

## STEEL SLAG GRANULATION

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### ABSTRACT

*For many years PT. Krakatau Steels has been facing environmental problem due to solid slag waste resulted from steel making operation. Even though the existing slag is dumped in a yard and utilized for road and filling materials, it produces dust and has very low value. The company is preparing to upgrade the quality of slag to be used as raw materials for Portland pozzoland cemen. This effort also will give benefit in reducing crushing cost, the CO<sub>2</sub> emission from the cement processing plant and in increasing the energy saving . This paper discusses the results of slag granulation experiment using water spraying unit. Based on the experimental results, a granulation plant is proposed to be built closely to the existing steel making plant. This study is part of a larger investigation work covering slag granulation and feasibility study on utilization of slag granules for Portland-pozzoland cement.*

### INTRODUCTION

Steel industry produces various types of steels to be used for many applications. However, this industry also produces solid waste (slag) which mainly consists of metals oxides as the results of oxidation of liquid metals and impurities during steel making. About 250 kilograms of slag waste is normally generated for every ton of iron produced in electric arc furnace or blast furnace. This slag waste is usually air-cooled and dumped in a pit and then send to landfills or used in low-level applications such as road base materials. Some electric arc and blast furnace operations spray the discharged liquid slag with water to produce glassy granules which then can be used for Portland cement, which is the key constituent of concrete.

It was reported<sup>(3)</sup> that producing one ton of Portland cement consumes about 3000MJ of electrical and thermal energy and emits about 900kg of carbon dioxide, mainly due to the decomposition of limestone in the cement kiln. Granulated slag can substitute for up to about 70 percent of the Portland cement, leading to significant energy saving and reduction in greenhouse gas emissions.

Slag waste granulation in Indonesian steel plants has not been implemented, despite the facts that granulated slag has high potential to be upgraded as the additional material for Portland cement. The slag of electric arc furnace (EAF) in PT. Krakatau Steel (PTKS) has been a serious environmental problem. With the average slag production of about 200,000 ton/year, this slag is dumped in a large stockyard and used for road based materials. Lots of fine dust is produced during transportation, dumping and moving of this material. Efforts to increase the added value of the EAF slag have been conducted, one of which is by producing granulated slag using water atomization. This method was intended to produce slag particles with the size in the range of minus 10 mm. Table 1 shows the minerals

composition EAF slag of PTKS.

Table I  
Mineral composition of EAF Steel Slag

Oxides	Composition (weight %)
FeO	44,21
SiO <sub>2</sub>	23,02
CaO	21,26
Al <sub>2</sub> O <sub>3</sub>	5,79
MgO	3,06
MnO	1,48
P <sub>2</sub> O <sub>5</sub>	0,18

The basic principle of this slag atomization is to spray the liquid slag at temperature of about 1600°C with high velocity water spray, and schematically is shown in Figure 1. The size distribution and the microstructure of the slag granules depend on process variables such as water jet pressure, angle between water spray and liquid slag flow, distance between water jet nozzle and liquid slag, viscosity of the liquid slag and the design of equipment. A mathematical model<sup>(1)</sup> to express all parameters of the atomization is as follow:

$$D = \beta \ln(P) / V \sin(\alpha) \dots\dots\dots (1)$$

- Where : D = diameter of particle obtained.  
P = atomization pressure  
V = water velocity  
α = angle between water jet and liquid slag flow  
β = constant which depends on slag properties and equipment

The droplets of liquid slag with spheres in shape will solidify immediately due to extraction of heat by the water jet. The equation (2) shows the critical radius of solid nuclei (r\*), which depends strongly on free energy difference per unit volume (ΔG<sub>v</sub>) and interface free energy between solid and liquid (γ<sub>SL</sub>), equation 2. Meanwhile, this value depends on the under-cooling of the process (ΔT) as indicated by equation (3). These equations show that the lower the under-cooling the finer the crystal size of the slag granules.

$$r^* = \frac{2\gamma_{SL}}{\Delta G_v} \dots\dots\dots (2)$$

in which:

$$\Delta G_v = \frac{L_v \cdot \Delta T}{T_m} \dots\dots\dots (3)$$

where  $L_v$  and  $T_m$  are latent heat of fusion and melting point of slag respectively.

