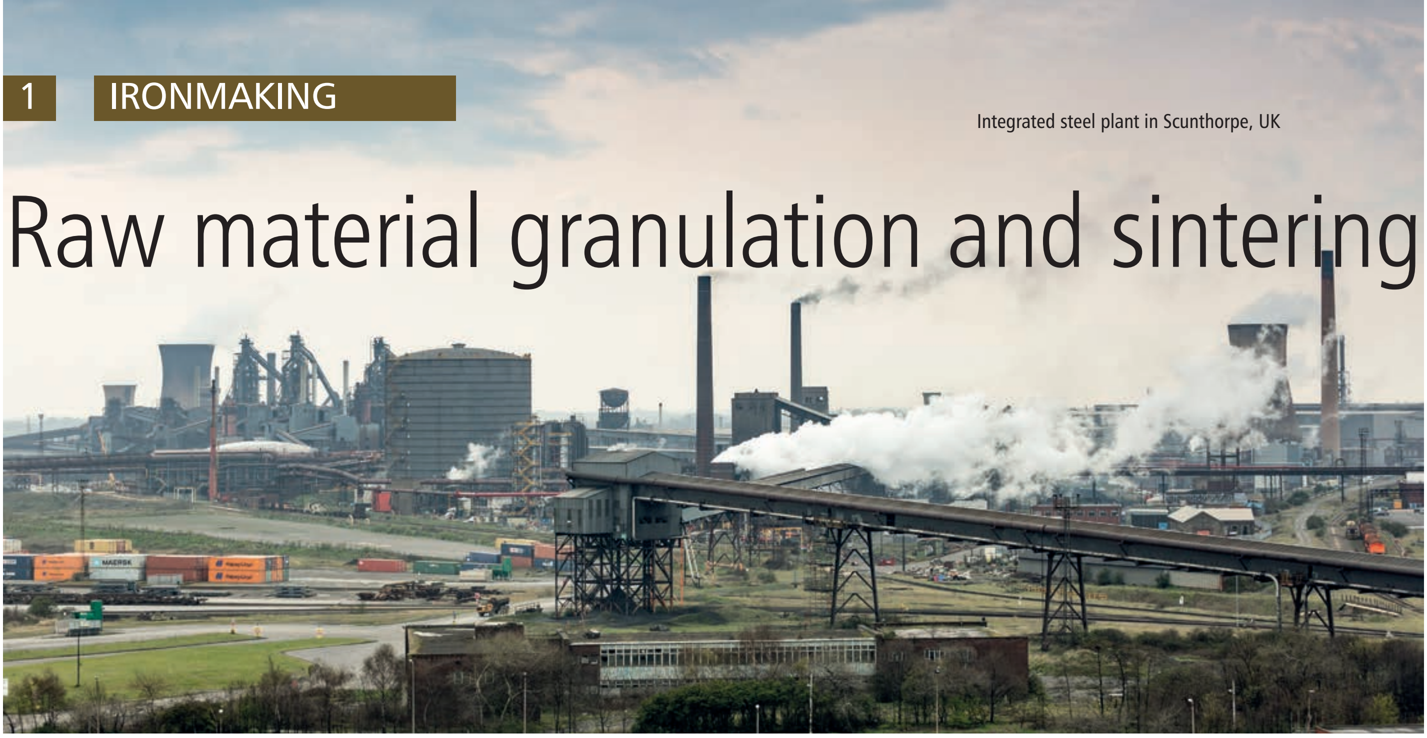
Raw material granulation and sintering



Integrated steel plant in Scunthorpe, UK

Granulation of raw materials is the single most important factor in controlling the permeability of the sinter bed and hence the productivity of the sinter line. Treatment of the binding water in a magnetic field reduced its surface tension enabling better binding of the small fraction size and so producing a stronger green ball generating fewer fines on feeding to the sinter bed, improving bed permeability and so enabling line speed to be increased by 11%. This paper reviews the literature and applies the findings to sinter machines at the Bokaro Steel Plant. By **S Dhara, M Roy, M K Singh, S Acharya, G M Chowdhury and S K Pan**

