Slag Atomising Technology: Unlocking Real Value

S. Mostaghel[1], L.So[1], M. Cramer[1], S. Faucher[1], S.K. Lee[2] andS.-Y. Oh[2]

[1] Hatch Ltd., 2800 Speakman Drive, Mississauga, Ontario, Canada; smostaghel@hatch.ca
[2] Ecomaister Co., Ltd., 104, 250, Geonjiro, Seo-Gu, Incheon, Korea

ABSTRACT

For most ferroalloy producers, slag has limited or no value after the smelting process is completed. In many cases, slag managementrepresents an increasingly expensive handling and storage challenge. Slag has untapped potential as a source of energy, revenue (from high-value slagsales) and un-recovered alloy droplets. Few, if any, of these traits have been valorized with the current technologies. Present ferroalloy markets are characterised by small margins and increasing regulations and costs. In order to compete in the current market, producers are forced to improve overall productivity in their current operations. Slag valorization plays an important role in generating additional revenue and in increasing operation efficiencies, while improving safety and reducing environmental impacts with limited capital commitment.

Ecomaister-Hatch Slag Atomization Technology (SAT) represents a commercially proven application of air blasting of ferroalloy slags at industrial scale. The technology is extremely robust, easy to install, and cost-effective. By air atomising slag into fine, solidified, and cool particles, the operator is able to avoid the safety risks associated with liquid slag handling and water granulation. This slag treatment method reduces dust creation and water consumption, and also allows for energy recovery from the molten material. Through innovative process designs, slag is now intrinsically valuable as a raw material for a number of other applications e.g. sand blasting, ballast, or roof shingles. The elimination of multiple cooling and treatment steps of a traditional slag handling results in higher throughputs, lower transport and crushing costs, a smaller footprint, and shorter slag cycle. These factors in combination provide short term revenue and long term sustainability.

The current paper will examine the design and benefits of the Ecomaister-Hatch Slag Atomization Technology when applied to, for example, ferrochrome production slags. A business case is also examined utilizing a 200,000 tonne per year ferrochrome operation including a metal recovery plant as an example.

1. INTRODUCTION

Slag and slag handling currently represents a significant safety, environmental, operational, and financial concern for ferroalloy production. With the majority of smelters producing slag/alloy mass ratio of 1.0-1.5, slag handling and processing post tap hole represent a significant part of any operation. Historically, slag treatments have differed across sites based on environmental legislation, available space and site location. Two processes have traditionally dominated the industry over time and are selected based on numerous site specific parameters. Slag is either 1) air cooled and handled dry or 2) granulated in a high pressure water stream and handled largely wet. Both options have some advantages and disadvantages, as will be discussed below. However, regardless of the selected handling option, the smelters need to address the challenging safety issues with the existing technologies, dust emission, energy consumption, environmental footprint, and cost competitiveness in the current market with marginal benefit for the metal producers. Therefore, there is a strong need for a new technology that can guarantee competitiveness of the smelters. The current existing technologies for slag handling are briefly reviewed below.

1.1 Air Cooling and Dry Handling

Multiple options exist for handling the material immediately after the tap hole. In the ferroalloy industry, the vast majority of furnaces have metal and slag exiting the same tap hole and there exists the immediate requirement to separate the two hot materials effectively. Overwhelmingly this is done by utilising the difference in density between alloy and slag. Two routes are equally common in industry: 1) transportation of slag using ladles/slag pots and 2) carbon block “skimmer” method, which is generally cheaper but can exhibit slag contamination in the metal. In both cases metal producers are generally limited to air cooling of the slag, although sometimes water spray is also used to accelerate the cooling rate (Figure 1). It typically takes several hours for the core of the slag to solidify and cool sufficiently so that front end loaders or excavators can extract the material. It can take several more days before the slag can be loaded into a crusher in the metal recovery plant. Primary crushing typically consists of a jaw crusher followed by cone crushers. Then the material is sent for density separation with pneumatic jigs and spirals.