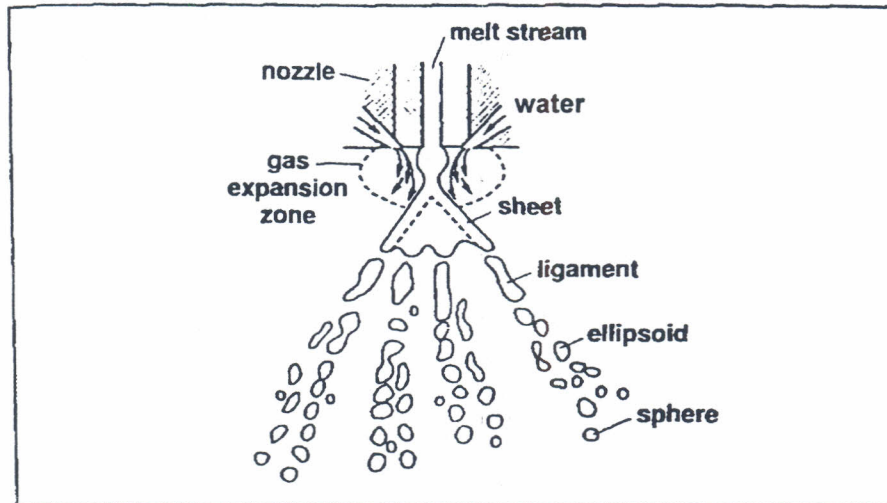


Figure 1  
Principle of water jet atomization<sup>(1)</sup>

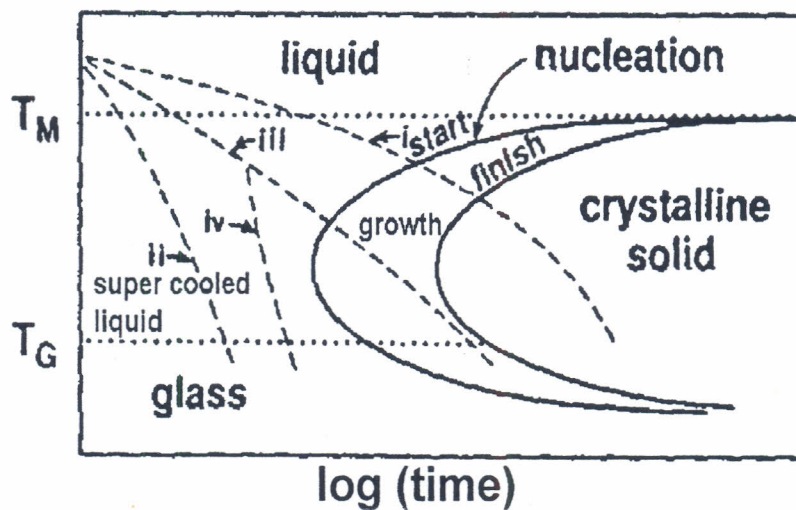


Figure 2. Temperature, time and transformation diagram for solidification of materials<sup>(7)</sup>

The solid particles formed could be in crystalline or glassy states depending on the cooling rate or water spray capacity. Figure 2 shows the characteristic of temperature, time and transformation (TTT) diagram of common materials. At slow cooling rate the solid could be crystalline. In this case the ions have adequate time to arrange their self to form certain crystal structure. On the other hand, at fast cooling rate the solid would be glassy as the ions have no adequate time to arrange into crystalline structure.

## EXPERIMENTAL PROCEDURES

In order to simulate the process of steel slag granulation, a set of equipment was made as shown in Figure 1. This consists mainly of launder, granulation tank, dewatering tank, waste water tank and fresh water tank. Solid steel slag obtained from PT. Krakatau Steel was melted in an induction furnace at 1610°C and then transferred and poured into the launder to which water was sprayed on the liquid slag flowing from the launder, as shown in Figure 4. The granulated steel slag and sprayed water was collected in the granulation tank which contains screens having opening of 20 and 100 meshes. The solid slag granules were collected from the screen as oversize, while the water containing fines particles was flowed into waste water tank. In this tank the clean water was circulated into a fresh water tank to be used as spray water for granulation experiment.