SINTERING is a thermal process by which a mixture of iron ores, return fines, recycled products of the iron and steel industry (furnace dusts and mill scale), slag-forming elements, fluxes and coke are agglomerated by incipient fusion caused by heat produced by combustion of the solid fuel within the mass itself. The aim is to produce a sintered product of a suitable chemical composition, quality and granulometry to be used as burden material in the blast furnace. The products that are usually agglomerated have a particle size lower than 8mm, while the resulting sinter, has a screened size of 5-40mm, and can withstand the pressure and temperature conditions in the blast furnace. The first step is acquiring a homogenous mixture of diversified raw materials, so as to obtain a sintered product of suitable properties. The second stage is raw materials granulation. This process is based on the homogenisation of the raw mix in a mixing drum for several minutes with the addition of 6-8% water. The product of this process of granulation, ie ball formation, is subsequently delivered as a layer onto the continuously moving grates or 'strands' of the sinter line – the commencement of the third stage of sintering. The coke breeze within the product is ignited with gas burners at the entry end of the strand, while air is drawn down through the bed causing the fuel to burn. In the sintering process, strand displacement speed and gas flow are controlled (flame front) with the purpose of completing the coke burn prior to the sinter being discharged. The temperatures reached in the process (1250-1350°C) cause the partial melting of the raw mix, that, after a series of reactions, crystallises into several mineral phases of different chemical composition and morphology (mainly hematite, magnetite, ferrites and gangue). The sintered product is broken up and screened when it reaches the end of the strand. As a result of the breaking and screening process, a fine fraction (<5 mm, return fines) is generated. These return fines are recycled to the beginning of the process. **Fig 1** depicts the process flow of a conventional sintering plant.

The objective of balling is to eliminate fines by layering them on the coarser size fractions which act as seed or nuclei, that is, by an auto-layering mechanism of growth[1]. The product, known as a green sinter ball (quasi-particle), is larger in size – with a mean size of 3.02mm – and has a smaller size distribution than the raw feed. Moreover, fines which react and melt readily at lower temperatures, are situated in the outer layers of green balls; while coarser particles, which are more reducible and resistant to hot degradation, form the core.

There are two kinds of attraction forces that govern granulation:

- Interlocking of the particles. This force can be varied in two ways:

(i) By altering the sequence of the mix to be sintered to favour the granulation nucleus action, which is provided by a certain component as it could be the return fines.

(ii) By modifying the sequence of the sinter mix formation with the purpose of including a selective granulation or pre-agglomeration process. An example of selective granulation can be observed at one steelworks of Nippon Kokan Keihin (now JFE Steel) where the return fines act as the nuclei and the lime act as the agglomerating agent. In this way, using a higher amount of fines without lowering productivity.[2]

The second kind of attraction forces that govern granulation is attraction by the

The authors are with the R & D Centre for Iron and Steel (RDCIS), Steel Authority of India Ltd (SAIL) e-mail: subhra@sail-rdcis.com

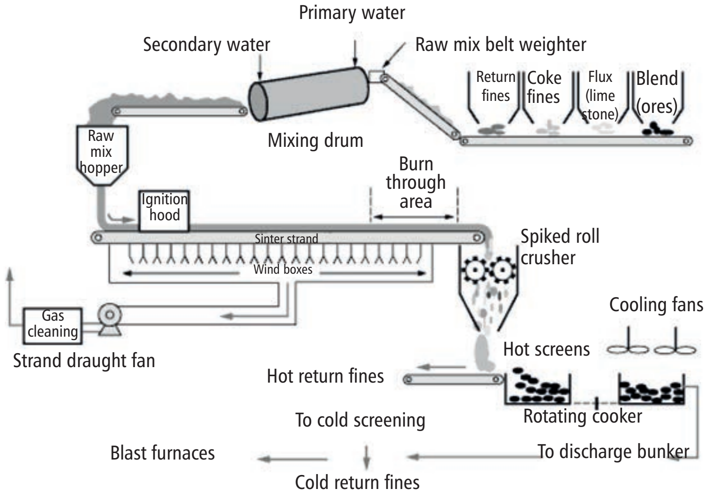


Fig 1. Process flow of conventional sintering plant

creation of liquid phase 'bridges' between particles, these forces can be heightened by means of additives. In any case, these forces have little importance being only strong enough to ensure that the granulate can be transported and deposited on the sinter grate without breaking. The size of the granulated product is between 1 mm and 10 mm.

Granule growth can be broadly classified into (a) wetting & nucleation (b) consolidation & growth (c) breakage & attrition. The auto-layering mechanism,[1] ie the coating of fines present in the feed onto the coarse size fractions which act as seeds or nuclei, provide granule growth. The auto-layering process is explained by many postulates. In the k-postulate, the rate of pickup of fine particles is proportional to the surface area of the rolling granule and a layer is formed of constant thickness irrespective of the nuclei size. Whereas in the more general p-postulate, the rate of layering is proportional to the volume of the rolling granule, and consequently, the granule size is proportional to the seed size. A mixed postulate is that layering occurs initially by a coating of fixed thickness, which is followed by proportionate growth of granules.

