBC in %, and the resulting BWI in Eq. 6 is dimensionless in the normalized sense described above.

The line-fit plots in Fig. 6 show the effect of each independent variable on ball wear. The close match between the model-predicted values and the experimental data indicates that the model accurately explains the relationship between the variable parameters and the wear results. This fit also confirms the R^2 value obtained from the ANOVA analysis.

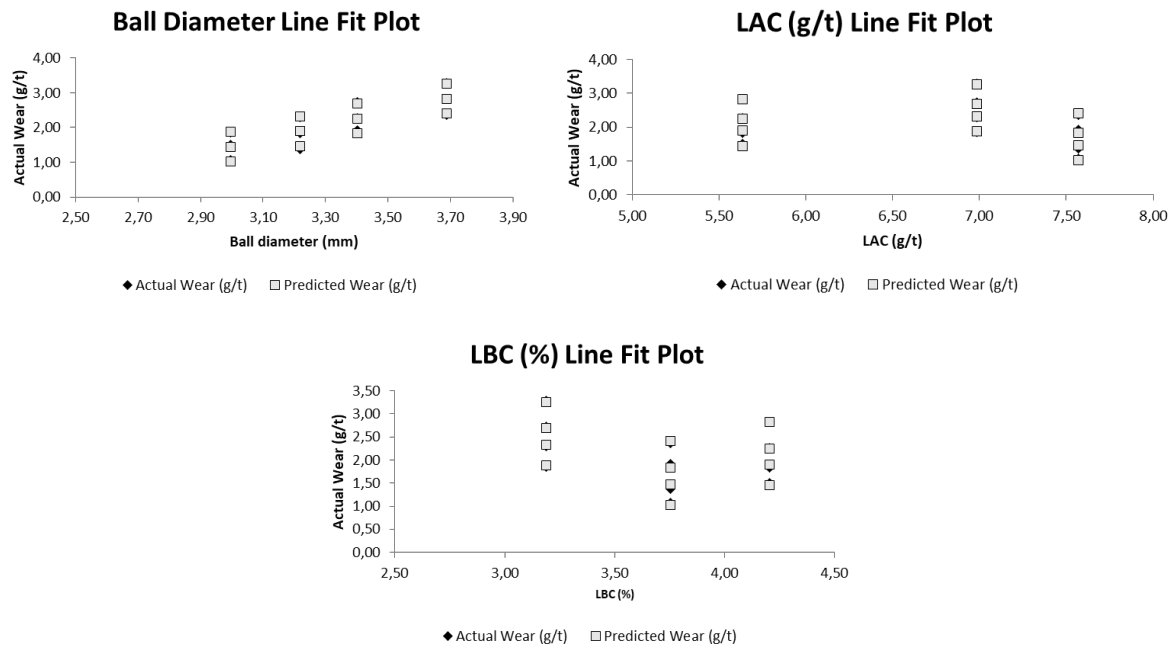


Fig. 6. Line fit plots showing the relationship between ball wear and independent variables: ball diameter, LCPC abrasivity index (LAC), and Breakability coefficient (LBC)

The identical statistical performance ($R^2 = 0.9932$) achieved by substituting the material-heavy Bond Work Index (W_i) with the rapid LCPC Breakability Coefficient (LBC) proves that rock friability and grinding energy tendencies are fully captured within the particle-size degradation characteristics of the short LCPC cycle. The tight, random distribution of residuals within the strict ± 0.1 margin in Fig. 7 mathematically verifies that the OLS estimators remain unbiased, preventing systematic forecasting errors across different media sizes.

