Effect of Grading of Chromite Ores on the Quality of Briquettes

Ranjan SEN,1) M. K. MITRA,2) Siddhartha MUKHERJEE2) and Rajib DEY2)

1) Tata Steel (KZN) (Pty) Ltd., Richards Bay, South Africa. E-mail: senranjan102@gmail.com
2) Department of Metallurgical & Material Engineering, Jadavpur University, Kolkata, India.

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In this paper, the concept of grading of the feed ores has been used for the purpose of evaluation of the compactness of the briquettes. Fuller curve, the most popular ideal grading curve, has been considered. Ideal grading curves can lead to the maximum extent of compaction in the briquettes, ensuring highest strengths of the briquettes. The strength of the briquettes from a given fine ore mix has been assessed in relation to the extent of shift of the grading curve for the feed mix, from its ideal Fuller curve. Two parameters, namely, root mean square deviation (RMSD) and coefficient of uniformity (CU) have been used as the measure of the shifts from the corresponding Fuller curves. Mathematical equations have been derived to establish the correlations between the shatter strengths and hot compressive strengths with RMSD and CU. It is observed from the current work that closeness of a feed mix to its Fuller curve can provide satisfactory strength of the briquettes, but the incremental benefit in strength of the briquettes is reduced progressively with closeness to Fuller curve. This approach can be used to produce briquettes of significantly high strength through selective and optimised grading of the feed mixes.

KEY WORDS: briquetting; coefficient of uniformity; root mean square deviation; shatter strength; hot compressive strength; Fuller curve.

1. Introduction

Chrome ore fines and concentrates cannot be charged directly into the smelting furnaces for reasons of safety and bad furnace performances. These materials need to be agglomerated before rendering them suitable for smelting. Briquetting is one of the very popular forms of agglomeration of fine particles. Besides other factors, strength of the briquettes is very sensitive to the size distribution of the feed ore particles. The present work attempts to establish a correlation of the mechanical properties of briquettes at room temperatures as well as elevated temperature (1000°C) and the size distribution of chromite ores.

2. Theoretical Background

2.1. Mechanism of Bonding of Particles

Feed ore particles are mixed uniformly with one or more combinations of binders, namely, molasses, hydrated lime, bentonite, cement, dextrin, starch, sodium silicate and others. The binders serve to coat each of the grains of the feed chromites individually and act as the agent linking the neighboring grains through a bond, mostly developed through some chemical reactions taking place over a reasonable period known as the curing time. For the current work all briquettes were made with molasses, hydrated lime and bentonite as the binders.

2.2. Mix Design Parameters

Good resistance to cracking and disintegration is considered as the primary property of good briquettes. The important parameters of a mix of fine ore particles for production of good quality briquettes are as follows:

- Properties of binders, such as viscosity for liquid binders and grain sizes for solid binders
- Effective binder content (EBC)
- Binder film thickness (BFT)
- Voids in mineral aggregate (VMA) or Porosity

2.3. Particle Size Analysis

Particle size analysis is the percentage by weight of particles within different size ranges. The standard size classifications in use are the following:

- Sieve (square apertures)
- Hydrometer or pipette sedimentation tests based on Stokes’ law, 1891

In the present work only sieve analysis using square sieves has been resorted to.

Some of the important key parameters of relevance for characterization of the feed materials with respect to their size distribution are given below:

\[ \text{Coefficient of uniformity: } \text{CU} = \frac{D_{60}}{D_{10}} \]

Where \( D_{60} \) and \( D_{10} \) are the square apertures for which 60% and 10% of the sample is smaller, respectively.

2.4. Porosity of an Aggregate

The distribution of sizes of all the particles in a given mass of chromite ore will decide the amount of void spaces in the briquettes. Porosity of a compacted mass is a measu-
ure of the total voids in the compact. Too much of coarse sizes, or too much of fine sizes of chromites in the feed cannot make a high degree of compactness in the briquettes, as that will fail to ensure intimate contacts between the individual grains of the feed chromites. So the higher is the porosity of a compact, the lower is the strength. Thus right grading of the feed ore is essential for achieving reasonably low porosity in the resultant briquettes through higher packing density of the feed chromite particles. The grading of the chromites is, therefore, a very important parameter.