Granulation is also affected by the pattern of movement in the drum[3]. For low degrees of filling, frictional force between the drum wall and sinter mix is large enough to overcome the coagulating force so the resulting sinter mix slips inside the drum. At a high Froude number (Froude No.$=Dn^2/g$, where D=Diameter of drum, n = rpm, g = gravitational acceleration), the frictional force and coagulating force balance each other and a steady rolling motion is obtained (cascading zone). The strongest balls are formed when balling drums are operated under cascading conditions. At a very high Froude number, and high degree of filling, the material falls freely (cataract zone) and open space is formed between falling materials and material layered on the bottom of the drum. In addition, the surface features of particles have great effect on the balling mechanism. In general, smooth and spherical particles are hard to conglomerate, while rough and irregular ones readily join together.[4]

Role of water in granulation

The molecular arrangement reveals that each Hydrogen nucleus is bound to the central Oxygen atom by covalent bond9; however, structurally a tetrahedral geometry in which the angle between electron pairs (and, therefore, the H-O-H bond angle) is 109.5°. But because the two non-bonding pairs remain closer to the oxygen atom, they exert a stronger repulsion against the two covalent bonding pairs, effectively pushing the two hydrogen atoms closer together. This results in a distorted tetrahedral arrangement in which the H-O-H angle is 104.5°.

The water molecule is electrically neutral, but the positive and negative charges are not distributed uniformly. The negative charge is concentrated at the Oxygen end, which constitutes an electric dipole of considerably high dipole moment as 1.85 D. This partially positive Hydrogen atom in one water molecule is electrostatically attracted to the partially negative Oxygen of a neighbouring molecule which is called the Hydrogen bond, a weak but unique bond existing in water.

When dry solid particles come into contact with water, the ore surface is wetted and subsequently coated with a water film. In place of contact between particles, water surface tension causes bridges to form. Subsequent rotation inside balling drums and contact of individual water droplets each containing one or many ore grains, result in agglomeration. Subsequently, more liquid bridges appear in places of large voids, inside loose agglomerates.

With further addition of water, the agglomerates condense. As more and more water is trapped between particles, agglomerates become increasingly condensed. At this stage, all pores are filled with water and capillary forces of individual water bridges hold particles together. The effect of this capillary force is visible as a concave outer surface on the agglomerated particles.

Fig 2. Quasi-particle schematic

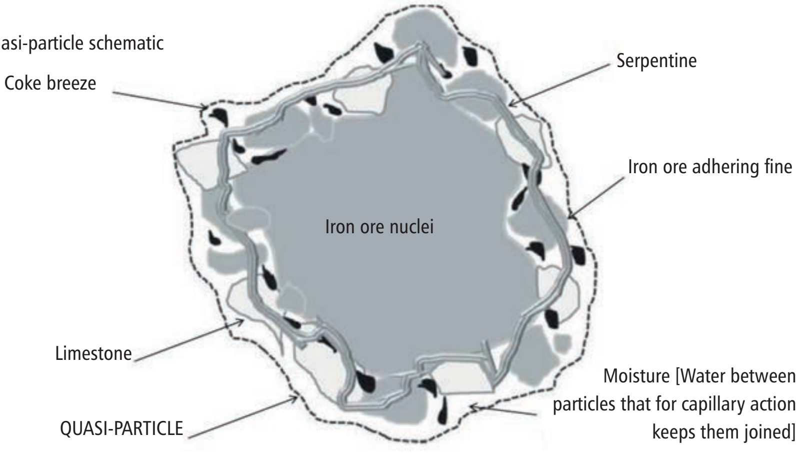
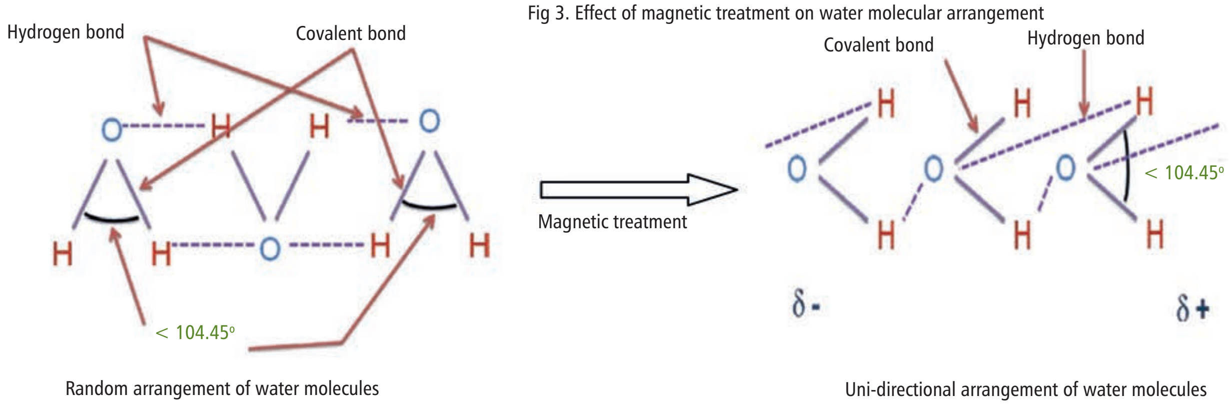


Fig 3. Effect of magnetic treatment on water molecular arrangement



The final stage is achieved when solid particles are fully coated with a continuous film of water. Now the surface tension of water droplets exceeds that of the capillary forces of the water bridges. Thus the surface of agglomerates, which previously appeared as dry and rough, becomes bright. The agglomerate is slightly more plastic but more resistant to dropping. If further water is added, the agglomerates turns to a slurry as capillary forces disappear.