Figure 1: Air cooling of slag in designated areas

Air cooling and dry handling of slag poses various challenges. Firstly, the dumping of liquid slag in an open area causes not only an aesthetic challenge but makes fume capture impossible. Secondly, handling air cooled slag faces a number of safety and operational challenges. Tapping frequency and plant layout determine the cooling period for the initial solidification of the slag, which in most cases is between 2 and 4 hours. Rapid turnaround means that molten slag may exist when loaders or excavators are handling the material. Removing semi-molten slag from a pit poses danger to both personnel and equipment, even when using modified mobile equipment or "hot" machines. Replacement and maintenance costs associated with ground engaging equipment are exponentially higher on "hot" machines utilised in these environments. Spraying water into a pit is a common solution to accelerate slag cooling. However, potential for molten material/water explosions remain ever present and the pooling of water can delay furnace operations. Lastly, transportation of air cooled slag from the pit to downstream crushers and metal separators poses additional safety and operational risks. Transportation of semi-molten slag via mobile machinery requires dedicated roads, specialised equipment and specialised training. It also increases the area in which special precautions need to be taken for molten material/water contact. The repeated loading and transport combined with crushing steps results in numerous dust emission sources and increased diesel consumption for mobile machinery.

1.2 Water Granulation

Although not as common as dry slag handling, water granulation of slag represents a significant part of the industry. Two major forms of granulation systems do exist: 1) at the end of launder attached directly to the furnace or 2) at a dedicated facility designed to accept slag pots or ladles. To maintain a safe and successful water granulation system, it is critical to maintain the temperature, flow and pressure of the water in accordance to the temperature and flow of the molten material. The slag is granulated with impact of the high-pressure water stream and forms small granules, approximately 2 mm in diameter. The slag is rapidly solidified in the initial water blast and then cools further in a settling tank (Figure 2). Various options then exist for dewatering of slag and subsequent transfer to either the stockpile or a metal recovery plant (1; 2; 3; 4; 5).

Figure 2: Water granulation of slag

There are significant operational, environmental, and safety challenges related to water granulation of slag. Firstly, a typical water granulation requires ~10 tonnes of water per tonne of slag granulated, out of which between 1 and 1.5 tonnes of water is lost to evaporation. This has both environmental and financial implications and in some areas, makes the technology simply not possible due to water limitations. The energy costs associated with pumping and cooling of large volumes of water increase the operating cost of the process. Precautions are also required for the overall treatment and de-sludging of the water circuit to remove the build-up of deleterious metals and potentially harmful/toxic dissolved species. Further, the placement of the granulation facility within the molten material zone of a furnace building also raises significant concerns and requires additional protection for both personnel and equipment. If the facility is located directly in front of the furnace, control of molten material through the tap hole and into the water stream is critical. Therefore, continuous monitoring and maintenance of the tap hole itself is an extremely important consideration.

2. LIMITATIONS WITH THE CURRENT SLAG HANDLING TECHNOLOGIES

2.1 Operating Cost

Slag has, with the exception of a few instances, been seen as an unavoidable but necessary cost of producing ferroalloys. The removal, treatment, and disposal of slag are considered a direct cost on the bottom line with no expectation of revenue generation. Industries outside of ferroalloys have successfully created a market into which all of the slag produced is sold as a value-added by-product. This potential opportunity exists in the ferroalloy industry too. The creation of viable revenue-generating slag product would drastically enhance the viability and sustainability of a producing complex. Treatment options either through water granulation or air cooling all carry operational costs over and above the long term environmental liability and closure costs.

2.2 Environmental Footprint

In most cases, ferroalloy production plants were originally designed to produce alloy under different environmental legislation in which slag was seen as a waste product that could be easily stored on-site in unlined dumps. However, producers are now under increasing pressure to not only cease dumping of slag on-site, but also to remediate the existing facilities and to provide a cleaner footprint.

Global concerns for climate change, sustainability, and resource consumption with an emphasis on carbon usage mean that facilities have to lower energy consumption, lower water consumption, and utilise resources more effectively, while simultaneously lowering the facility’s impact on the immediate environment. This means using less water in water granulation and cooling, reducing or eliminating dust created by crushing and loading, as well as reducing transportation of materials and associated diesel consumption. Slag storage represents a significant environmental legacy for any plant that is unable to turn the slag into a usable product.

2.3 Heat Recovery Obstacles

The molten slag discharged from the metallurgical furnaces is a tremendous energy stream leaving the reactor and in some cases can reach up to 80% of the total energy input to the process (6; 7). This energy represents a significant cost which is currently not recovered. In air cooling, this energy is dissipated to the environment and cannot be reclaimed. In water granulation, energy recovery from hot water was attempted, but such a heat recovery system was never commercialized due to the associated high costs and low quality of heat source. A number of different technologies have been developed (8; 9; 10; 11) to recover the heat before disposal/water granulation or during a dry treatment of the molten slag. However, due to technical and economical reasons, none of these technologies passed the piloting stage. Ideally, slag energy should be recovered in the form of hot gas, steam or electricity and reintroduced to the operation to minimize the total energy consumption of the plant.

