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Slag Use in Highway Construction – the Philosophy and Technology of its Utilization

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Abstract: Recent research, development, and applied utilization activities conducted by the author for the increased use of ferrous and nonferrous slags in civil and highway construction are presented. Quantification work that leads to usability criteria has been conducted to ensure its appropriate use of slag in highway construction. Criteria and guidelines on slag expansivity to further the use of appropriate quality steel slags, with demonstrated acceptable performance, in granular subbase/base, hot-mix asphalt, concrete, and cementitious applications are outlined. Examples are presented for each usability criterion. The use of air-cooled nickel slag is also presented, based mainly on recent positive developments 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 is an excellent aggregate in granular base, engineered fill, and hot-mix asphalt.

***Key words**: Construction; Highway; Pavement; Slag.*

Introduction

The use of industrial solid by-products is becoming increasing important in the construction practice for energy, natural resources, and environment conservation considerations [1, 2]. Particularly, researchers have conducted research worldwide on various ferrous and non-ferrous slag use in different construction applications, such as hot-mix asphalt [3, 4], concrete aggregate [5], and granular materials [6]. However, it is noted that most of the research is in the laboratory experiment stage.

Slag is the main by-product produced in metallurgical industries. Molten slag is co-produced by many metallurgical and special coal fired thermal plants and is subsequently cooled by different methods, including air, pelletized, foamed, or granulated, for use, or, unfortunately in too many cases, disposal. Ferrous, i.e., iron and steel, and nonferrous, i.e., copper and nickel, metals are the most commonly used structural and functional materials worldwide. 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 specifications and quality requirements are the trilogy of slag use development for highway construction. The ultimate purpose of any slag utilization study is to open 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 by-product or co-product (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 bulk and cementitious uses. The philosophy of utilization of slag and quantification work that leads to usability criteria has been conducted by the author to ensure its

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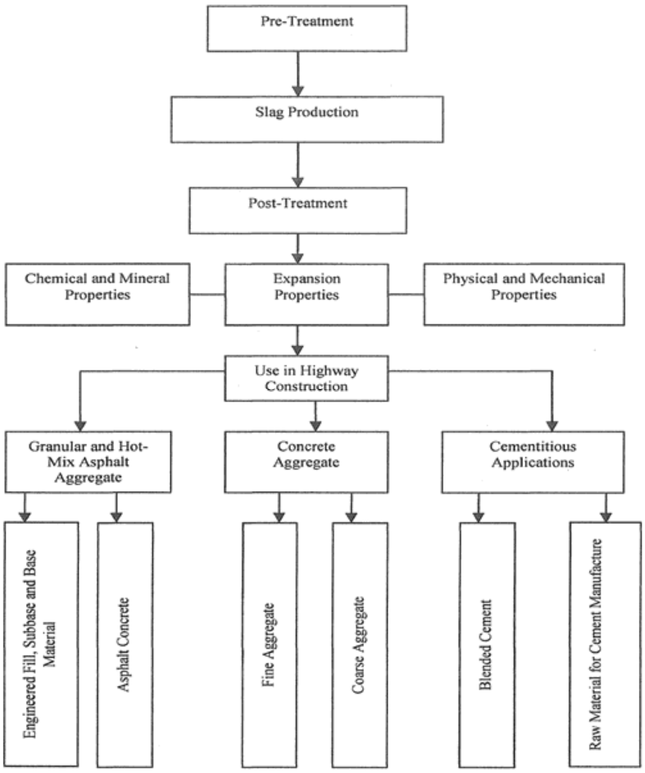

Fig. 1. Overall Process of Slag Utilization in Highway Construction.

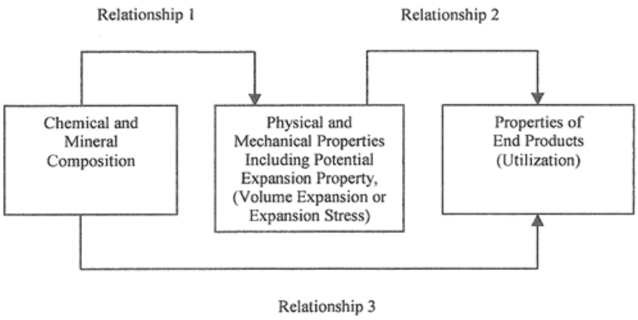

Fig. 2. Three Key Relationships for Slag Utilization in Highway Construction.

appropriate use of slag in highway construction are presented in this paper.