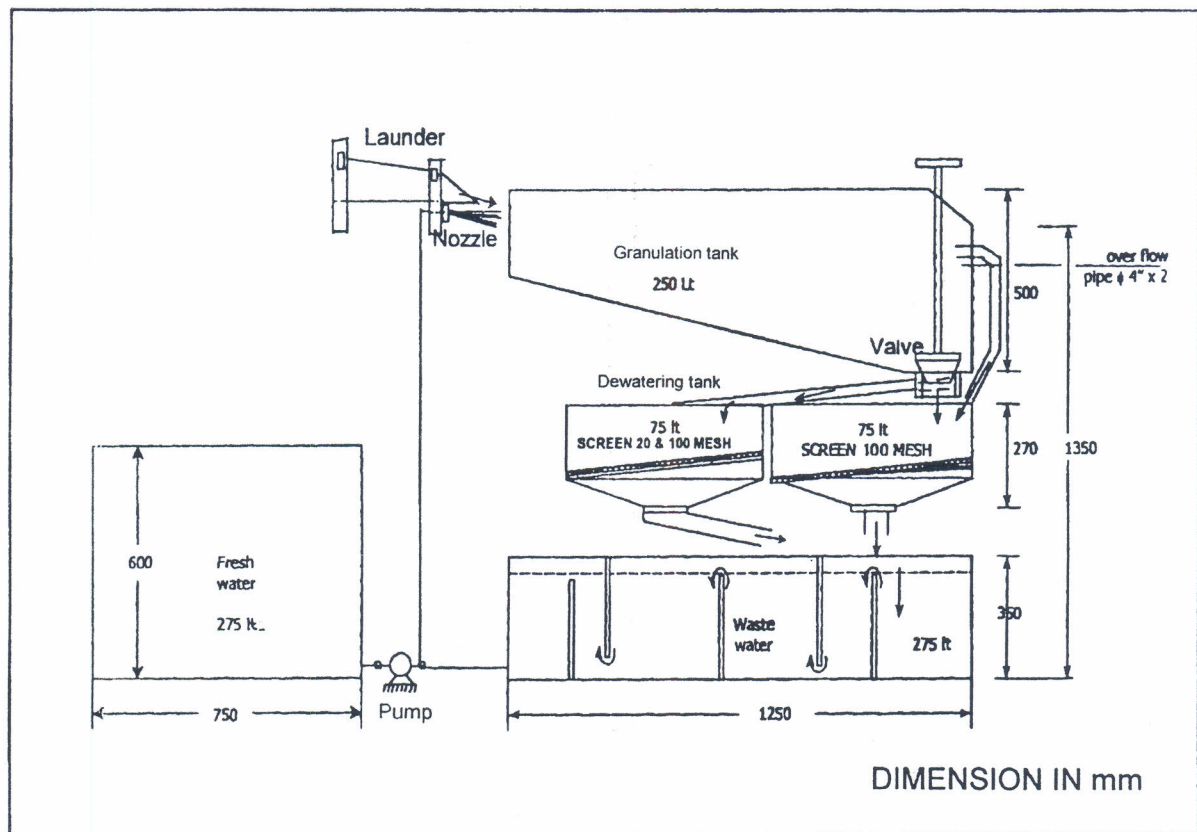


Figure 3  
Equipment used for slag granulation experiment

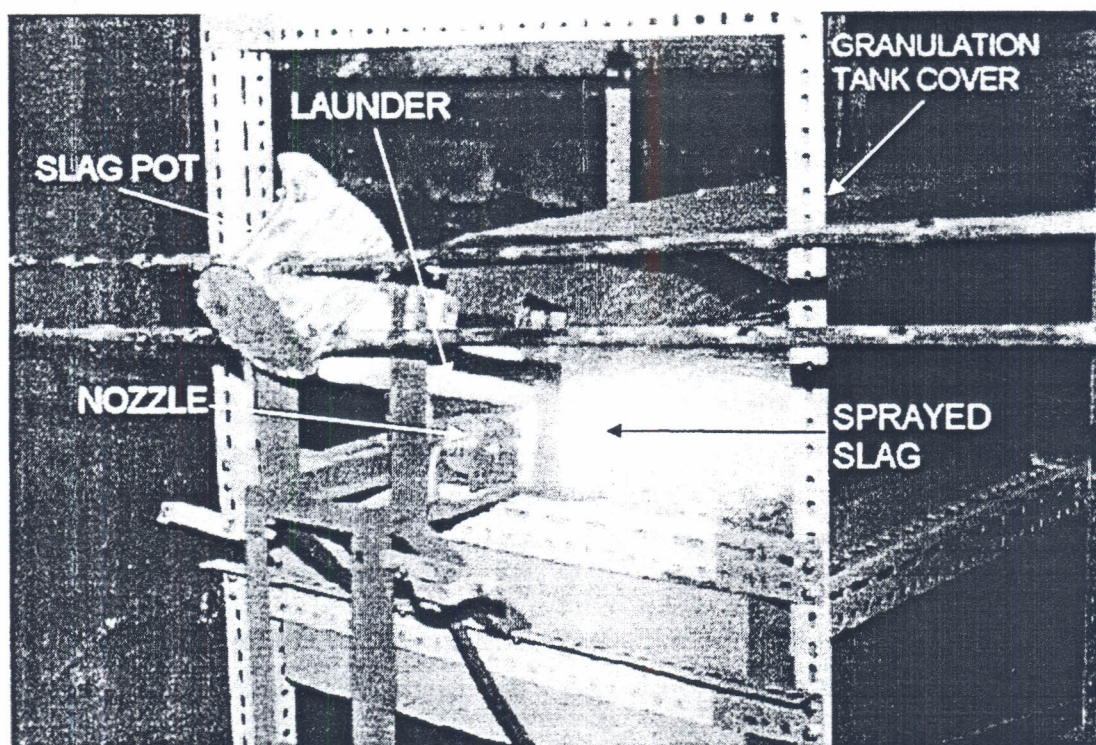


Figure 4  
Slag granulation experiment in progress

In this experiment the process variables were as follows (1) ratio between water spray velocity and slag flow velocity, (2) angle between water spray direction and slag flow direction, (3) water volume in the tank, and (4) nozzle to melt distance. The slag flow rates were varied at 1.7, 2.3 and 2.6 litre/minutes, while the angle between water spray direction and slag flow direction was set at  $80^\circ$ ,  $90^\circ$  and  $100^\circ$ , and the volume of water in fresh water tank was varied in 100, 150 and 200 litres.