In the course of balling, agglomerates undergo a continuous gradual compaction, at least in the initial period of growth. As a result, the void spaces become increasingly filled with water. Two forces contribute to the tensile strength of the bond in an additive fashion; the pull due to surface tension at the solid-liquid-gas contact line directed along the liquid surface and the negative capillary pressure existing in the liquid bridge. Hence ball strength increases with increasing water content, up to an optimum level. The maximum adhesive strength of green sinter balls is thus reliant on the correct amount of balling water, which depends on the physical properties of the ore, for example, porosity, wettability, moisture capacity and so on.

During mixing, amalgamation of water films around the particles take place and binding of free water at the point of contact produces capillary bonding leading to mutual adhesion of grains. Thus together with favourable granulometry and optimum moisture, the necessary condition for the successful progress of balling depends on the presence of nuclei and presence of definite compressive loads. The balled material is subjected to dynamic action when colliding with the stationary layer or the walls of the balling drum. At this moment, a major part of kinetic energy, which the balls acquire during rolling down, is consumed on completion of residual deformation-on shifting of grains and the compression of balls. In this connection there should be a minimum size for the ball at which it acquires sufficient kinetic energy during rolling down. If the mass of a ball is less than the critical value, the accumulated energy is insufficient for compression work and this ball cannot become a nuclei.

Due to repeated falling and collision with the stationary layer of materials, balls are compressed, meaning granules are packed more closely; this imparts strength to the balls. The addition of colloidal substances, such as lime, increases the plasticity of nuclei and prevents them from breaking during rolling. When particles come closer to each other, the thickness of the water film becomes increasingly less and the adhesive strength increases. In the regime of balling drum operation, there exists a minimum thickness of water films within the ball; which compresses to the value of dynamic loads. When this limit is reached, further release of water to the surface of the ball ceases, the balls stop growing and its strength reaches maximum value.

Factors effecting granulation

Granulation has been widely researched by many authors. Major factors influencing balling are the capacity of the mixture to hold water (maximum water content absorbed by the bed of iron ore particles in a natural state), size range, and amount of balling water.[5] Factors influencing the size of agglomerates in the granulation process from big to small is water addition, mass fraction of size range 0.7-3mm and the capacity of the mix to retain moisture. The first two are positive factors while moisture capacity is adverse for balling.[6]

Nippon Steel Corporation[7, 8] defined the term 'quasi-particle' on the structure of granulated raw mixes. A quasi-particle (**Fig 2**) consists of an iron ore nuclei, not melted during the sintering process, surrounded by fine ore grains with silica gangue in the presence of high basicity (CaO/SiO_2). Particles with a size greater than 0.7mm are nuclei while particles with a size lower than 0.2mm act as adherent fines. The proportion of particles in the size range 0.2mm to 0.7mm should be minimal because they affect the mix permeability in two ways depending on the role that they could play:

- Being nuclei: They give rise to a smaller quasi-particle size, lowering the bed permeability.
- Adherent fines: They are poorly bonded and easily separated from dry particles. Increasing the water content in the raw mix during granulation helps these intermediate particles to adhere to the coarse nuclei, but they quickly detach during drying.

Granulation particles

Venkatramana et al[9] divide feed to the balling drums into three components: coarse (seeds or nuclei), intermediates and fines (layering material). Maeda[10] considers there is no intermediate particle range, rather a smooth transition from completely adhering to nuclei particles as particle size increases. In the intermediate size ranges, for one particular size fraction, some particles act as nuclei while other particles of the same size are adhering. Distribution of particles between adhering and nuclei is a function of moisture content.

The Nippon Steel Corporation[7, 8] in a research project has defined the 'G index'

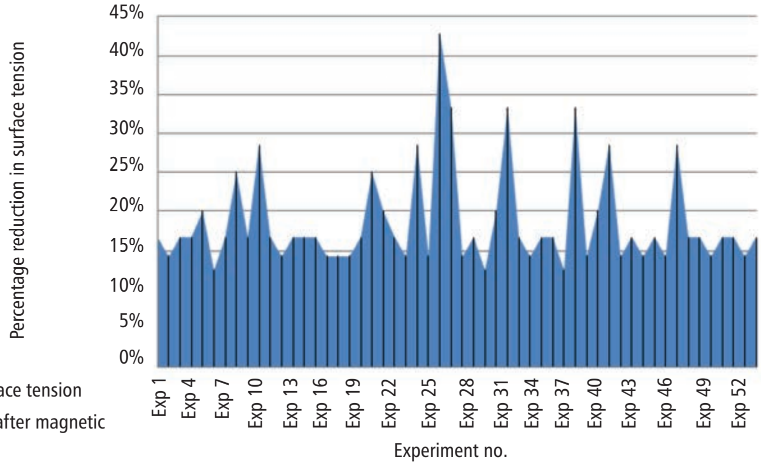


Fig 4. Surface tension reduction after magnetic treatment

for the raw materials granulometric classification according to their behaviour in the sintering process. The G index has been established as a result of practical observation that some fractions have a positive behaviour for granulation and others negative.