The Philosophy of Slag Utilization

In the broad sense, the comprehensive utilization of slag will have significant benefits in three major ways. Firstly, there will be a substantial reduction in environmental pollution due to changes in current practice, whereby the existing material is disposed off by dumping and stockpiling. Secondly, the use of such material will supplement, or replace, the need for using natural materials, thereby resulting in protection of natural, non-renewable resources and a reduction in energy requirements associated with the winning of natural materials. Thirdly, there exists the possibility of altering, or modifying, physical and chemical properties of the basic materials to produce special engineering materials which can be utilized for specific applications.

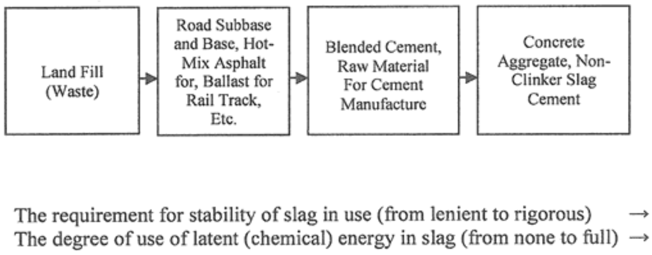

Fig. 3. Typical Grades of Slag Utilization in Highway Construction.

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 Fig. 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 Fig. 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 filler media); use as portland cement concrete aggregate; and use in cementitious applications (slag cements).

There are three relationships to be considered for slag utilization, as shown in Fig. 2: (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.

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), and how the negative properties can affect the performance of the end products (uses). It is necessary to treat and modify the properties of the specific slag and conduct related quality control during slag process. It is essential to enable the slag, with known or modified properties, to be put into use in civil or highway construction. Once the physical and mechanical properties meet the requirements for the end-products, the utilization becomes viable. In Fig. 2, the process is illustrated by the three relationships. 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 behavior and/or deleterious components are thoroughly checked and evaluated for a specific slag in terms of the intended and optimal use requirements.

Table 1. Steel Slag Samples Used in Volume Expansion Test.

Slag Sample 1		Slag Sample 2	
γ_o	γ_s	γ_o	γ_s
1.845	2.997	1.627	3.38
Free lime content: 2.86%		Free lime content: 2.93%	

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 by-product and co-product (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 Fig. 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/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 author 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 [7, 8, 9]. 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 [10, 11]. A usability criterion for unconfined applications has been developed based on the physical properties of a given slag [12]:

$$F < \frac{0.075(\gamma_s - \gamma_o)}{0.38\gamma_s^2} \times 100\% \quad (1)$$

or

$$F \leq k\frac{(\gamma_s - \gamma_o)}{\gamma_s^2} \times 100\% \quad (2)$$

Here 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 that can be determined based on the testing results of 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 [13].

It states if free lime content in the steel slag is less than the right-hand term, the steel slag will not expand macroscopically, or the expansion resulting from free lime can be "absorbed" by the void volume of steel slag itself under a pressure of 25 g/cm^2, which is the test condition. In other words, overall expansion will not occur if this condition is met. It simply provides a convenient estimation for a given steel slag with a known content of free lime content and physical properties. The condition, surcharge of 25 g/cm2, is easy to meet, because for normal asphalt pavement structure, the thickness of base and subbase should be 100-300 mm or thicker.

Two slag samples, as presented in Table 1, have been chosen for volumetric testing. Based on Eq. (1), the allowable free lime contents for the two slag samples are 2.53% and 3.03%, respectively. The measured free lime contents for the slag are 2.86% and 2.93%. Based on the volumetric criterion, Sample 1 cannot be used safely as a granular material, which may cause apparent expansion, and Sample 2 can be safely used as a granular material. The laboratory volume expansion tests conducted according to ASTM D 4792-00 [14] indicate that at 7 days Sample 1 has 0.5% volume expansion and Sample 2 has 0.02% expansion, which can be safely used as a granular material such as base or subbase.

Volumetric Stress Measurement and 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 by the author [10]:

$$\sigma_d = k\frac{\pi\, d\sigma_e}{R\phi} \le \sigma \tag{3}$$

Here σ_d is the "dangerous" stress level of the slag aggregate (N/m^2); k is a factor of safety larger than 1, which can be determined based the deviations of expansion testing results; 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 [9, 10].