For each test variable, the slag granules which were collected from the top deck of the screens in the dewatering tank were then dried and used for particle size distribution test. The internal structures of the slag granules were observed using optical microscope. In this case some particles obtained from various test variables were mounted in resin. The mounted samples were then ground and polished to  $0.1 \mu\text{m}$  finish before optical microscope observation was conducted. To ensure whether the slag granules were crystalline or amorphous, some slag particles from each test result were examined using X-ray diffraction.

#### EXPERIMENTAL RESULTS AND DISCUSSION

The operating variables for slag granulation had significant impact on the resulting granules characteristics. Among all variables, the ratio between ratio between water spray velocity and slag flow velocity and the angle between water spray direction and slag flow direction were considered the most affected variables that influenced the average particle size and size distribution of slag granules. The nozzle to melt distance was not included in this paper since

the effect of this variable was less significant compared to the other three, which are reported in the following passage.

Figure 5 shows the effect of ratio between water spray velocity and slag flow velocity on particle size distribution, from which, relatively fine particles with narrow particle size distribution were found for ratio of 17.6:1. This figure also indicates that at the ratios of 11.5:1, 13:1 and 17.6:1 the average particle size decreased from about 0.922 mm to 0.838 mm and to 0.582 mm respectively. The results also shows that the higher the water flow velocity or the higher the pressure of water spray, the finer the particles would be obtained, as it is clearly stated in equation 1.

The effect of the angle between water spray direction and slag flow direction on particle size distribution is shown in Figure 6. This figure shows that the finest particle size and narrowest particle size distribution was obtained at the angle of 90°. The particle size would be coarser when the angle was away from 90°. The average size of particles for the angles of 80°, 100° and 90° were 0.870 mm, 0.816 mm and 0.582 mm respectively. Figure 7 shows the relation between particle size and weight percent of slag granules for various volume of spray water in the tank. For 100 litres, 150 litres and 200 litres of water the particle sizes of the slag granules decreased from 1.054 mm, 0.838 mm and 0.866 mm respectively. These results show that compared to the previous variables, the water volume in the fresh water tank gave larger size and wider size distribution. This variable is considered as less operating variable compared to the ratio between water spray velocity and slag flow velocity and the angle between water spray direction and slag flow direction.

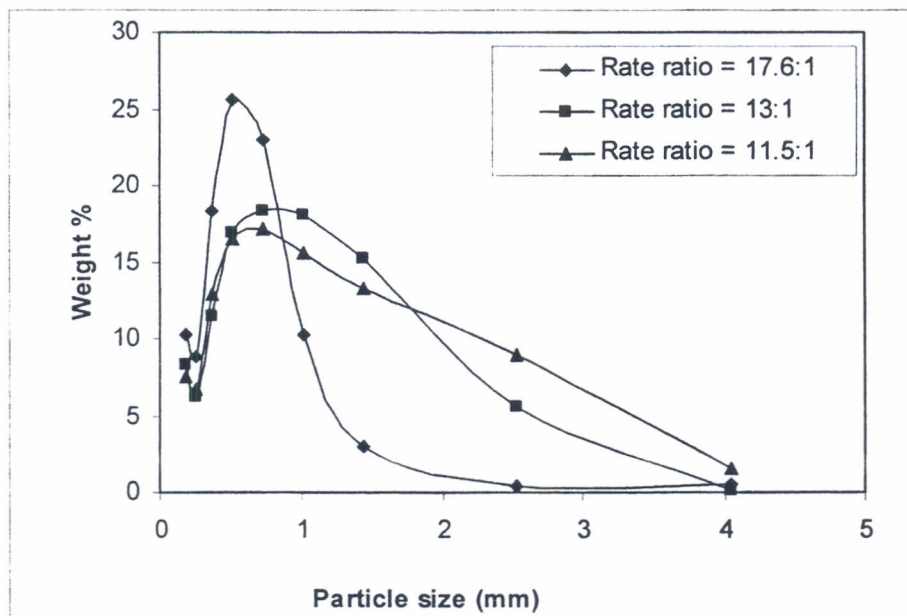


Figure 5. Particle size distribution of granulated slag at various ratios between water spray velocity and slag flow velocity

Figure 8 shows that mostly the slag granules were in sphere shape. However, some of which have irregular shapes. The particle shapes depends on the atomization mechanism during spraying. Sphere particles will be formed when the cooling rate is relatively slow, while irregular form is normally obtained when the cooling rate is fast.