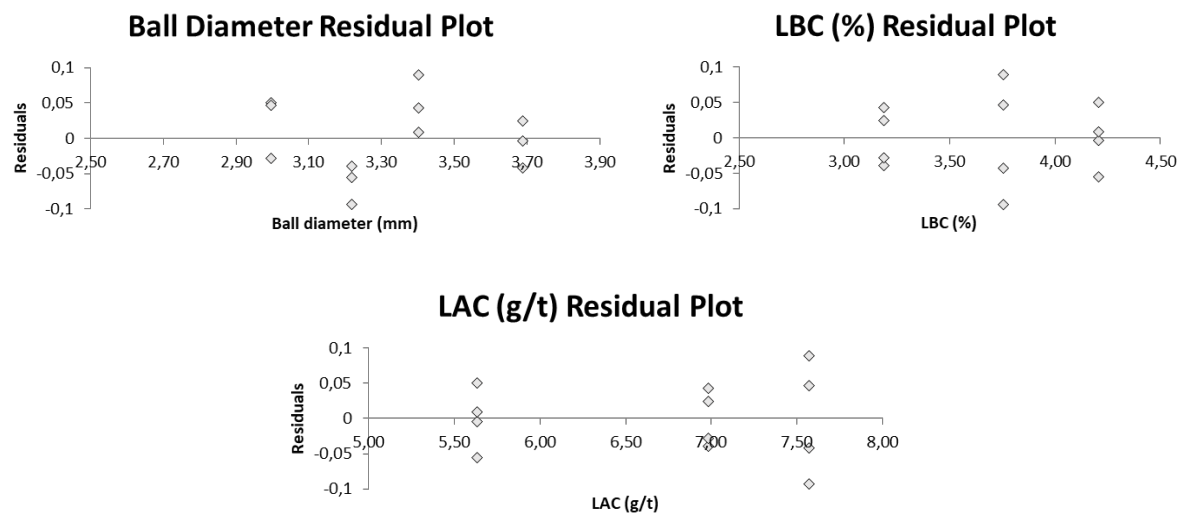


Fig. 7. Residual plots showing the distribution of prediction errors for the independent variables used in the regression analysis: Ball diameter (mm), LBC (%), and LAC (g/Mg)

Fig. 8 shows a normal probability plot used to assess the statistical assumptions of the multiple linear regression analysis. The data points on the plot progress along a diagonal line with a clear linear slope. This consistency indicates that the correlation coefficients were not obtained from random outliers.

Fig. 9 presents an actual vs. predicted wear graph summarizing the model's performance. This graph obtained a correlation coefficient higher than that of the regression analysis, with an R^2 value of 0.9968.

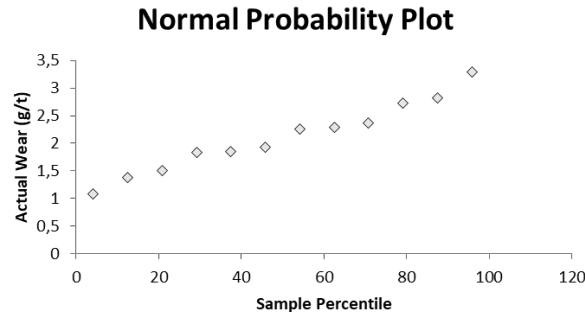


Fig. 8. Comparison between experimentally measured wear values and predicted wear values obtained from regression model 2

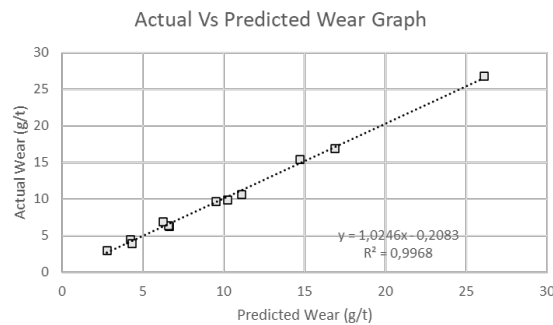


Fig. 9. Actual vs. predicted wear graph

A standard classification scale, shown in Table 10, has been defined to evaluate the performance of grinding media balls. Using this scale, *BWI* results can be evaluated in four different categories ranging from 0.00 to 1.00. The four-tier classification scale presented in Table 10 was constructed using equal-width intervals (0.20) across the normalized 0–1 *BWI* range. This discretization approach follows the established practice in geomechanical and mining engineering classification systems, where continuous numerical indices are commonly divided into equal-interval categories to facilitate practical interpretation—for example, the Rock Mass Rating (RMR) system, which classifies a continuous 0–100 score into five equal 20-point bands ranging from "very poor" to "very good" rock quality (Bieniawski, 1989). As *BWI* is a newly proposed index derived from a limited set of ore types, the four-tier scale presented here should be regarded as an initial screening classification; its boundaries may be refined and statistically validated as the *BWI* model is extended to a broader range of ores in future studies.

Table 10. Wear classes

BWI	Wear Class
0.00-0.20	Low
0.20-0.40	Low-Medium
0.40-0.70	Medium
0.70-1.00	High

The experimental results obtained suggest a consistent relationship between LCPC test results and ball wear observed in the laboratory environment. The regression-based modelling study highlights the combined effect of ball size and ore properties. Together with the LCPC test data, the findings provide

useful inputs for evaluating grinding media wear under test conditions. To better understand the underlying reasons for this observed relationship, the physical mechanisms governing abrasivity and grinding media wear are discussed below.