2.5. Grading of Feed Ores

Higher property values for the briquettes are achieved through better compaction of the feed ore particles during the process of briquetting. Right proportion of particles of coarse and fine sizes ensure placement of particles in right places to produce more compacted briquettes. The overall size distribution of the particles is termed as the grading of the feed.

Grading is defined as relation between size of standard sieve $X_i$ (mm) and the total amount passing through this sieve $Y_i(X_i)$. Grading of a given feed ore is best understood by comparison with standard curves for gradation, more commonly known as “ideal grading curves”. There are different types of “ideal” curves prepared on the basis of theoretical calculations and practical experiments. These curves are Bolomey's curves, Fuller's curves, Graf's curves and Rissel's curves.

The most known, acceptable and popular form is Fuller’s ideal curve, named after Fuller and Thompson (1907). Ideal grading for maximum density packing is obtained by plotting the ideal percentage of material passing through a given set of standard sieves, which is given by

$$p_i = \left( \frac{d_i}{d_{\text{max}}} \right)^n \times 100$$

Where $p_i$ = % passing square aperture size $d_i$, $d_{\text{max}}$ = maximum particle size, mm, $n = 0.5$, grading co-efficient for Fuller’s curve

The Fuller curve describes the uniformity properties of the spherical particles for the densest possible state of packing. The coefficient of uniformity (CU) for the ‘ideal’ Fuller curve is 36.21 CU of a given material is a good measure of the shift from its Fuller curve.

Feed mix aggregates of the ores that follow the Fuller's curve have just enough fines to fill all the spaces left by the coarse particles. If the grading is above the Fuller’s curve, it has more fines than the space between the coarse particles, resulting in poor contact amongst the coarse particles. Below the Fuller’s curve, there may not be enough fines to fill all the spaces between the coarse particles.

3. Materials and Method

3.1. Feed Mixes for Briquettes

One grade of chromite concentrate from India and three grades of concentrates from South Africa have been used in the study. The names of the concentrates from South Africa are (i) Niemkor, (ii) Nkomati and (iii) UG-2. During loading of cured briquettes into smelting furnaces, some fines were generated and screened with 6 mm screen. The under-size from the screen (<6 mm) was also recycled with the raw ores for making briquettes. Batches of briquettes with both raw ores and mixture of raw ores and dry recycled briquettes have been studied in the present work. Altogether nine batches have been tested in the current work through briquetting. Four more batches were included for the study of correlation of two parameters, namely coefficient of uniformity (CU) and root mean square deviation (RMSD) from ideal curves.

3.2. Binders

The three binders used in this work are (i) molasses, (ii) hydrated lime and (iii) bentonite. While molasses and hydrated lime are known to impart adequate cold strengths to the briquettes through curing, bentonite increases the mechanical strengths under load at high temperatures to combat disintegration of briquettes back into fines during their descent inside the smelting furnaces.

3.3. Process of Briquetting

Dried concentrates were mixed with the binders in mixers to ensure homogeneous mixing. The proportions of molasses, hydrated lime and bentonite were kept around 4%, 2% and 4% respectively. The mix was then compacted in hydraulically operated roller type briquetting presses to produce green briquettes.

3.4. Screen Analysis Tests

Sieve analyses have been done for every batch for briquetting with different feed ores. Altogether 9 batches have been investigated. Standard sieves have been used and the sizes are 0.038 mm, 0.063 mm, 0.09 mm, 0.125 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 4 mm, 4.75 mm, 5.6 mm, 6.3 mm, 10 mm and 20 mm. From the results of the retained weights of materials on each screen, the percentages of materials passing through any screen have been calculated.

3.5. Fuller Curves

Based on the applicable range of the sieve sizes for any given feed, the corresponding inputs for the Fuller curve are computed using the formula given in Sec. 2.5 of this paper for a grading coefficient of 0.5. For every given feed material for briquetting, besides the size distribution curve, the Fuller curve has also been drawn. Therefore, two distribution curves are drawn for every material that has been used in the current work.

3.6. Root Mean Square Deviation

For each of the feed mixes, RMSD has been calculated between the normal gradation curve and the corresponding ideal Fuller curve. The values of RMSD for the feed grades have been considered as a measure of the degree of grading of the feed mixes.