Table 2 shows the density of solid slag obtained from granulation and that obtained from direct pouring from EAF. This density data is necessary as the granulated slag will be used as the mix material for Portland-pozzoland cement. It is seen that the density of the granulated slag was less than that of EAF slag which indicates that the granulated slag particles contain more pores or internal cracks than that of slag which give benefit when it is grinded during cement processing. More over, as seen in Figure 9 and 10, the slag granules either in amorphous or crystalline forms, contain micro cracks, indicating that the granules would be easily grinded in the cement processing plant.

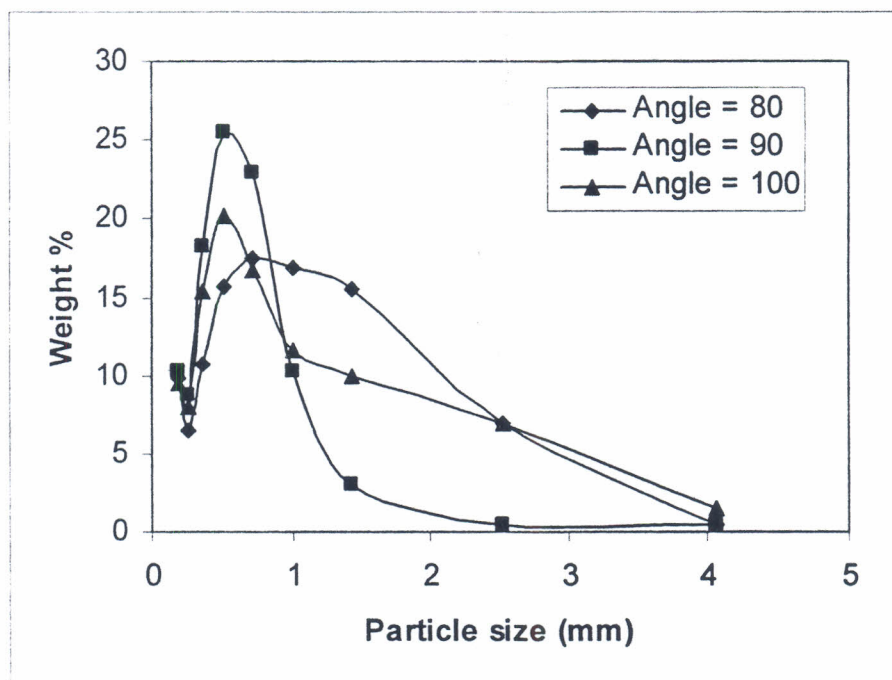


Figure 6. Particle size distribution of granulated slag at various angle between water spray direction and slag flow direction

Table 2.

Bulk density of slag obtained from granulation compared with non granulated slag

Condition	Bulk density (g/cm <sup>3</sup> )
Granulated slag	2,09
Non granulated slag	2,6

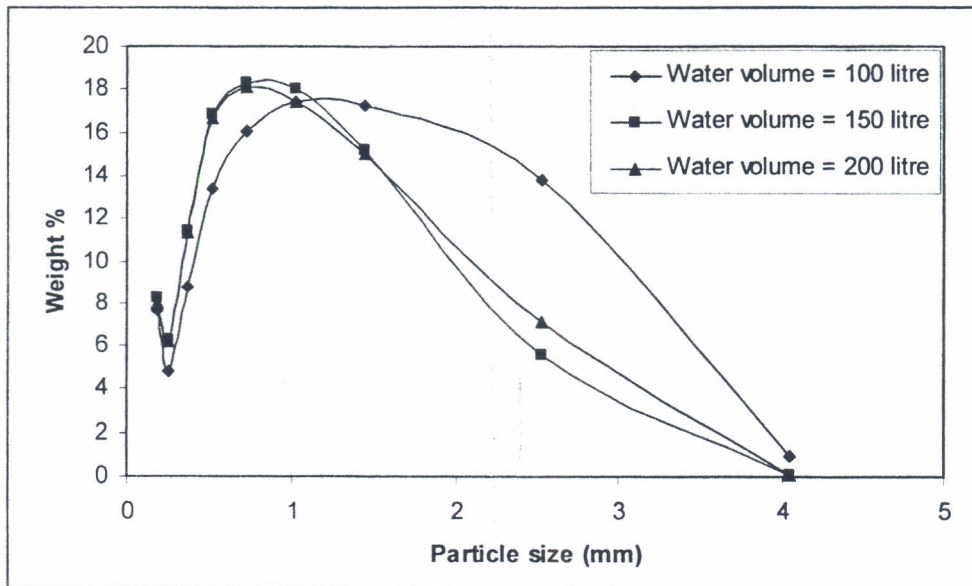


Figure 7. Particle size distribution of granulates slag at various water in fresh water tank.