In this way the number of particles, N (between 0.7 and 8mm) is an excellent support for the formation of granules. F – the fraction of fine particles (<0.2 mm) adhere to the particles of N fraction to provide stable granules. However, an M fraction (between 0.2 and 0.7 mm) is undesirable because the particles are neither large enough to form stable nuclei or fine enough for adhering. The M fraction would stay in hollows between granules and would reduce bed permeability and so lower productivity.

Moisture content

Moisture content in the raw mix to be sintered is a very important parameter in the granulation stage because the process of adhering fine particles to the nuclei to form quasi-particles is very strongly influenced by the moisture available for granulation[11]. Achieving the maximum air permeability requires a higher moisture addition than the maximum production[12], so it is common practice to work with 0.85 times the requirement for maximum permeability, a practice carried out because moisture condenses in the bottom layer of the sinter bed following evaporation in the upper part as the flame front approaches. Condensation is reported to happen during the first two minutes of sintering before the raw mix reaches its dew point temperature[13].

Research has been carried out into the effect of moisture addition and wettability on granulation by determining the contact angle between iron oxide and water and the iron ore granulation fitness[10]. The study considered one reagent grade hematite, three hematite ores and three goethite ores, determining interaction between the following parameters: nature of ore; porosity (range from 5 to 20); moisture content (11.8, 12.8, and 13.8% vol); wettability time (0 to 20 min); measurement of ore-water contact angle by the sessile drop method (50 to 100°); surface roughness (1.4 to 6.7μm); rpm of the pelletising machine (20, 30 and 40); adherent fine ratio (AR) of fine particles to nucleus (0 to 1); and fracture strength (FS) of quasi-particles (0 to 6).

Several research works have proposed different equations for calculating the optimum moisture content, which could be defined as the lowest amount necessary to achieve maximum bed permeability. The first equation was proposed by Lv et al.[14] They defined a new parameter that is known as moisture capacity (mc, maximum water content that can be retained between ore particles). Moisture capacity increases in line with the external surface area and decreases as the ore pore volume rises. It was established that a sample with high moisture capacity needs more water to achieve the best bed permeability. However, it has not been possible to directly relate permeability with the nature of the ore.

Magnetic field & water surface tension

Studies[15, 16] reveal that, randomly arranged water molecules are arranged in a uniform direction when subjected to a magnetic field. This mode of arrangement causes a decrease in the covalent bond angle to less than 104.5°, leading to a subsequent decrease in the degree of consolidation between water molecules. A diagram of this effect is shown in **Fig 3**. This change in water molecular structure reduces the surface tension of the water.

Magnetic treatment lab experiment

Laboratory scale trials were conducted to measure the effect of magnetic treatment on water surface tension. Magnetic water conditioners were installed on water supply lines, and samples collected before and after these magnetic water conditioners. The surface tension of respective water samples were measured using a capillary method. The reduction in surface tension in percentage terms is reported in **Fig 4**.

Magnetic treatment in industrial sintering

The activation of water treatment using magnetic field depends on the following conditions:

- Magnetic flux density;
- Duration of exposing water to the magnetised field (velocity of water flow);
- Quantity of water exposed to the field;
- Temperature of water;
- Purity of water.

