TECHNOLOGY OF SLAG UTILIZATION IN HIGHWAY CONSTRUCTION

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ABSTRACT

Research and applied utilization activities for the increased use of ferrous and nonferrous slags in civil and highway construction are presented. The overall use of blast furnace slag is relatively well known for a range of highway construction applications from granular base to supplementary cementitious materials. In contrast to blast furnace slag, which is volumetrically stable and straightforward in its construction uses, steel slag contains hydratable oxides that can result in volumetric instability that must be dealt with through appropriate steel slag aging, testing and quality control to ensure its appropriate use in highway construction. Particular care must be taken to prevent potential steel slag expansive behaviour in confined applications. Quality requirements and guidelines on steel slag expansivity to further the use of appropriate quality steel slags, with demonstrated acceptable performance, in aggregate and cementitious applications are outlined.

There is a full range of proven civil and highway construction uses - from aggregate to cementitious materials - for copper, nickel and phosphorus nonferrous slag. The use of air-cooled nickel slag is presented, based mainly on practical highway experience and in the Dominican Republic with ferronickel slag. It has been shown in the laboratory, and more importantly during highway construction, that air-cooled, crushed nickel slag can be an excellent aggregate in granular base, engineered fill and hot-mix asphalt. There is a good potential for increased ground, granulated copper and nickel slags use as supplementary cementitious materials that is being developed, which takes advantage of the 'latent energy' content. The scope of a new technical text on the technology of slag utilization is reflected throughout to provide a practical context for the highway engineer.

INTRODUCTION

Slag is the molten byproduct or coproduct of many metallurgical and special (coal-fired thermal plants for instance) operations, that is subsequently cooled (air, pelletized, foamed or granulated) for use, or, unfortunately in too many cases, disposal. Ferrous (iron and steel) and nonferrous (copper and nickel for instance) metals are the most commonly used, world-wide, structural and functional materials. The resulting large quantities of slags produced and their potential impact on the environment have prompted materials scientists and civil engineers to explore the technically-sound, cost-effective and environmentally-acceptable use of a wide range of slags in civil and highway construction.

Research and laboratory testing, field evaluation, and practical utilization demonstration in construction with appropriate specification and quality requirements, are the trilogy of slag use development for highway construction. The ultimate purpose of any slag utilization study is to open up avenues for the appropriate use of a particular slag with specific characteristics. There are three main points fundamental to conducting the effective study of a specific slag, which forms the basis for uses in highway construction.

- First, there must be a sound understanding of the overall compositional and physical properties of the specific slag being investigated, especially any potentially negative characteristics (volume expansivity related to hydratable oxides for instance). The slag properties to be considered are chemistry (typically as oxides), composition (mineralogy), physical and mechanical including a comparison of these properties with those of other slags and related materials which may be replaced by the specific slag, or used in conjunction with the slag.

- Second, in order to achieve appropriate and optimum utilization of a specific slag, it is essential to have a comprehensive understanding of the production, properties, design methods, construction uses and specifications of the conventional material(s) that the slag may replace or incorporate the slag. The conventional materials could be bulk (aggregate for instance) or cementitious (portland cement for instance). The relationship of the processing methods and properties between conventional material(s) and slag(s) must be understood and investigated so that any potential use of the specific slag in highway construction can be thoroughly exploited.

- Third, it must be recognized that slags are distinct, rather unique materials, and generally different from any natural mineral materials. Like any other byproduct or coproduct (or waste unfortunately too often), slag is a type of special raw material with its own characteristics, that must generally have additional processing for uses in highway construction. It is important, therefore, that highway material and construction specifications based on conventional mineral resources and materials do not preclude the use of suitable quality slags with demonstrated satisfactory performance for the intended purpose. The importance of proper slag processing, with quality control, for approved highway uses cannot be over emphasized.

Each specific slag, in terms of type, process and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for aggregate and cementitious uses.