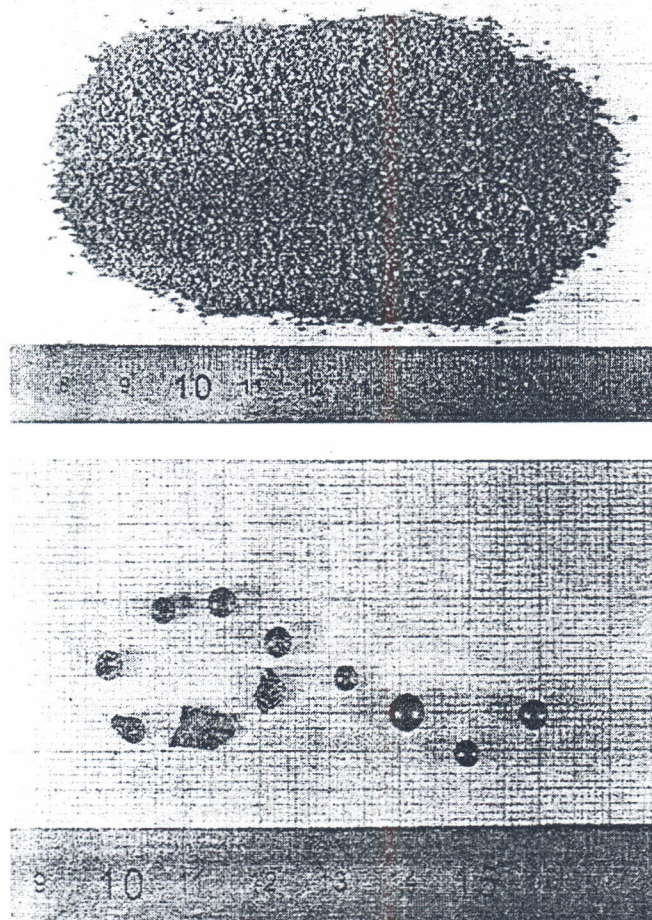


Figure 8. Several granulated slag particles obtained from slag granulation test. Figure 7.b. shows that mostly the particles having rounded or sphere in shape, but some of which have irregular shape.



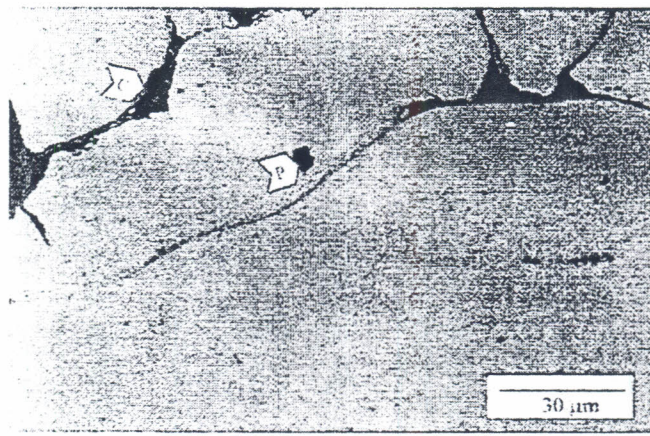


Figure 9. Microstructure of granulated slag obtained from granulation at the ratio between water spray velocity and slag flow velocity of 17,6:1 showing amorphous structure. C indicates micro cracks, while P indicates micro pore

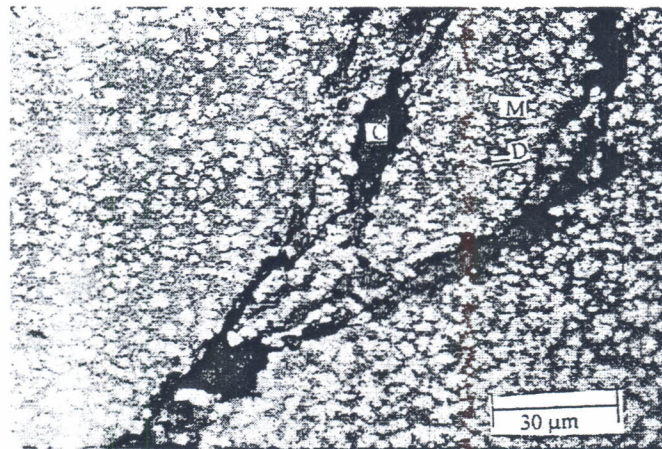


Figure 10

Microstructure of granulated slag obtained at the ratio between water spray velocity and slag flow velocity of 11,5:1 showing crystalline structure. M shows the matrix of FeO and D indicates the dendrites of  $\beta$ -Ca<sub>2</sub>SiO<sub>4</sub>, while C indicates micro cracks.