Laboratory expansion force test conducted for a steel slag sample that has a maximum expansion force at 13 days, which is 4,023.6 N. Based on Eq. (3) (k = 1.25), the slag can be used in a cement-based confined matrix. It is assumed that the allowable tensile strength of cement mortar is 3.2 MPa [Eq. (4)]. Portland cement concrete cylinders were prepared using the steel slag sample as coarse aggregate (cement: natural sand: steel slag coarse aggregate = 1:1.68:3.81, w/c = 0.47). The volume stability has been excellent under three hours autoclave testing at 357 kPa, 137°C, for the concrete specimens containing steel slag coarse aggregate.

$$\sigma_d = k\frac{1.5\pi\times 0.016\times 4023.6\times 10^6}{12\times 0.03\times 0.67\times 2260} = 0.70 \text{ MPa} \quad < [\sigma] = 3.2 \text{ MPa} \tag{4}$$

Volumetric stable nickel slag samples have also been used as coarse aggregate in making portland cement concrete in laboratory. The volumetric stability has been acceptable. Concrete mix designs were developed to assess the workability of the fresh concrete and the strength development of the hardened concrete containing nickel slag samples (Nickel slag 1 and Nickel slag 2). The concrete mixes were proportioned using 100% nickel slag, for non-air entrained concrete mixes. A control mix using conventional (natural) concrete coarse and fine aggregates was also prepared and tested for comparison purposes. Table 2 summarizes the compressive strength results at 7, 14, and 28 days. Fig. 4 shows concrete cylinders containing air-cooled nickel slag after breaking.

The concrete mixes containing two nickel slag aggregate both give higher compressive strengths than the control concrete mix.

Table 2. Compressive Strength Results of Concrete Containing Nickel Slag Samples.

Mix	Average compressive strength (MPa)		
	7 days	14 days	28 days
Nickel slag 1	47.7	56.2	61.7
Nickel slag 2	41.7	49.5	52.0
Control aggregate	35.1	43.2	48.1

Fig. 4. Concrete Containing Air Cooled Nickel Slag as Coarse Aggregate after Breaking.

Autoclave Disruption Testing

A laboratory autoclave disruption testing method [10, 15] has been developed by the author 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, normally 100 or 50, of slag particles are chosen to test each size fraction of the slag. The slag sample is then placed in an autoclave for testing. The autoclave for disruption test was set at 357 kPa, 137°C for 1-hr testing. The pressure is approximately 3.5 atm and was selected at the mid range of the autoclave used in the testing. The temperature is the actual temperature measured. The disruption ratio is given by Eq. (5). The disruption ratio (R) is then used in evaluation of the expansion potential.

$$R = \frac{N_c}{N_t}\times 100\% \tag{5}$$

where, N_c is the amount of particle cracked or powdered after test; and N_t is the amount of particles selected for the test.

The test results of a nickel slag samples that underwent autoclave disruption testing are summarized in Table 3.

Nickel Slag Use in Highway Construction – a Case Study

There is a full range of proven highway construction applications for suitable quality nickel, copper, and phosphorus slags. One of the

Table 3. Autoclave Disruption of Air Cooled Nickel Slag.

Size Fraction, mm		Total Number of Particles	Number of Particles by Quality after Autoclaving Good	Fair	Poor	Disruption Ratio, %
Sample 1	19.0 to16.0	50	26	24	0	0
	16.0 to 13.2	50	33	17	0	0
	13.2 to 9.5	50	47	3	0	0
	9.5 to 4.75	50	45	5	0	0
	Average	50	38	12	0	0
Sample 2	19.0 to16.0	50	30	20	0	0
	16.0 to 13.2	50	39	11	0	0
	13.2 to 9.5	50	43	7	0	0
	9.5 to 4.75	50	45	5	0	0
	Average	50	39	11	0	0
Test Average		50	39	12	0	0

Table 4. Summary of Test Results of the Nickel Slag Aggregates.