SLAG UTILIZATION PHILOSOPHY

Slag utilization in highway construction is an overall process which includes several stages from slag production to end uses. Successful utilization is generally based on several stages or links. The overall general process consists of seven links, as shown in Figure 1, any one of which might affect the final use of the specific slag in highway construction. These links include: pre- or post-treatment of slag; chemical and physical (particularly potential expansion and deleterious components) properties and the factors which affect them; and the evaluation of potential field performance for the intended uses. Comprehensive slag utilization studies consist of three main stages: treating and processing; intrinsic properties; and properties of end products (uses). The slag uses shown in Figure 1 are divided into three broad areas: use as granular material or hot-mix asphalt aggregate (there is often a wide range of aggregate uses - from granular material to special applications such as filter media); use as portland cement concrete aggregate; and use in cementitious applications (slag cements).

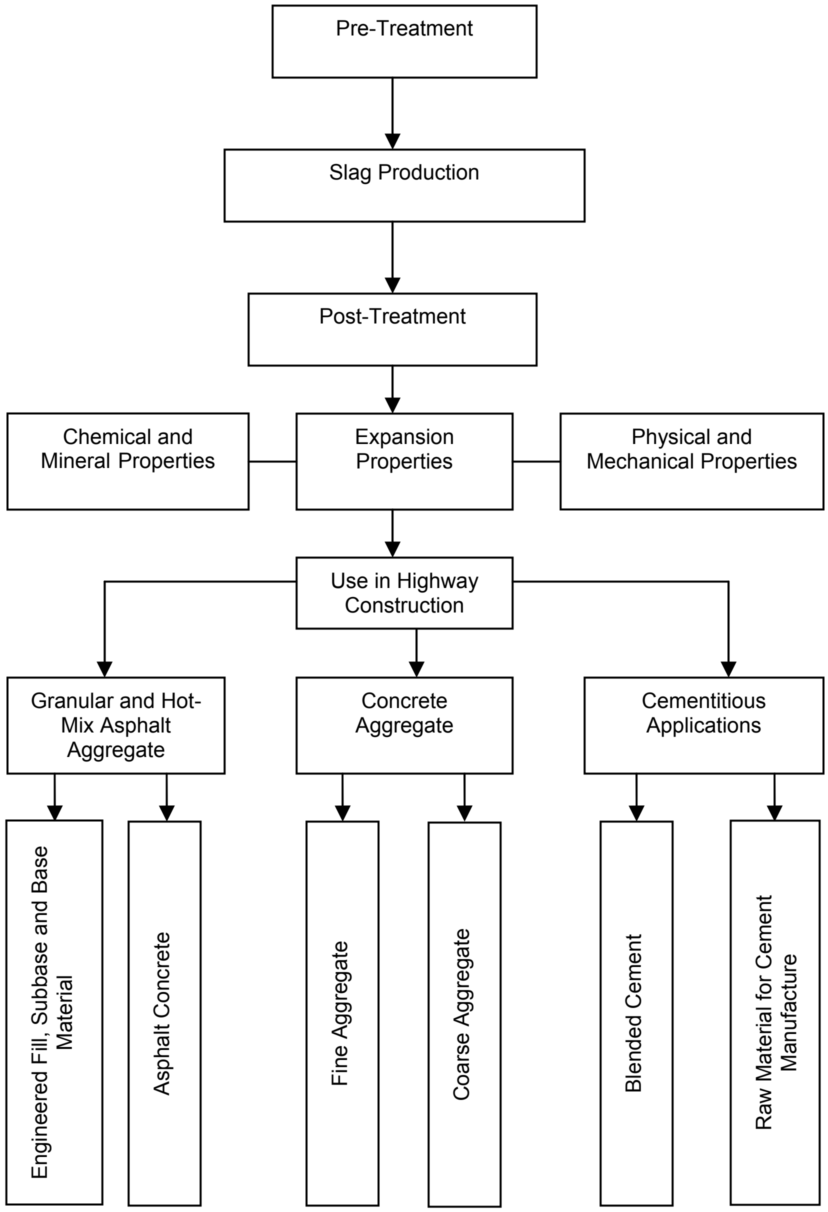


Figure 1 - Overall Process of Slag Utilization in Highway Construction

There are three relationships to be considered for slag utilization, as shown in Figures 2 and 3: (i) the relationship between chemical and mineral composition and any potentially 'negative' properties; (ii) the relationship between any negative slag properties and the performance requirements and properties of the end products (uses); and (iii) the rational use of slags with different properties to ensure optimum use of the specific slag. For example, volume expansion is the