This distinct microstructure appearance, as shown in Figure 9 and 10, was believed affected by the different in cooling rate during solidification process. With the ratio between water spray velocity and slag flow velocity of 17,6:1 it gave amorphous or glassy structure, indicates that the cooling rate was fast enough to retain the ions to arrange their self to be crystalline in structure. On the other hand, with the ratio between water spray velocity and slag flow velocity of 11,5:1, the slag granules were crystalline in structure, indicates that the cooling rate is considered slow enough for ions to form crystalline solid, as clearly shown the concept in Figure 2. The dendrite phase with white in colour as shown in Figure 10 is  $\beta$ -Ca<sub>2</sub>SiO<sub>4</sub>. This dendrite phase particles embedded in the matrix

of FeO shows the development of crystalline solid and this is supported by the X-ray diffraction results as shown in Figure 12, which is different with that for amorphous granules, Figure 11 with low peaks for its diffraction pattern.

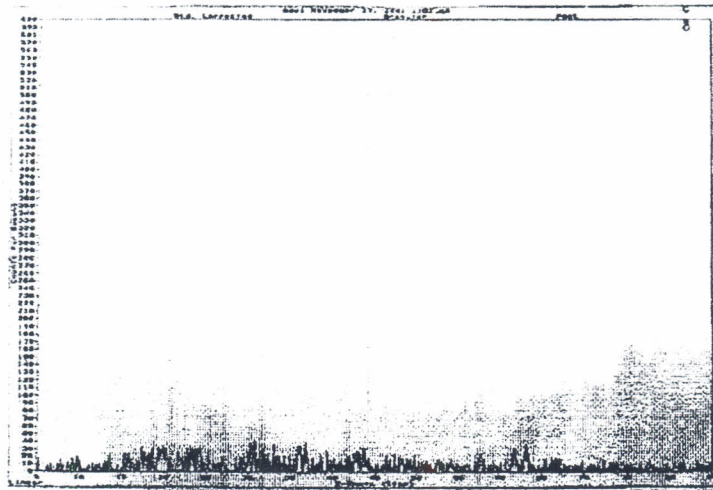


Figure 11. X-ray diffraction pattern of amorphous granules

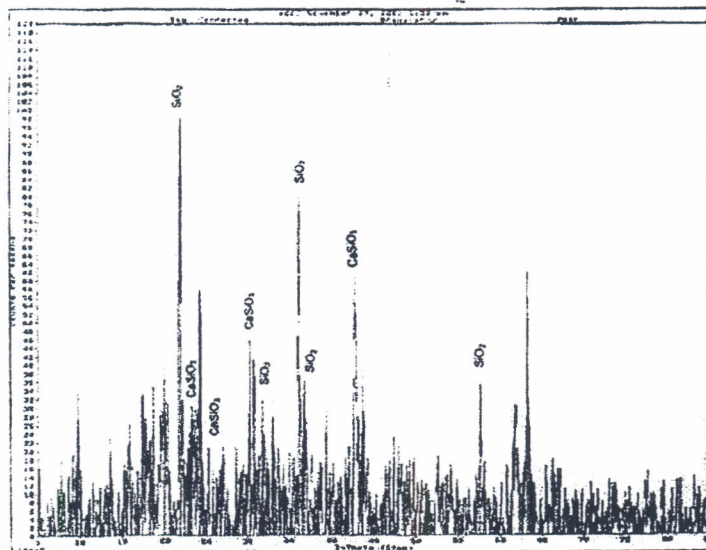


Figure 12. X-ray diffraction pattern of crystalline granules

### PROPOSED GRANULATION PLANT

Based on the experimental results, it is clearly seen that the EAF slag of PT. Krakatau Steel would be possible to be granulated with various size distribution. A proposed granulation plant is required which should be located relatively closed with the existing steel making plant. Figure 13 shows the top view and side view of the proposed granulation plant suitable for PT Krakatau Steel with the capacity of 200.000 ton/year.

During the cycle of steel making, the EAF slag is poured into a slag pot with 50 ton capacity. Apparently, it would be brought to the granulation plant using a crane. The slag is then poured, by tilting the slag pot, into a tundish which has a bottom hole for which the liquid slag will flow down to the launder. A nozzle located under the launder has been activated prior to the pouring of liquid slag to produce water spray for granulation. With the ratio between water spray velocity and slag flow velocity of 17.6, the amount of water required for this operation is about 8 ton/minute. This spray water can be recycled using water treatment facility. It is important to note here that the slag pot, tundish and launder should be preheated to high temperature before the liquid slag is poured.

The slag granules collected in the granulation chamber are taken out using a spiral conveyor and fed into belt conveyor 1. A magnetic separator is installed at the head of the belt conveyor 1 to remove steel particles in the slag granules and collected in a silo through belt conveyor 2. The slag granules are then collected in a silo with the total capacity of 100 ton. The slag granules are then ready to be transported to the Portland– pozzoland cement plant. The overflow water in the granulation chamber flows into an overflow tank through overflow launder and is ready to be treated to become make-up water for granulation operation..