Test	Sample: Nominal 25 mm Minus Sample #1	Nominal 25 mm Minus Sample # 2	Nominal Retained 25 mm Minus Sample
Autoclave Disruption Test	Pass		
1.18 to 2.36 mm	50/0/0 (Good/Fair/Poor)	50/0/0	—
2.36 to 4.75 mm	50/0/0	49/1/0	—
4.75 to 6.7 mm	50/0/0	50/0/0	—
6.7 to 9.5 mm	50/0/0	50/0/0	—
9.5 to 13.2 mm	50/0/0	50/0/0	—
>25 mm	—	—	12/0/0
	Pass	Pass	Pass
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).			
Slag Aggregate Petrographic Examination	Pass		
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.			
Expansion Test	Pass		
Percent Expansion, 7 days at 60°C	0.06 (negligible)	0.04 (negligible)	Not Tested

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. The specific nickel slag is a co-product of ferronickel production by the smelting of laterite ore by Falcondo at Bonao.

Background Information

The reconstruction and widening of 140 km of the Dominican Republic's Duarte Highway from Santo Domingo (capital and largest city) north to Santiago (second largest city) was completed at a cost of some $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 was "fragmented" to a convenient size for engineering fill and granular subbase use. There

(a) (b)

Fig. 5 (a). Marshall Specimens Containing Nickel Slag **(b)** Superpave Specimens Containing Nickel Slag.

Table 5. Summary of Hot-Mix Asphalt Design – Marshall Properties.

Properties	Marshall Properties		Required by Local
	Slag 1	Slag 2	Specifications
Voids (%)	4	4	3.5 – 4.5
Flow, 0.25 mm	14	13.6	8 minimum
Stability (N)	16,691	17,354	8000 minimum
VMA (%)	14.5	15.7	14.0 minimum
Asphalt Cement Content (%)	5.2	5.3	4.7 minimum

Table 6. Summary of Hot-Mix Asphalt Design – Superpave Properties (Traffic ≥ 30 × 106 Equivalent Single Axle Loads [ESALs]).

Superpave	Mix Design Data		Superpave Requirements
Properties	AC Slag	EP Slag	AI - SP-2
Air Void (%)	4.0	4.0	4.0
Voids in the Mineral Aggregate (VMA, %)	14.0	15.2	13.0(Minimum)
Voids Filled with Asphalt (VFA, %)	71.5	73.7	65-75
Dust to Binder Ratio	0.9	0.8	0.6-1.2

was a concern for the volume stability and leachate characteristics of the nickel slag aggregate based on the erroneous assumption that it is similar to steel slag, which does exhibit volumetric stability problems, as discussed above [12, 15].

Laboratory Testing Results

Laboratory testing program was completed for the SEOPC to check the volume stability and leachate characteristics. Table 4 summarizes the testing results for nickel slag aggregates used in the Duarte Highway construction. Based on considerable practical positive international experience, satisfactory local use for several years, leachate characterization, mineralogical evaluations, and the favorable comprehensive accelerated stability/durability testing (Table 4), the nickel slag was given full project approval for engineered fill, granular subbase, and hot-mix asphalt aggregate use. Several million cubic meters of the Falcondo aggregates were used during the project, thus replacing a substantial amount of river gravels, making a very positive contribution to the environment. Additionally the regular construction industry use of Falcondo aggregate is being established for domestic and export markets.

Furthermore, the hot-mix asphalt designs were made to check both Marshall and Superpave properties. The summaries of Marshall and Superpave properties of the hot-mix asphalt containing nickel slag samples are presented in Tables 5 and 6.

Fig(s). 5 (a) and (b) show the Marshall and Superpave hot-mix asphalt specimens, respectively.

Some 10 million tons of Falcondo nickel slag aggregate were used for engineered fill, erosion protection stone, granular base material, and hot-mix asphalt aggregate during the reconstruction/widening of the autopista Duarte project. This has resulted in further market development and a clear demonstration of technically sound, economic, and environment friendly use of byproduct slag Falcondo nickel slag aggregate.

Conclusion

Quantified usability criteria are imperative for utilization of various slags in a full scale. The criteria developed for slag use as a granular material and as an aggregate in confined matrices are reliable and practical in use. To correctly utilize slags in highway construction and ensure the use is technically sound and durable, the following steps have to be followed: (i) select the right criterion for a specific use; (ii) conduct relevant laboratory testing to quantify the given sample; (iii) determine the usability based on relevant criterion; (iv) conduct field quality control; and (v) monitor long term performance, which are the same as the use of normal natural materials. In this paper, it has only been possible 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 the 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.

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