3.7. Coefficient of Uniformity

For any given grade of feed, based on the percentages of materials passing through the complete set of screens, the equation of the best fit curve has been prepared. The values of $D_{10}$ and $D_{60}$ in mm have been determined from the respective equations. Coefficients of uniformity (CU) have been calculated for the given feed mixes from the corre-
sponding $D_{60}$ and $D_{10}$. The values for CU have been computed also for the ideal grading situations from the Fuller distribution curve for each of the feed materials. CU values for Fuller distribution curves for all the grades are 36.00 in conformity with the published data. The values of CU are also considered to represent the degree of grading, and therefore, besides the RMSD values, CU has also been taken as a basis for characterisation of the feed.

For all the feed mixes, the values of CU are less than 36, indicating clearly that more fines are present compared to the ideal situation. So in the present study, a higher value of CU (subject to a maximum value of 36.00) denotes lesser shift from the Fuller curve.

3.8. Properties Considered for Characterization

3.8.1. Shatter Strength

Shatter strength is a measure for the resistance of the briquettes under impact loading conditions, as required for achieving adequate resistance of the briquettes to disintegration into fines during storage and handling of the briquettes. This denotes the percentage by weight of the briquettes retained on a 20 mm square screen after dropping a batch of 4 kg of briquettes from a height of 2 meters consecutively for 4 times. For every batch of briquettes considered in the current work, the shatter strength values have been monitored for a period of one week, and the average figures for the respective batches have been considered for reporting. In the current work shatter strength has been considered as the parameter to represent the strength of briquettes in cold condition, as impact loading conditions apply to the briquettes during handling of cold briquettes.

3.8.2. Hot Compressive Strength

When briquettes follow the process of descent within a submerged arc smelting furnace, both the load on the briquettes as well as the temperature conditions which they are subjected to, keep on becoming more severe progressively in course of the descending process. The briquettes are required to retain adequate strengths during this passage so as to avoid regeneration of fines till they reach almost the hot effective zone within the furnace where the actual smelting reactions start taking place. These conditions were simulated by heating the briquettes in a muffle furnace at the rate of 10 to 15°C/min up to 1000°C, with a soaking period of 1.5 h at 1000°C. The strengths tested for such briquettes at the elevated temperature of 1000°C under red hot condition were taken as the hot compressive strengths of the briquettes. Tailor-made compressive strength testing machines have been used for measuring the compressive strengths of the briquettes. The compressive strength values represent the force in Newton just to initiate a crack in the briquettes. Like the shatter strength values, hot compressive strengths values were also monitored for a period of one week and the average strength in Newton was taken for evaluation of the hot properties of the briquettes.

3.9. Curve Fitting of Experimental Points

The best-fit curves have been derived from the results of the current work in order to understand the trend of the data points. The best fit curves for the experimental points have been derived with the help of a standard curve-fitting tool, "CurveExpert". This tool generates the best fit equations using regression models, nonlinear regression models, interpolation and splines. The best-fit equation is chosen based on the (i) standard error, (ii) correlation coefficient, (iii) tolerance of fit and (iv) number of iterations required to achieve the fit.

4. Results and Discussion

4.1. Size Distribution and Fuller Curves

From the results of the sieve analyses, the size distribution of thirteen batches and the corresponding Fuller curves were drawn. The normal curve and the Fuller curve for Feed 13 are given in Fig. 1 as a specimen.

4.2. RMSD and CU of the Feed Batches

Based on the sieve analyses results of thirteen batches, the RMSD and the CU values of every feed mixes have been worked out and given in Table 1 below.

4.3. Results of Shatter and Hot Compressive Strengths

Results of shatter tests and hot compressive strengths for the briquettes produced from the nine feed mixes during this work are given in Table 2 below.