The relationship between LCPC abrasion indices and grinding media wear at the laboratory scale can be physically interpreted in terms of the dominant wear mechanisms in both environments. LCPC tests, under controlled impact and shear conditions, can be thought of as increasing micro-shearing and sliding mechanisms, analogous to ball-ore contacts in ball mills, where the same physical mechanisms are expected to occur through repeated particle-surface interactions.

Grinding media wear generally results from abrasive interactions between hard, angular mineral phases and balls. Although stress states and contact geometries differ between the LCPC device and grinding conditions, properties such as hardness, angularity, and roughness exhibit similar mechanisms of action in both systems. Consequently, the LCPC index does not directly represent an abrasion value. However, it can be used as an effective indicator because it captures the relative abrasiveness tendencies that influence the grinding medium's abrasion behaviour under laboratory conditions.

When examining the abrasion index classification, differences in behaviour were observed between Samsun copper slag and Artvin Murgul silica. This difference serves as a good example of the model's abrasion prediction behaviour. Despite its high *LAC* value, Samsun slag is classified as moderately abrasive. XRD and SEM-EDS analyses (Table 3) showed the slag to consist predominantly of crystalline fayalite ($(\text{Fe,Mg})_2\text{SiO}_4$, 84.9 wt%) together with magnesioferrite and cuprospinel spinel phases, rather than an amorphous glassy matrix. While this dendritic silicate structure presents a locally hard surface that produces high friction under the high-speed steel impeller of the LCPC test, it is characteristically brittle under multidirectional impacts, consistent with observations that brittle crystalline phases tend to fracture and generate fines under impact rather than sustaining prolonged abrasive contact (Iwasaki et al., 1985; Radziszewski, 2002). Because the slag has a high breakability (*LBC*) value of 42.70, a large amount of fine particles is produced during grinding, which, combined with the cushioning effect during grinding, also results in reduced wear on the balls.

As a counterexample, Murgul Silica, which falls at the upper limit of the high-wear class, was examined. XRD confirmed this sample to be essentially monomineralic quartz (100 wt%; Table 3), consistent with MLA modal mineralogy (64.1 wt%; Table 4). This high wear is due to a combination of low brittleness and a massive quartz structure. Unlike slag, which has a brittle structure, these particles increase ball wear by retaining their sharp, angular edges due to their resistance to grinding in the grinding medium, consistent with the general observation that hard, angular mineral phases such as quartz sustain abrasive and micro-cutting wear mechanisms over extended grinding periods (Jankovic, 2003). This comprehensive mechanism confirms that the developed index not only correlates statistical inputs but also effectively maps the physical and mineralogical structural degradation in industrial grinding environments.

4. Conclusions

This study established a quantitative relationship between ore abrasivity, characterized by the LCPC test, and grinding media wear measured through 100-hour marked ball wear tests. The results confirm that LCPC-based regression models can predict ball wear with high correlation coefficients ($R^2 > 0.99$), offering a faster and less material-intensive alternative to the traditional Bond abrasion index.

Ball diameter was found to be a key parameter, with specific mass losses consistently increasing with ball size across all ore types. Notably, the Samsun copper slag exhibited the highest LCPC abrasiveness index but the lowest ball wear, owing to its brittle, crystalline fayalite-spinel structure that generates fine particles rather than sustaining abrasive contact; in contrast, the Artvin/Murgul silica ore, with its hard and angular quartz structure, produced the highest wear despite a lower *LAC* value. This contrast underscores that ore mineralogy – not abrasivity index alone – governs the dominant wear mechanism, and it is captured by the proposed dimensionless Ball Wear Index (*BWI*).

While the developed *BWI* model shows strong internal consistency, it remains limited to the specific laboratory mill dynamics and the three ore types tested. Future work should expand the ore range, test additional ball chemistries, and validate the model against industrial-scale data.

Acknowledgments

The materials used in this study were obtained from the Adıyaman, Murgul, and Samsun sites owned by ETİ Bakır C.O, as well as grinding balls used at the experiments are sourced from ETİ Bakır C.O ball production plant. All tests, analyses, and other experimental procedures conducted in this study were carried out at the ETİ Bakır C.O R&D center. A part of the results reported in this paper were presented at XX Balkan Mineral Processing Congress BMPC 2026 entitled "Investigation of the effects of ore abrasivity index on ball wear in wet ball milling operations with lab scale tests".

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