main factor likely to affect the successful use of a specific steel slag as a highway construction material; volume expansion is dependent on the chemical and mineral composition of the specific slag and thus critically affects the evaluation of the slag and its quality control.

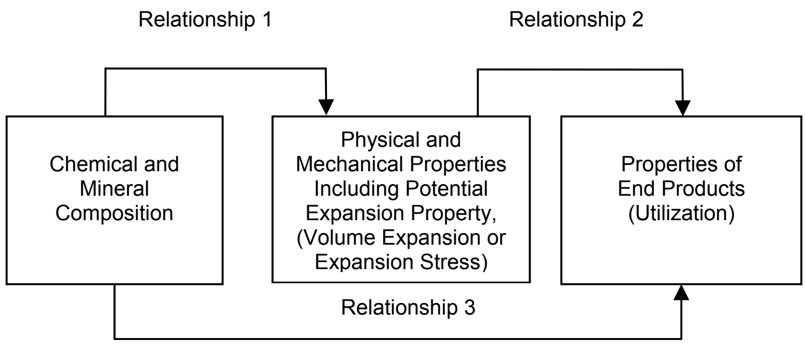
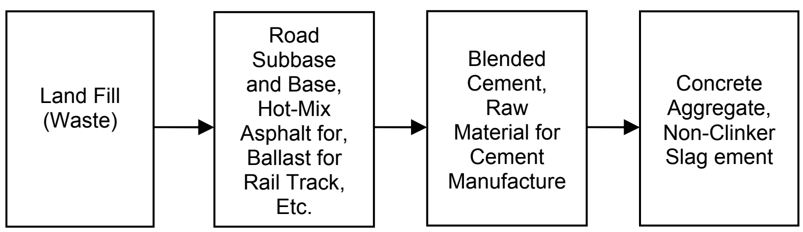


Figure 2 – Relationships for Slag Utilization in Highway Construction



The requirement for stability of slag in use (from lenient to rigorous) →
The degree of use of latent (chemical) energy in slag (from none to full) →

Figure 3 – Typical Grades of Slag Utilization in Highway Construction

To effectively use a slag, it is necessary to know how its chemistry and mineral composition affect any potential negative properties (volume expansion of steel slag for instance) (Relationship 1), and how the negative properties can affect the performance of the end products (uses) (Relationship 2). Relationship 3 is dependent on Relationships 1 and 2. Relationship 1 determines the necessary treatment modification of the properties of the specific slag and related quality control. Relationship 2 is essential to enable the slag, with known or modified properties, to be put into use in civil or highway construction. Once Relationship 2 is known quantitatively and demonstrated, the use becomes viable. Once Relationship 1 is known, suitable Relationship 2 treatment methods, if necessary, can be chosen and then Relationship 3 for optimal end uses established. It is imperative that all potential negative behaviour and/or deleterious components are thoroughly checked and evaluated for a specific slag in terms of the intended and optimal use requirements (Figure 3).