4.4. Correlation between CU and RMSD

Based on the data given in Table 1, a plot was drawn between the two parameters RMSD and CU. The objective was to understand the correlation, if any, between these two parameters. An exponential relationship with an inverse

Table 1. RMSD and coefficient of uniformity of raw feeds.

| Type of feed | RMSD | CU for feed |
|--------------|------|-------------|
| Feed 1       | 25.93| 2.41        |
| Feed 2       | 35.88| 1.91        |
| Feed 3       | 22.87| 2.79        |
| Feed 4       | 28.18| 2.32        |
| Feed 5       | 31.30| 2.23        |
| Feed 6       | 28.39| 2.41        |
| Feed 7       | 31.44| 2.34        |
| Feed 8       | 27.88| 2.43        |
| Feed 9       | 29.44| 2.37        |
| Feed 10      | 26.95| 2.45        |
| Feed 11      | 24.90| 2.60        |
| Feed 12      | 24.22| 2.77        |
| Feed 13      | 37.82| 2.00        |
variation is observed, as shown in Fig. 2. In this context it is very interesting to note the following points.

1. Higher CU means more closeness to the ideal Fuller grading curve.
2. Lower RMSD indicates lower extent of shift from ideal Fuller curve, or more closeness to the ideal fuller curve.
3. Such inverse relationships can exist only if the above two statements are true.
4. The correlation shows that both the statements 1 and 2 are true.
5. Therefore, it is logical to study the effect of both these parameters, namely, RMSD and CU on the strengths of the briquettes. Consistent and coherent behaviours are expected for both the cases.

4.5. Impact of RMSD on Strengths of Briquettes

Shatter strengths and hot compressive strengths for the briquettes have been plotted with the RMSD values of the feed mixes. The plots are presented in the Figs. 3 and 4 below. With lower values of RMSD, higher strengths have been achieved.

Closeness to ideal Fuller curve helps to attain more favorable grading conditions in terms of reducing the amount of void space left in the aggregate. As a result, better intergranular contacts are realised as the grading approaches the ideal Fuller curve condition, ensuring better strength through more intimate and enhanced particle-to-particle contacts.

4.6. Impact of CU on Strengths of Briquettes

4.6.1. Relationship between CU and Porosity

For a given shape of materials and given level of the pressure for compaction, higher values of CU, limited to a maximum value of 36, are supposed to make briquettes of higher strengths. On the other hand, the lower is the porosity, the higher is the strength values of the briquettes produced. It has been established for compacted soils, concretes, polycrystalline materials, tablets for pharmaceutical industry, ceramic composites and concrete, that porosity has an inverse relationship with strength. To the best of the knowledge of the authors, no published literature is available for similar work for briquettes.

The relationship between porosity and the CU can be expressed by the following equation:

\[
P = 0.255(1 + 0.83^C)
\]

where \(P\) = porosity and \(C\) = coefficient of uniformity.

By differentiation,

\[
\frac{dP}{dC} = -0.0475 \cdot 0.83^C
\]

and

\[
\frac{d^2P}{dC^2} = 0.0088 \cdot 0.83^C
\]

From Eq. (2) and Eq. (3) it can be noted that the value of \(dP/dC\) is always negative and \(d^2P/dC^2\) is always positive for all possible values of \(C\).

Therefore, the following points are observed.

1. Porosity and CU have an inverse relationship, porosity falls with increase in CU.
2. The rate of fall of porosity increases with increasing value of CU.

From the above, the following hypothesis can be put for-
Hypothesis 1 – As it is already known, the strength depends on the porosity, minimum porosity leading to maximum strength. From Eq. (1) to Eq. (3) it appears that the relation between the strength and CU should not be linear. An exponential relationship is expected to be more logical.

Hypothesis 2 – It is possible that the maximum advantage in terms of strength of the compacts is achievable much before attaining the ideal Fuller curve situation with CU = 36.

4.6.2. Relationship between Strength and Porosity

A relationship between strength and porosity is available for compacts made by powder metallurgy process. The process of briquetting using hydraulic presses has very good similarity to powder metallurgy process. The strength (S) and porosity (P) of the compacts are related by the following formula.7)

\[ S = S_0 (1 - hP) \] ................................(4)

where \( S_0 \) is the zero-porosity strength, \( P \) is the porosity of a compact and \( a \) is a constant, characteristic of the material. This equation is known as Ryshkewitch–Duckworth equation. This strength refers to the yield strengths of the compacts. This equation has been widely used for polycrystalline brittle materials. But this equation holds good only over the lower end of the range of porosity.9)

Several other investigators have shown that a linear function is more appropriate for covering the entire range of porosity.10,11) The concerned equation is given below.

\[ E = E_0 (1 - hP) \] ................................(5)

where \( E \) is the yield strength of a compact, \( E_0 \) is the zero-porosity yield strength, \( P \) is the porosity of a compact and \( h \) is a constant, characteristic of the material.