2.4 Metal Loss to the Slag Phase

A large portion of ferroalloy production sites utilise density separation technology at a dedicated plant for recovery of entrained alloy droplets from the slag prior to the long term storage or sale of the material. These plants are generally low capital cost plants with high throughputs and are fed a mixture of new slag from the furnaces and recycled slag from existing stockpiles, if any. The technology is well proven and effective. However, the recovered metal tends to have higher slag content than the furnace metal. Thus, it is usually sold at a slight discount or recycled internally to casting beds or to the furnaces themselves. Critical to the metal recovery and grade in this process is the size distribution of the slag. Although the plant will typically have a series of crushing steps, the recovery peaks in the 1 – 10 mm range for most ferroalloys. The larger size fraction has lower slag contamination and particles below 1 mm will typically exhibit metal recovery rates 10% below other size fractions.

Although water granulation provides a narrower size distribution, limitations are imposed by the temperature and flow rates of both slag and water as well as slag composition. Water-cooled slag is quenched and thus metal droplets are often frozen in a matrix of slag requiring extensive crushing to liberate. Similarly, air cooled slag must be crushed, as it has slow cooled into large slabs. Crushed air cooled slag has a much wider particle size distribution resulting in a variance of performance in the metal recovery plant as well as throughput limitations depending on the design of the plant.

2.5 Slag Sales as By-product of the Operation

The sale of barren slag from operational sites varies greatly across the globe with a numerous factors influencing the amount of material sold or revenue generated. The selection of post tap hole slag handling processes will be heavily influenced by the market requirements for slag. Three key aspects have to be taken into account as elaborated in the following sub-sections.

2.5.1 Slag physico-mechanical properties

Often key to the final customer is the physical structure of the slag encompassing the mineralogy, size, strength, grindability etc. If a glassy amorphous phase, for cementitious properties, is required for the downstream processes, the slag must be rapidly cooled and/or water quenched. Aggregate in civil engineering applications is another large market for slags (12; 13; 14) but do not require amorphous properties and thus air cooling is sufficient. It is clear that the choice of cooling condition immediately limits the slag to certain markets.

2.5.2 Distance to market

Ferroalloy smelters are often not located close to large urban areas; hence, the ability of a slag to compete in the aggregate market with local sources of natural materials (e.g. stone) is largely dependent on the transportation cost shipping requirements. As the production site moves further from the market, the slag intrinsic value must increase to remain competitive.

2.5.3 Environmental legislations

Strict environmental legislations play a key role in applicability, and thereby marketability, of the slag for different applications (15; 16; 17). Initially, legislation must allow for slag sales to take place and the slag must then be classified as non-hazardous material. If the slag is classified as a hazardous material the producer will have no option but to stockpile it appropriately. On the other end of the spectrum, if legislation allows for the sale of the material and limits the stockpiling on site, the incentives for the development of slag markets is greater.

3. ECOMAISTER-HATCH AIR ATOMIZATION TECHNOLOGY

An ideal slag handling process should 1) be safe and economical, 2) enable slag sale as a useful by-product, 3) enable enhanced metal recovery, and 4) enable heat recovery from slag. Ecomaister-Hatch has developed a reliable air atomization technology that can meet all the above mentioned requirements for an ideal slag handling process.

The Ecomaister-Hatch process involves the air granulation of slags utilising a high power, low pressure jet of air to fragment and cool the slag stream (Figure 3). The material can be introduced via a launder either directly from the tap hole or by decanting a slag pot or ladle. The slag solidifies in droplet or granules almost immediately and then lands in a stockpile area where the balance of cooling occurs. Air flow is provided by blowers ensuring ease of maintenance and high reliability combined with low operating costs. The technology is well-proven with multiple commercial installations producing millions of tonnes of slags per year from ferrous and non-ferrous metal production processes.