Slag is actually an energy-containing material, particularly when rapidly solidified (pelletized or granulated) from the molten state to a vitrified form (process energy locked in - latent energy). In determining the uses of a specific slag, proper attention should be paid to the optimum use of this energy potential. This is one of the three objectives of byproduct and coproduct (or waste) utilization: protection of the environment; full use as a bulk and/or energy resource; and technical beneficiation for value-added uses. The term “slag utilization” can be defined as the effective use of a specific slag to achieve these objectives. Under this definition, landfill is clearly not utilization and does not contribute to a sustainable society. On the other hand, any cementitious use of a slag could be considered as energy recovery and the highest value added. For example, the use of slag as a skid-resistant aggregate involves the use of its surface characteristics such as hardness, where hardness is a strength related property with little energy recovery. On the other hand, use as a cementitious material in blended cement essentially recovers the latent (invested) energy. It is very important to focus on cementitious (energy) uses of slags where possible, rather than just aggregate (bulk) uses. More quantitative assessment is generally needed for higher end uses of a slag. This is shown in Figure 3, where from left to right, increasing potential invested (process) energy is 'recovered', necessitating a higher degree of stability and more rigorous quantitative work to quantify slag performance properties.

QUANTIFICATION IN SLAG UTILIZATION

The reason for a specific slag not currently being fully utilized is often due to a general lack of quantification work on the properties of the slag (expansion potential for instance) and the performance requirements of the end products (uses). A technical opinion unsupported by thorough characterization and performance testing is not sufficient to encourage the use of a slag in the construction industry without misgivings or concerns. Unfortunately, the impact of past utilization mistakes is very difficult to overcome even for proven uses. Usability criteria and properties of composites made from a specific slag can be determined from a study of the basic properties of the slag and the specific application specifications for a use, particularly stability and deleterious materials control requirements.

The relevant, necessary slag quantification work for engineered fill, rail ballast, subbase and base material, erosion control material and hot-mix asphalt aggregates includes: laboratory testing (volume expansion characterization for instance); evaluation; establishing processing requirements; establishing specification requirements and quality control procedures; and combining this technical suitability with a check of environmental factors and cost-effectiveness. For slag use as portland cement concrete aggregate, the quantification requirements are more detailed given the importance of long-term durability and stability in a wide range of environments and structures. For slag use in blended cement, in addition to the quantification of pozzolanic/hydraulic properties, stability and durability for various substitution ratios, the grindability (cost) of the slag is very important.

Recent quantification work carried out by the authors has resulted in some useful criteria for slag utilization. It should be noted that each specific slag must be fully quantified and checked for each specific use as these are only general guidelines.

Prediction of Volume Expansion – Criterion for Slag Use as a Granular Material

For steel slag use as a granular material (aggregate) in unconfined applications such as granular base and hot-mix asphalt aggregate, volume expansion (stability) is still of major concern[1]. (**A detailed quantification for confined applications such as structural fill or concrete aggregate is imperative and these uses must always be viewed with great care as only special quality steel slags will demonstrate the required volumetric stability** [1,2].) A usability criterion for unconfined applications has been developed based on the physical properties of a given slag:

$$F \leq k \frac{(\gamma_s - \gamma_o)}{\gamma_s^2} \times 100\% \qquad \text{Equation 1}$$

where F is the hydratable oxide content (CaO and/or MgO) of a given slag; γ_s is the specific gravity of the slag; γ_o is the bulk relative density of the slag; and k is a constant related to the slag's physical properties. When the hydratable oxide content of a given steel slag is less than the right hand term, the slag will not expand macroscopically when used as a granular material. This must then be confirmed through standard slag expansivity testing [3].

Volumetric Stress – Criterion for Use in Rigid Applications

For slag used in a rigid matrix (portland cement concrete for instance), the resulting integrity and volume stability are basically controlled by the minimum allowable stress of the matrix material and the maximum volumetric stress (expansion stress) of the slag used in the matrix. A criterion for this has been developed as follows [2]:

$$\sigma_d = k \frac{\pi d \sigma_e}{R \phi} \leq \sigma \qquad \text{Equation 2}$$