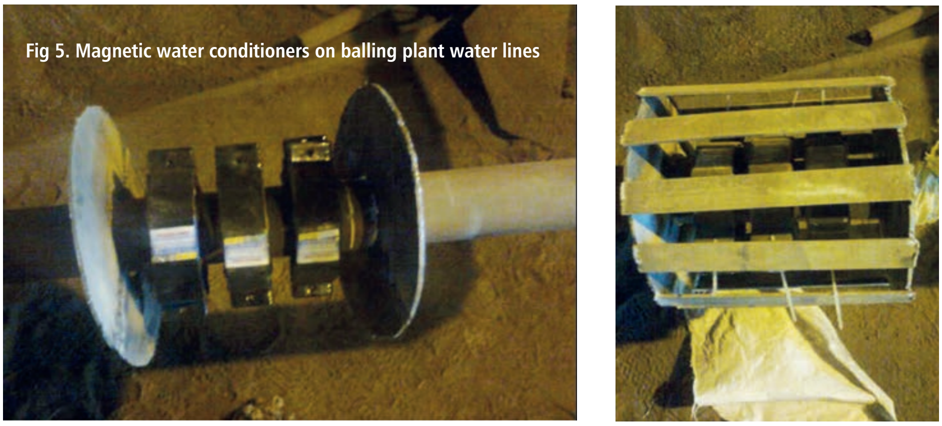


Fig 5. Magnetic water conditioners on balling plant water lines

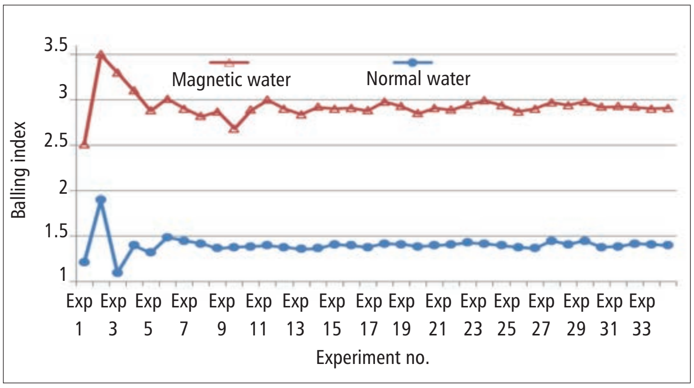


Fig 6. Effect on balling index of magnetic treatment of water

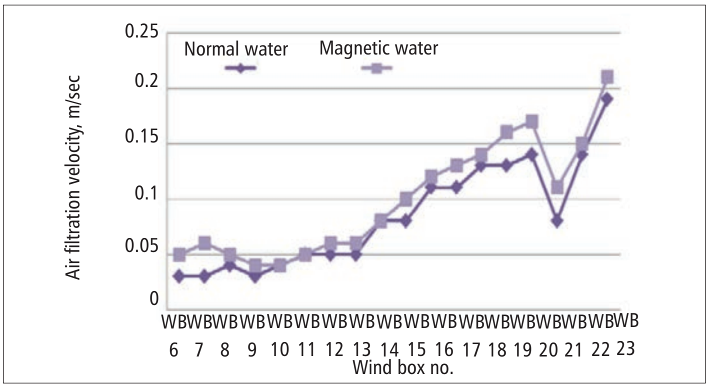


Fig 7. Air filtration velocity sinter line #1 for treated and untreated water

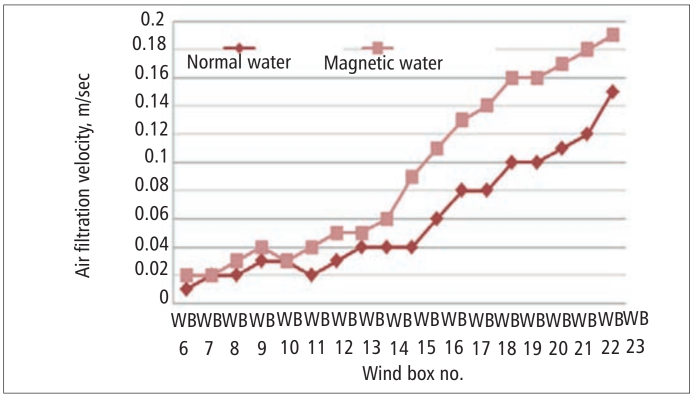


Fig 8. Air filtration velocity sinter line #2 for treated and untreated water

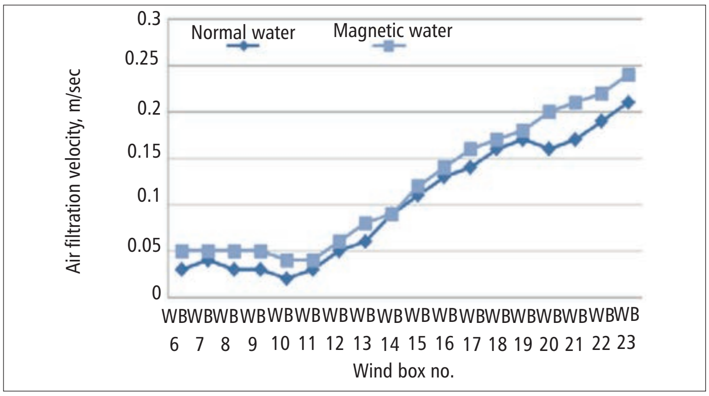


Fig 9. Air filtration velocity sinter line #3 for treated and untreated water

Six magnetic water conditioners of calculated magnetic strength were installed around the water lines of all balling drums at Bokaro Steel's sinter plant (**Fig 5**). The locations of these conditioners were designed, keeping the distance of the balling drum water spray nozzles and variations in water flow rates in mind.