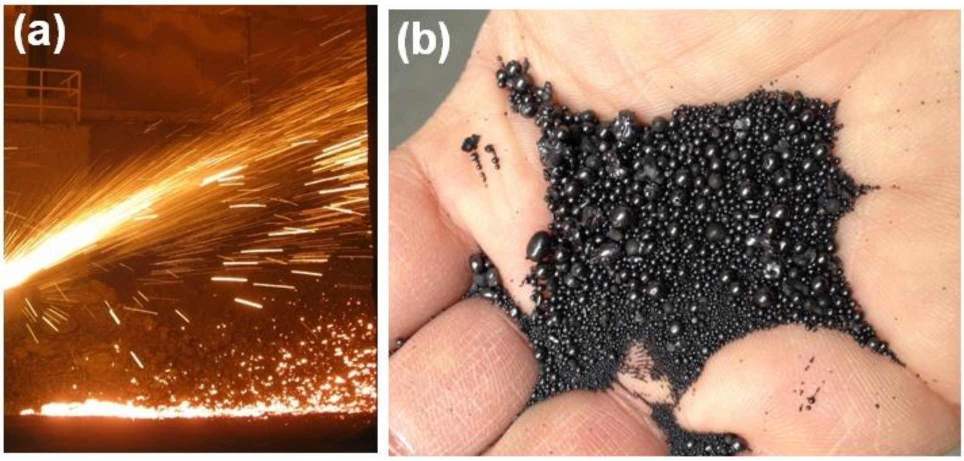

Figure 3: Current commercial operation of Ecomaister-Hatch Dry Slag Atomization Technology: (a) Atomization process and (b) cooled solidified slag granules.

The Ecomaister-Hatch air atomization technology limits molten material transportation, which not only lowers its associated safety risks but also inherently decreases the cost and maintenance requirements for "hot" machines. Another proven benefit of the atomization process is producing a sellable value-added by-product that can be used in a number of different applications, as explained below. The atomized slag granules are typically in particle size range between 0.5-5 mm. Unlike slow cooled materials, air atomized slag does not require costly and dust-generating size reduction operations. Further, as explained below and in the provisional US-patent application 62/094,370 (18), metal recovery from atomized slag is facilitated. Lastly, air atomization also allows for heat recovery. The only viable method for heat recovery from molten slag is to granulate the material into numerous small particles (generating a large specific surface area and increasing the heat transfer from slag) and recover heat from the generated hot air.

Considering all abovementioned benefits, the process reduces the overall energy consumption of the operations, decreases the environmental footprint, eliminates the health and safety risks associated with melt handling for slow cooling and/or water granulation, and provides a considerable saving for the plant. The following sections summarize a business case highlighting the financial benefits that can be obtained.

4. BUSINESS CASE

The Ecomaister-Hatch Slag Atomising Technology has several financial benefits. Depending on the site specific cost profile and operations, the financial benefits will manifest in one or more of the following ways, namely lower slag handling costs, greater metal recovery from slag, slag sales, and heat recovery. The model assumes ferrochrome operation producing 200,000 tonnes of alloy per year from the furnaces and a slag-to-metal ratio of 1.2. A recovery plant is utilised fully and can process 1,000 tonnes per day of slag.

4.1 Lower Slag Handling Costs

Handling molten or hot materials is expensive. Not only does it require specialised equipment and training but the equipment experiences accelerated wear and fatigue due to the cycling between hot and cold environments. If the plant operator owns and manages this equipment itself, all of these costs are absorbed by the operation, whereas a rental agreement with a third party typically includes higher rates for hot material movement. Regardless of the operating model, the costs of running a "hot" machine moving hot material is typically in the range of 2-3 times more expensive than running a "cold" machine. Many operators are forced to handle slag in a semi-molten or hot state due to restrictions on slag bays and launders volume and the interval between successive taps. Additional to the effects of the hot material is the requirement that the machine possess the strength to "break" large blocks of frozen slag prior to loading. Fully molten transport of the slag via specialised haulers adds complexity and cost to an operation which can be minimised by air atomising the material. Air atomised slag is loose, cold and analogous to sand for handling. It can be loaded and hauled with standard bulk material machinery at no risk to the operators or equipment. Typical air atomised slag is below 200°C and can be handled within 30 minutes of atomisation. This translates into direct savings per tonne of material handled. Lower machines costs and less wear means that machines last longer and have higher availability rates resulting in a smaller fleet. As a result of the generic nature of the equipment, machine utilisation rates can be improved by using the same machine across site. For a 200,000 tpa ferrochrome operation, with hot slag handling costs of $8.8 per tonne and cold slag handling at $2.5 per tonne, the ability to atomise 80% of the slag would result in a cost saving of $1.2 million per year. These calculations are simply the costs savings in machine rates and exclude any other additional potential benefits (e.g. wear and maintenance fees).