where σ_d is the 'dangerous' stress level of the slag aggregate (N/m^2); k is a factor of safety larger than 1; d is the particle size of the slag aggregate; R is the particle cracking ratio; σ_e is the volumetric expansive stress of a compacted mass of the slag on a unit area at unit height (N/m^3) which is obtained from a laboratory accelerated autoclave testing for a given slag; and ϕ is a filling factor for the slag aggregate. When the maximum tension stress of a given slag is less than the allowable stress σ, the entire product will not fail or lose strength owing to the fact that the matrix strength is sufficiently high to constrain the expansion stress generated from the slag particles. Once again, it is necessary to confirm this through detailed durability testing of the concrete incorporating the specific slag. **It is imperative that only special quality steel slags, of clearly proven suitability, are considered for concrete aggregate, cementitious and confined application uses** [1,2].

Autoclave Disruption Testing

A laboratory autoclave disruption testing method [3] has been developed to evaluate the quality of slag aggregates for use in highway construction. In this test, a slag sample is separated into different size fractions and examined petrographically. Specific amounts of slag particles are chosen to test each size fraction of the slag. The slag samples are then placed in a simple autoclave for testing. The disruption ratio is then used to assist in evaluating the expansion potential and/or deleterious material content of the slag aggregate.

NICKEL SLAG USE IN HIGHWAY CONSTRUCTION

There is a full range of proven highway construction applications for suitable quality nickel, copper and phosphorus slags. One of the recent positive developments was the use of large quantities of air-cooled nickel slag in the reconstruction and widening of the Duarte Highway in the Dominican Republic [4,5]. The specific nickel slag is a coproduct of ferronickel production by the smelting of laterite ore by Falcondo at Bonao.

Background Information

The reconstruction and widening of 140 kilometres of the Dominican Republic's Duarte Highway from Santo Domingo (capital and largest city) north to Santiago (second largest city) was completed between 1994 and 1996 at a cost of some US $150 million. This Project was completed under the supervision of the Secretaria de Estado de Obras Públicas y Communicaciones (SEOPC) to the highest of international standards.

Aggregate Selection

The SEOPC took considerable efforts to mitigate the impact of the Duarte Highway construction work on the physical environment. The terrain, at several points along the route, required very deep and difficult cutting and filling, with extensive watercourse protection throughout and the use of large quantities of granular borrow fill. In addition to these borrow fill requirements (engineered fill), there was the requirement for large quantities of granular subbase and hot-mix asphalt crushed aggregates. The prime sources of these aggregates were large river bed gravel deposits that were selected, processed and rehabilitated to minimize environmental impacts. The SEOPC also implemented the use of nickel slag aggregate (stockpiled 'waste' slag) as a large, environmentally-friendly, suitable aggregate source from the Falconbridge Dominicana, S.A. (Falcondo, part of Falconbridge, a Canadian company) laterite ore ferronickel smelter.

The Falcondo ferronickel smelter was conveniently located near the middle of the project with large quantities of nickel slag 'stockpiled' in the slag disposal area. Due to the thermal shock of air-cooling, the molten nickel slag is 'fragmented' to a convenient size for engineering fill and granular subbase use. There was a concern for the volume stability and leachate characteristics of the Falcondo nickel slag aggregate, based on the erroneous assumption that it is similar to steel slag which does exhibit volumetric stability problems, as discussed above [3]. A thorough technical literature review and laboratory testing program was completed for the SEOPC to check the volume stability and leachate characteristics. The testing results for nickel slag aggregates used in the Duarte Highway construction are summarized in Table 1. Based on considerable