Chrome ore briquettes are brittle and the breaking strengths for testing of briquettes is the load at which a crack has just initiated in the briquette. Considering these two facts, the yield strengths in Eq. (5) can be safely substituted by the compressive strengths of the briquettes. Equation (5) can be modified as

\[ S = S_0 (1 - hP) \] ................................(6)

where \( S \) is the compressive strength of a compact, \( S_0 \) is the zero-porosity compressive strength, \( P \) is the porosity of a compact and \( h \) is the material constant.

In this paper Eq. (6) will be used for further treatments.

Combining Eq. (1) and Eq. (6), Eq. (6) can be rewritten as

\[ S = S_0 (1 - h(0.255 + 0.255 \cdot 0.83^C)) \]
\[ = S_0 - 0.255S_0 h - 0.255S_0 h \cdot 0.83^C \] ................(7)

By differentiation,

\[ dS/dC = -0.255S_0 h \cdot \ln 0.83 \cdot 0.83^C \]
\[ = -0.255S_0 h \cdot (-0.1863) \cdot 0.83^C \]
\[ = 0.0475S_0 h \cdot 0.83^C \] ................(8)

and

\[ d^2S/dC^2 = 0.0475S_0 h \cdot \ln 0.83 \cdot 0.83^C \]
\[ = 0.0475S_0 h \cdot (-0.1863) \cdot 0.83^C \]
\[ = -0.0088S_0 h \cdot 0.83^C \] .......................(9)

It can be seen that for all possible values of \( S_0, h \) and \( C \), \( dS/dC \) is always positive and \( d^2S/dC^2 \) is always negative. Therefore, with increase in CU the strengths will increase but the rate of rise of strength will fall. This behaviour is in agreement with the two hypotheses mentioned in Sec. 4.6.1.

4.6.3. Strength–Uniformity Relationship from Results

Shatter strengths and hot compressive strengths for the briquettes have been individually plotted with the CU values of the feed mixes and the resulting graphs are presented in the Fig. 5 and Fig. 6 below. While drawing the curve for shatter strength vs. CU, besides the experimental results, two other extreme points have been considered. The lower extreme point is CU = 0, fully sorted mix, which has no capability to form briquettes, and hence the corresponding shatter strength would be zero. The upper extreme point is CU = 36, fully graded mix, which is expected to give the full shatter strength, i.e., 100%. It should be mentioned here that both these extreme points are ideal to achieve in practical situations, however, these two points have been included for obtaining the most realistic and practical relationship in the working range of the values of CU.

As can be seen from Fig. 5 and Fig. 6, with higher values of CU's, higher strengths have been achieved. Since higher values of CU's mean more closeness to the ideal grading conditions, it is observed that shifting of a given feed mix for briquetting towards the ideal Fuller curve will ensure...
higher strengths of the briquettes. This is also true for hot compressive strengths at 1 000°C. The equations obtained from the experimental results and given in Table 3 and are reproduced below.

(A) For shatter strength vs. CU the equation is

\[ S_1 = 98.89 - 98.89e^{-1.13C} \] ..........................(10)

and

\[ dS_1/dC = 117.75e^{-1.13C} \] ..........................(11)

\[ d^2S_1/dC^2 = -126.27e^{-1.13C} \] ..........................(12)

Therefore, from the experimental results, it can be mentioned that for any value of \( C \) in the range of 0–36,

(i) \( dS_1/dC \) is always positive, which means that the strength increases with increasing \( C \).

(ii) \( d^2S_1/dC^2 \) is always negative, which means that the rate of rise in strength decreases with increasing value of \( C \).

(B) For hot compressive strength vs. CU the equation is

\[ S_2 = 12429 - 12429e^{-0.046C} \] ..........................(13)

and

\[ dS_2/dC = 571.73e^{-0.046C} \] ..........................(14)

\[ d^2S_2/dC^2 = -26.30e^{-0.046C} \] ..........................(15)

Here also it is observed that for any value of \( C \) in the range of 0–36,

(i) \( dS_2/dC \) is always positive, which means that the strength increases with increasing \( C \).