4.2 Greater Metal Recovery Rates

One of the advantages the system delivers that is not immediately apparent is to allow the operator to debottleneck the metal recovery plant and thereby increase the treatment of historical tailings dumps on-site. Due to advances in jigging and recovery technologies, these stockpiles often have a much higher metal content than currently produced slag, and feeding more old material into the metal recovery plant can increase the overall metal production.

The majority of the metal entrained in the slag in ferroalloy operations often comes from operational instability rather than metallurgical inefficiency. The causes can be as simple as a inattentive operator, tap hole clay gun failure, launder collapse, or simply a large variation in proportion of metal and slag leaving the tap hole in skimmer operations. Air atomisation allows the operator to immediately react to the undesirable condition, interrupt the air stream, and cease atomisation when a large proportion of metal is present. The material would then simply cascade into a slag pit and cool for recovery via traditional methods of excavation, crushing and jigging. Thus the operator has the ability to produce a very barren slag stream which can bypass further treatment and a highly metallised stream for further processing. Due to different densities some separation of metal droplets does occur within the atomised stream allowing additional recovery if warranted.

By creating a metal barren stream the operator can effectively open up additional capacity in the metal recovery plant. Considering the example case of a 200,000 tpa ferrochrome plant in which 80% of the slag is atomised and that contains a 1,000 tpa recovery plant, the operator is now able to free up 192,000 tonnes of slag treating capacity, or in other words increase the capacity for treatment of the historical material from 120,000 tpa to 312,000 tpa. Assuming a recoverable grade of 3% alloy in the historical material, compared to 2% in current slag produced, and accounting for some losses in the barren stream, the plant will produce an additional 4,800 tpa alloy. Assuming a very low sales price of 60USc/lb chrome and a 48% Cr-content in the recovered alloy, equivalent to $3 million per year additional revenue can be generated.

4.3 Slag Sales

Slag sales and revenue from slag sales differ greatly from jurisdiction to jurisdiction and indeed from producer to producer. The differences often result from local legislations, environmental regulations, geographic location, and aggregate market size or location. Producers that are allowed to sell slag typically have to enter a market saturated with other aggregates with a lower cost due to transport costs. Essentially, it is often cheaper to quarry locally than to transport a zero-cost material for a significant distance. However, all producers in these scenarios are attempting to sell a basic product with few tangible benefits to the purchaser. Thus, the amount of product differentiation achievable is limited, i.e. slags are compared on a cost basis only with local aggregate.

Air atomization, however, has the ability to change this presumption. Ecomaister-Hatch air atomization technology is able to control the size of the slag granules generated, and in some cases physical properties of the material can be tailored to meet specific requirements. Therefore, the process is not only a slag treatment method but also an operation to produce a real product with intrinsic value. Typical end uses of slag are abrasive blasting material, counter weight and ballast materials on cranes or forklifts, roofing granules in tar shingles, filter media in water or other filtration systems, specialised concrete production and road pavement aggregate. By preparing the slag to a specific standard and thereby creating a value added by-product, the operator not only opens up new markets but also changes the potential revenue streams and the economic case for purchase. Slag sales can generate otherwise unrealised revenue for firms when pricing slag at anything between $5 and $50 per ton depending on market and location. This revenue can be accounted for directly as profit in most operators books as all the costs associated with slag handling are assigned to the metal. Quantifying the long term costs savings associated with smaller stockpiles and lower environmental liability costs is not straightforward. These "hidden" costs only manifest many years after the material is dumped and can also consume high levels of capital when new dump areas need to be cleared, built and permitted.

4.4 Heat Recovery from Slag

Numerous attempts have been made to economically recover energy from the slag. In slow air cooling of slag, the energy is simply lost to atmosphere, and with water granulation the low quality steam generated cannot typically be applied for reuse of the energy.

Ecomaister-Hatch Air Atomisation technology is currently used in two full-scale smelting sites for heat recovery. The air stream is used to quench and granulate the material; this hot air can then, cost effectively, be transported to any position on-site for utilization. Existing commercial slag air atomising facilities are operating with air temperatures post atomising chamber in the 350-400°C range. This is more than sufficient for most drying purposes. Considering the example case of a 200,000 tpa ferrochrome plant in which slag is atomized at a rate of 18 tph, approximately 40% of the total energy, or 5 MW_{th}, can be recovered in the form of hot air.

4.5 Financial Evaluations

By combining the various aspects and financial implication detailed above it becomes clear that the Air Atomisation Technology represents a prudent use of capital to lower operating costs and increase in revenue, while decreasing site risks to personnel, equipment and the environment.