Table 1
Summary of Test Results
Nickel Slag Aggregates – Dominican Republic

<table>
<tr><td>TEST</td><td colspan="3">SAMPLE</td></tr>
<tr><td></td><td>Nominal 25 mm Minus Sample 1</td><td>Nominal 25 mm Minus Sample 2</td><td>Nominal Retained 25 mm Minus Sample</td></tr>
<tr><td colspan="4">JEGEL Slag Aggregate Autoclave Disruption Test Pass</td></tr>
<tr><td>1.18 to 2.36 mm</td><td>50/0/0 (Good/Fair/Poor)</td><td>50/0/0</td><td>-</td></tr>
<tr><td>2.36 to 4.75 mm</td><td>50/0/0</td><td>49/1/0</td><td>-</td></tr>
<tr><td>4.75 to 6.7 mm</td><td>50/0/0</td><td>50/0/0</td><td>-</td></tr>
<tr><td>6.7 to 9.5 mm</td><td>50/0/0</td><td>50/0/0</td><td>-</td></tr>
<tr><td>9.5 to 13.2 mm</td><td>50/0/0</td><td>50/0/0</td><td>-</td></tr>
<tr><td>>25 mm</td><td>-</td><td>-</td><td>12/0/0</td></tr>
<tr><td></td><td>Pass</td><td>Pass</td><td>Pass</td></tr>
<tr><td colspan="4">Autoclave disruption testing was also completed for two particles of nickel slag which exhibited cracking attributed to thermal shock. Both particles passed the autoclave disruption test (remained sound and did not exhibit any additional cracking).</td></tr>
<tr><td colspan="4">Slag Aggregate Petrographic Examination [3] Pass</td></tr>
<tr><td colspan="4">A 1700 g sample of the nominal 25 mm minus nickel slag (passing 25 mm, retained 4.75 mm) was examined by a petrographer. The sample was found to consist solely of hard nickel slag. Occasional cracked particles were identified (thermal cracking) as well as some very vesicular particles, but no deleterious or non-slag particles were identified. One particle of nickel slag appeared to have some cemented sand attached to it, but the particle itself was hard.</td></tr>
<tr><td colspan="4">Slag Aggregate Expansion Test [3] Pass</td></tr>
<tr><td>Percent Expansion,
7 days at 60°C</td><td>0.06 (negligible)</td><td>0.04 (negligible)</td><td>Not Tested</td></tr>
</table>

practical positive international experience, satisfactory local use for several years, leachate characterization, mineralogical evaluations and the favourable comprehensive accelerated stability and durability testing, the Falcondo nickel slag was given full project approval for engineered fill, granular subbase and hot-mix asphalt aggregate use. Several million cubic metres of the Falcondo nickel slag were used during the project, thus replacing a substantial amount of river gravels and making a very positive contribution to the environment. The regular construction industry use of Falcondo nickel slag is now being established for domestic and export markets.

CONCLUSION

It has only been possible here to outline the guiding philosophy for slag utilization and provide a fairly detailed example based on nickel slag use as engineered fill, granular subbase and hot-mix asphalt aggregate during the Duarte Highway reconstruction and widening project in the Dominican Republic. Hopefully, the requirements for a full quantification of a specific slag and thorough evaluation for intended uses have been clearly indicated along with the sustainable development objective of taking advantage of the full range of potential uses, particularly cementitious. A technical text "Technology of Slag Utilization" giving a much more detailed and comprehensive treatment of slag utilization in civil and highway construction will be available from the authors in late 2004.

REFERENCES

1. Wang, G., "Properties and Utilization of Steel Slag in Engineering Applications", 1992, Ph.D. Thesis, University of Wollongong, New South Wales, Australia.

2. Wang, G. and Montgomery, D., "Criteria for the Use of Slag in Concrete - A Numerical Method", Proceedings, Symposium on Use of Fly Ash, Silica Fume, Slag, Natural Pozzolans and Other By-Products in Concrete and Other Construction Materials, 1992, Milwaukee, USA.

3. Farrand, B., and Emery, J., "Recent Improvements in the Quality of Steel Slag Aggregate", Transportation Research Record, 1468, 137-141, 1995.

4. Emery, J., "Asphalt Technology for Mega Transportation Projects", Proceedings, Canadian Technical Asphalt Association Annual Meeting, 1999, Québec, Canada.

5. Caribbean Fast-Track, World Highways, 4 (5), 25-28, 1995.