Results

A series of trials were conducted to compare sinter plant performance with and without magnetic treated water.

Improvement in granulation

Samples were taken from the conveyor belt before each drum and a granulometry analysis using a 3mm screen carried out. Samples were also collected from the discharge end of the same drum and analysed for granulometry. Care was taken to collect the sample from the drum outlet just three minutes after collecting the input samples to match the normal traverse time from charging to discharge of the baling drum. The absolute weight and percentage of +3mm particles was measured for normal water and for water that undergone magnetic treatment. On average, a doubling of the balling index was achieved after magnetic treatment (**Fig 6**).

The reduction in water surface tension following magnetic treatment increases the dispersion of water among the fine raw mix inside balling drum. Hence each layer has sufficient water to form strong water bridges without compromising on feed rate or residence time. The granules so formed are stronger in terms of compression, with a subsequent reduction in breakage due to abrasion. A 9% increase in the degree of granulation was achieved.

Air filtration velocity

The velocity of air filtration (the vertical flow of air through the sinter bed) was measured across the width of the sinter cake using an anemometer for the three sinter lines for both magnetically treated water and untreated water. **Figs 7, 8 & 9** compare the results. The stronger balls produced using magnetically treated water retained their structure better during discharge onto the moving pallets of the sinter machines, resisting breakage due to abrasion and thus generating less fines. Thus the mean size of the green sinter balls was improved following water treatment, which subsequently increased the packed bed permeability. Enhanced bed permeability could increase the air filtration velocity through the sinter bed by an average of 17.9%.

Sinter machine speed

The increase in air filtration velocity through the bed enabled an increase in the flame front speed, thus the strand speed could be increased by an average of 11.35 % (**Fig 10**).

Under size generation

Under size sinter (below 5mm fraction in the sinter skip) was monitored on a daily basis and plotted in **Fig 11**. It is evident that the stronger balls produced following magnetic water treatment resulted in an overall reduction of 7.9% in the minus 5 mm fraction.

Specific coke breeze consumption

The improved dispersion of the balling water among the fine charge particles increases the efficiency of water to act as a binder. Hence the specific water content required for balling could be reduced by 8%. (**Fig 12**).

This reduced water content subsequently decreased the water load in the sintering process, specifically on the drying and re-condensing stages. This results in less

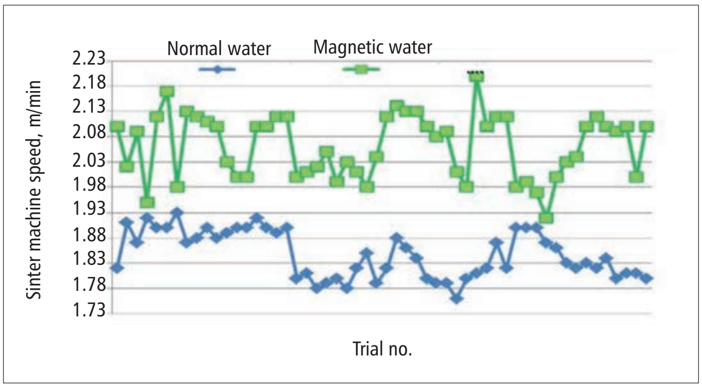


Fig 10. Sinter machine speed possible for treated and untreated water

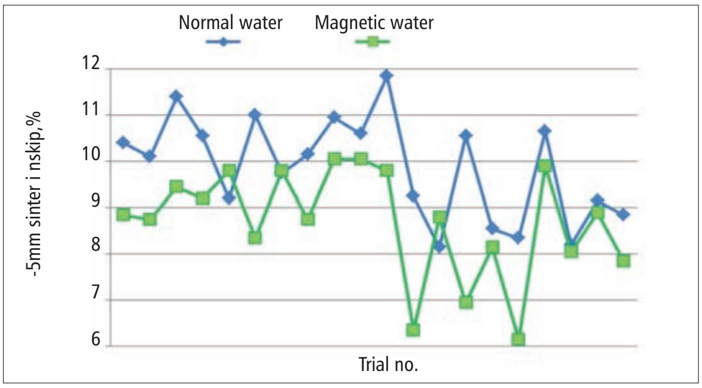


Fig 11. (above) Undersize sinter generation for treated and untreated water

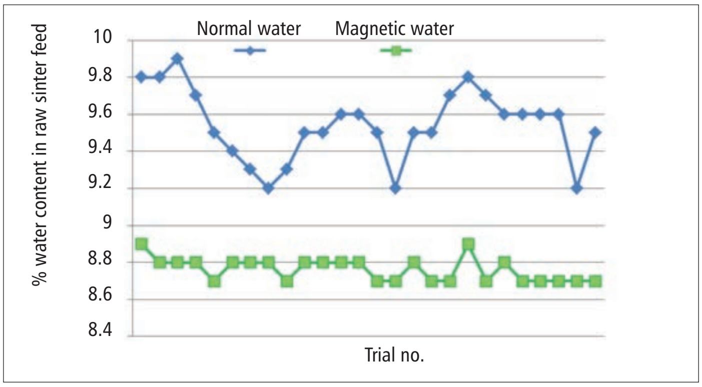


Fig 12. (left) Percentage water content in raw sinter feed for treated and untreated water

water to be vaporised in the drying zone and lower specific water in the moisture re-condensing zone. Thus the likelihood of filling void spaces in the bed bottom layers with free water is substantially reduced, resulting in improved bed permeability.