(ii) \( d^2S_2/dC^2 \) is always negative, which means that the rate of rise in strength decreases with increasing value of \( C \).

In both the cases (A) and (B), the nature of the first derivative is positive. This shows that the strength values increase with increasing values of CU. The second derivatives being negative in both the cases, the rate of increment of strength is decreasing with increasing values of \( C \). This means that as we approach the ideal Fuller curve, the incremental benefit in strength is going down progressively. The results of the treatments of the experimental data are also found to be in full agreement with the theoretical treatments done based on prior work, as given in Eqs. (8) and (9).

### 4.7. Check on the Validation of the Results

It is observed from the relationships obtained from the results that the nature of such relationships are in good agreement with the derivations as made in Sec. 4.6.1 and 4.6.2 from the published literatures for the interdependencies of porosity, coefficient of uniformity and strengths of compacts. The following relationships have been obtained from the experimental results.

**Relationship 1** – RMSD and CU have an exponential relationship.

**Relationship 2** – Shatter strengths and hot strengths hold linear inverse relationship with RMSD.

**Relationship 3** – Shatter strengths and hot strengths have direct exponential relationship with CU.

**Relationship between the strengths and CU as obtained from the results are also found to be in agreement with hypothesis 1 mentioned in Sec. 4.6.1.**

### 4.7.1 Validation of Shatter Strength and CU Relationship

It is possible to combine the relationships 1 and 2 in Sec. 4.7 to arrive at the relationships between the strengths and Coefficients of Uniformity, which is in principle the same relationship as determined in relationship 3. In this section, the equations generated for the relationships 1 and 2 have been combined and the equation so derived has been compared with the equation obtained for strength-Uniformity relationship.

The equation for shatter strength vs. RMSD as seen from the results are also found to be in agreement with hypothesis 1 mentioned in Sec. 4.6.1.
Fig. 3 is

\[ S_1 = 100.10 - 0.29D \] .................................(16)

where \( S_1 = \text{shatter strength} \) and \( D = \text{RMSD} \).

The equation for RMSD vs. CU as seen from Fig. 2 is

\[ D = 109.09e^{-0.56C} \] .................................(17)

where \( D = \text{RMSD} \) and \( C = \text{CU} \).

Combining Eq. (16) and Eq. (17), the equation for shatter strength vs. CU should be

\[ S_1 = 100.10 - 0.29 \cdot (109.09e^{-0.56C}) = 100.10 - 31.64e^{-0.56C} \] .............................(18)

The equation obtained for shatter strength vs. CU from the results as given in Fig. 5 is

\[ S_1 = 98.89 - 98.89e^{-1.13C} \] ..........................(19)

Both Eq. (18) and Eq. (19) are of the same exponential form.

The same validation check for hot compressive strength vs. CU establishes the exponential form of the equation obtained from the experimental results.

The outcome of the validation check is summarised in Table 3.

It can, therefore, be stated that the relationships obtained through the experiments are fairly reliable.

5. Conclusions

The following major conclusions could be drawn based on this study:

(1) Fuller curve can serve to be an ideal guideline for assessment of a given feed mix with respect to the strengths of the briquettes to be produced.

(2) Although the distribution curve of a given feed mix should be as close as possible to its ideal Fuller curve distribution to get high strength of briquettes, the incremental benefit is progressively reduced with increasing closeness to the Fuller curve. This means that it is not necessary to struggle to make a synthetic feed-mix with CU value close to the ideal CU value of 36. Reasonably good strength can be expected even at lower values of CU due to the exponential nature of relationship.

(3) Two parameters, namely (i) the coefficient of uniformity and (ii) the root mean square deviation for the distribution curve of a given feed mix from its ideal Fuller grading curve, can be used very reliably for assessment of the shift from ideal Fuller curve, and thereby evaluation of the strengths of the briquettes to be produced from such feed mixes.

(4) Both the parameters, namely (i) the coefficient of uniformity and (ii) the root mean square deviation demonstrate a high degree of correlation for prediction of the shatter strengths and hot compressive strengths within a reasonably close band of strength values.

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