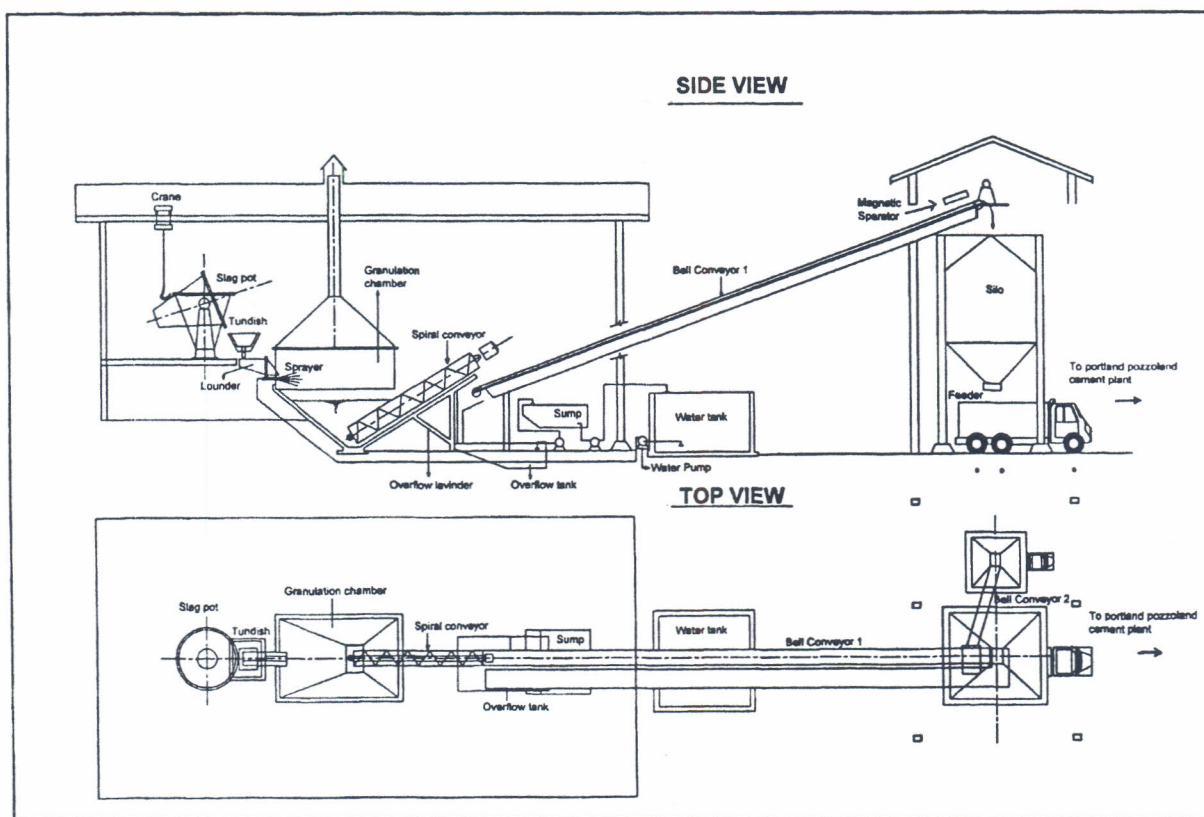


Figure 13. Proposed slag granulation plant at PT. Krakatau Steel

## CONCLUSIONS

The present investigation into the granulation of EAF slag of PT. Krakatau Steel has revealed that the higher the ratio between water spray velocity and slag flow velocity and the higher the angle between water spray direction and

slag flow direction, the finer the slag granules obtained. With the ratios between water spray velocity and slag flow velocity of about 17:1 and the angle between water spray direction and slag flow direction of about 90°, a proposed granulation plant for EAF slag of PT. Krakatau Steel could be designed with annual capacity of 200,000 ton to be used as raw material for Portland-pozzoland cement. With this plan, the environmental problem faced by PT Krakatau Steels would be resolved, in addition to the reduction of CO<sub>2</sub> emission during the processing of Portland pozzoland cement.

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#### REFERENCES

Randall, M, *Powder Metallurgy Science*, Second Edition, Metal Powder Industries Federation, 1994, p.3.

Sule, D., et al., *Laporan Akhir Penelitian Pemanfaatan Terak Tanur Listrik* PT. Krakatau Steel, LPPM-ITB, 2003.

Kalyoncu, R.S., *Slag-Iron and Steel*, Iron and Steel, 1997, p.702.

Leyser, P. and Cortina, C., *INBA Slag Granulation System-Environmental Process Control*, Paulworth, April, 2005, p. 139.

Mucciardi, F., Palumbo, E., and Jin, N., *A waterless Caster for Matte/Slag Granulation*, [www.mmpc.mcgill.ca/~frank/caster 99pdf](http://www.mmpc.mcgill.ca/~frank/caster 99pdf).

Mansfield, K., *The Spent Pot Lining Treatment and Resource Recovery Project*, The SPL Team 1994-2001, Portland, Victoria, Australia.

Porter, A., *Phase Transformation in Metals and Alloys*, Van Nostrand, Reinhold Co. Ltd., 1981.