Conclusion

Granulation is important in many respects for sintering iron ore. By granulation, fine particles of diversified chemistry and property are homogenised with a subsequent increase in mean size, suitable for charging to the moving sinter pallets. Feed characteristics and the role of water and process variables of balling operation all affect the process.

Water surface tension is a necessary factor in the sintering process. On one hand, it helps in granulation by forming water bridges among fine particles; on the other hand it restricts the rate of water dispersion among fines during industrial scale continuous operation.

The water Hydrogen bond causes surface tension to exist and the dispersion rate of water is inversely proportional to surface tension. The application of a magnetic field to the water arranges the random orientation of the water molecules into a single direction, causing the water molecules to condense with a resultant reduction in surface tension.

A laboratory study revealed 16.92% reduction in water surface tension as a result of magnetic treatment. Accordingly magnetic water conditioners were designed and installed in all three sinter machines at the Bokaro Steel Plant enhancing sinter line productivity by 11%.

The average results of the magnetic water addition can be summarised as:

- Granulation degree improved by 9%;
- Sinter machine speed could be enhanced by 11.35%;
- Air filtration velocity through sinter bed increased by 17.9%;
- Under size generation reduced by 7.9%;
- Water content in the sinter feed could be reduced by 8%. ■

References

1. P. C. Kapur et al., International Journal of Mineral Processing, Vol. 39 (1993), p.239
2. Formoso, A., Moro, A., Fernández-Pello, G., Muñiz, M., Jiménez, J., Moro, A., and Cores, A., 2000
3. Recent progress In sintering technology-high reducibility and improvement of fuel consumption", Y. Ishikawa, Ironmaking proceedings, AMIE 1982, Pittsburg, p: 80-89
4. Indication of measurement of Surface Area on Iron Ore Granulation" L. V. Xuewei et al., ISIJ International Vol. (51) 2011, No. 9, pp: 1432-1438
5. X. Lv. et al. Ironmaking & Steelmaking Vol. 37 (2010), No. 6 p: 407, X. Lv. et al. ISIJ International Vol. 50 (2010),No. 5, p: 695
6. ("Prediction of size distribution of iron ore granules and permeability of its bed" Journal of mining & metallurgy), X. Lv. et al. Vol. 47 No. 2 (2011), p: 113-123
7. Furui, T., Sugawara, K., Kagawa, M., Uno, S., Kamazu, S. M., Fujiwara, T. and Sawamura, A., Nippon Steel Tech. Rep. (Overseas), vol. 10, pp. 36-46, 1977
8. Hida, Y., Sasaki, M., Sato, K., Kagawa, M., Miyazaki, T., Soma, H., Naito, H. and Taniguchi, M., Nippon Steel Tech. Rep. (Overseas), vol. 35, pp. 59-67, 1987
9. Venkataramana, R., Gupta, S.S., Kapur, P.C. & Ramachandran, N. : "Modelling of iron ore sinter fed granulation" Tata search 1997, pp. 91-97
10. Maeda, T., Fukumoto, C., Matsumura, T., Nishioka, K., and Shimizu, M., 2005, "Effect of adding moisture and wettability on sinter granulation"
11. Litster, J. D., Waters, A. G., and Nicol, S. K., 1986, "A model for the size distribution of product from granulating drum." Transactions of the Iron and Steel Institute of Japan, 26, pp. 1036–1044
12. Rankin,W. J., 1986, "Pre-agglomeration and its role in iron ore sintering." 2nd International Symposium on Beneficiation and Agglomeration, pp. 107–117
13. Wild, R., and Dixon, K. G., 1962, "Pressure and water gradients through a sinter bed." in Agglomeration, New York: W. A. Knepper, Interscience Publishers, pp. 565–580
14. Lv, X., Bai, C., Qiu, G., Zhang, S., and Hu, M., 2010, "Moisture capacity: definition, measurement, and application in determining the optimal water content in granulating." ISIJ International, 50, pp. 695–701
15. Ahmed, S.A. : "Effect of magnetic water on engineering properties of concrete", College of Engineering, Water Resource Department, University of Mosul, Iraq, Martyenko,
16 V.A. et. Al. : "Effect of sintering with water subjected to magnetic field", No 5, Metallurgist 1967