Although total capital costs of the project will vary due to slag flow rates, layouts, and other site requirements, the expected NPV for a ferrochrome smelter with operating details as shown in Table 1 will generate a payback period of less than 8 months and an Internal Rate of Return (IRR) of 13%. This value includes sales of 50% of the new slag at $50 per tonne and no heat or energy recovery. For these calculations a 2-year project life is assumed, after which historical stockpiles have been depleted.

Table 1: Operating parameters of a hypothetical ferrochrome producer

Parameter	Value
Alloy Production Rate	200,000 tonnes per annum
Slag to Metal Ratio	1.2 tonnes of slag per tonne of metal
Recovery Plant Capacity	1,000 tonnes per day slag
Recoverable Metal in New Slag	2 mass-%
Recoverable Metal in Historical Slag	3 mass-%
Slag reporting to Barren Stream	80 mass-%
Chrome price for recovery material	0.6 USc/lb contained Chrome
Chrome grade	48% Chrome

5. CONCLUSIONS

Air Atomisation technology can eliminate the safety concerns associated with slag treatment methods (slow cooling or water granulation) and presents a remarkable solution to change the way operators see post tap hole slag management. For true advancement in this area, slag needs to be seen as a valuable by-product and not a waste. With this perspective, furnaces must be seen as generating three streams of value: metal, slag and gas. The costs of handling these streams should be aimed at adding value rather than limiting cost. The Ecomaister-Hatch Slag Air Atomisation Technology is an investment to both reduce costs and create value in a plant slag stream.

6. REFERENCES

[1] Langdon B.. Dewatering system apparatus and method for dredging buckets. US7350322 B2 2008.
[2] Riise M.M.. Sludge dewatering system. US4382863 May 10, 1983.
[3] Wright D.M.. Rake classifier. US2155748 Apr. 25, 1936.
[4] Sharonov M.A.. Apparatus for granulating molten slag. US4230477 Oct. 28, 1980.
[5] Miller-Spath E.. Process and apparatus for dewatering granulated material especially granulated blast furnace slag. US4196078 Apr. 1, 1980.
[6] 6.Rodd L., Koehler T., Walker C., Voermann N.. Economics of slag heat recovery from ferronickel slags.Vancouver : 49th Annual Conference of Metallurgists (COM2010). pp. 1-12. CIM, 2010.
[7] Nejad S. K., Liu S., Kozlowski M., Candy I.. Energy recovery opportunities in pyroprocessing of nickel laterites. Ralph Harris Memorial Symposium (COM2013). pp. 83-98. Montreal : CIM, 2013.
[8] Kotaro I., Masahiko M., Tomoyuki O.. Method for recovering heat from molten slag and an apparatus therefor. US 4147332 A Apr. 3, 1979.
[9] Kobe R.O., Kakogawa H.F., Toyada K.. Recovery of heat from molten slag from metallurgical processes. US 4111159 A Sep. 5, 1978.
[10] Kakogawa H.F.. Apparatus for heat recovery from molten slag. US4350326 Sep. 21, 1982.

[11] Hooykas C.W.J.. A process and apparatus for recovering energy from molten slag. EP0023727 B1 Aug. 3, 1979.
[12] Yang Q., Haase B., Han F., Engstrom F., Li F., Xu J., Bjorkman B.. Laboratory treatment of EAF slag for its use in construction. Advanced Materials Research, Vols. 726-731, pp. 2921-2930, 2013
[13] Sakkas K., Nomikos P., Sofianos A., Panias D.. Utilisation of FeNi-Slag for the production of inorganic polymeric materials for construction or for passive fire protection. Waste and Biomass Valorization , Vol. 5, 3, 2013
[14] Wang G., Thompson R.. Slag Use in Highway Construction - the Philosophy and Technology of its Utilization. International Journal of Pavement Research and , Vol. 4, pp. 97-103, 2, 2011
[15] Leaching behaviour of aged steel slags. al., F. Engstrom et. 4, 2014, Steel Research International, Vol. 85, pp. 607-615.
[16] A study on solubility of pure slag minerals. al., Engstrom et. 2013, Minerals Engineering, Vol. 41, pp. 46-52.
[17] Mostaghel S., Engstrom F., Yang Q., Samuelsson C., Bjorkman B..The effects of cooling rate on leaching behaviour of some ferrous and non-ferrous slag systems. 9th International Conference on Molten Slags, Fluxes and Salts. pp. 1-11, Beijing : s.n., 2012.