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ECONOMIC AND ENVIRONMENTAL BENEFITS OF DIRECT REDUCTION STEELMAKING SLAG UTILIZATION IN NIGERIA'S AGGREGATES INDUSTRY

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Abstract: The Delta Steel Company (DSC) test steel slag, produced through the direct reduction electric arc steelmaking technology process, presents a potential solution to address Nigeria's heavy reliance on natural aggregates for construction, building, and transportation industries. The slag, composed of lime sourced from Mfamosing limestone in Calabar, Nigeria, direct reduced iron from low phosphorus iron ore in Liberia, and scrap iron, had been stored in the company's slag dump site for an extended period, leading to environmental concerns for both the company and the community.

Despite Nigeria's abundant natural aggregates, the country's dependence on these resources persists due to a lack of research knowledge regarding the utilization of solid industrial by-products like blast furnace and steelmaking slags. While previous research has explored the properties of steelmaking slags, their historical use as aggregates in construction, transportation, and building industries has been well-documented, highlighting potential issues related to unsoundness stemming from hydratable oxides, particularly lime and magnesia.

This study aims to assess the viability of incorporating the test slag into Nigeria's aggregate industry, offering a sustainable alternative to conserve natural resources. By investigating the physical and mechanical properties of the test slag, the research seeks to determine its potential contribution to the country's aggregate sector. This effort aligns with the broader goal of reducing the country's dependency on natural aggregates and exploring the beneficial reuse of industrial by-products, such as steel slags, in support of environmental sustainability and resource conservation.

Keywords: Steel slag, Aggregates, Industrial by-products, Resource conservation, Environmental sustainability

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Introduction

The Delta Steel Company (DSC) test steel slag was produced using the direct reduction electric arc steelmaking technology process. Lime obtained in the plant from the Mfamosing limestone, Calabar, Nigeria, direct reduced iron obtained from low phosphorus iron ore from Liberia and scrap iron were used as feed. The slag had been left in the slag dump site in the company for long, accumulated in heaps unacceptable to company and community environmental conditions. Nigeria has continued to depend on her abundant and seeming inexhaustible natural aggregates use in the construction, building and transportation industries because of the ignorance of research knowledge on the solid industrial by-products like the blast furnace and steelmaking slags the country had produced. Many researchers have worked on steelmaking slags and the historical use of steelmaking slag in the construction, transportation and building industries as aggregates based on their physical/mechanical properties including their possible unsoundness arising from the presence of hydratable oxides, (lime and magnesia) has long been well documented. This work was carried out to determine the possible contribution of the test slag in Nigeria's aggregate industry, complimentary to and conservation of the natural resources.

LITERATURE REVIEW

Based on the physical/mechanical and hydraulic properties, Behm, in 1963, reported the use of steel slag in low cost side street paving. Hosking, (1968), Gutt, (1972); Gutt and Nixon (1972); reported on the use of steel slag as skid resistant roadstone and Heaton et al, (1976) as skid resistance and road surfacing stone and for use in asphaltic concrete. Many other researchers also reported their findings on the use of steel slag in base stabilization (Lanigan, 1979), in highway construction and airport pavements (Emery, 1976, 1977, 1982; Glazier, 1980, Collins and Ciesielski, 1994, Kubodera, et al 1979), as railroad ballast (Eggleston, 1981, National Slag Association (NSA: 1973, 1985), in roads and walks (NSA, 1967), for road surfacing and as an aggregate in asphaltic concrete (Heaton, 1976, 1979), for bridges, airport pavements, embankments and miscellaneous structures construction, (NSA 181-14).

The use of steel slag as Bituminous concrete fine aggregate was reported by Kandahl and Hoffman (1982), in Bituminous mixtures by Norton, (1979), in Hot-Mix Asphalt (Emery, 1993) and in cold mix or surface treatment which require proper processing of steel slag and special quality-control procedures (Noureldin and McDaniel, 1990; Collins, 1994). Steelmaking slag can be processed into coarse or fine aggregate material for use in dense- and open-graded hot mix asphaltic concrete pavements (Rossini-Lake et al, 1995). The general conclusion is that the use of steel slag has resulted in the reduction of steel slag heaps and environmental pollution and thus improved environmental authenticity.

This work investigated the physical/mechanical properties and the CaO and MgO contents of the Delta Steel Company steelmaking slag in accordance with BS 812 part 3 1975:1988 standard specifications for use as coarse or fine aggregate in the construction, transportation and building industries. It is also aimed at ridding the steel plant environment of unsightly slag/skull that litter it to improve its authenticity.

MATERIALS AND METHODS

Materials

Slag sampling was by random spot hand picking of samples of about 2kg per spot from the slag dump (N7-N21) at the Company. The hand-picked slag samples were bulky ranging in sizes between about 5.30cm x 3.00cm x 2.90cm to about 31.70cm x 22.30cm x 19.65cm of very irregular shapes (Figure 1). Suitable sizes were broken off with a sledge hammer and taken as samples. Breakage seems to have been along cracks in fracture surfaces. All the samples had high densities judged by hand, contained some entrapped and attached metallics with minor entrapped refractory impurity pieces and whitish surface coating of probably undissolved lime occurring as free CaO, (FHWA-RD-97-148). Some samples had rusty specks and patches probably arising from oxidation of un-oxidized iron.

Methods

The method applied in this investigation including sample preparation was in accordance with BS812, 1975:1988 standard specifications. Blocks of samples were cut into suitable sizes of coarse and fine grades using laboratory rock cutting machine. The reduced samples were sieved through the various sieve sizes shown in Table 2 to obtain the grade size distribution after magnetic separation to remove entrapped and attached metallics. The samples were then subjected to laboratory tests to determine their physical/mechanical properties using appropriate grade size and equipment. Specific Gravity (S.G.), Bulk Density, Porosity % (n), Moisture Content % (m), Water Absorption, Loss on Ignition, Coefficient of thermal expansion, Flakiness Index, pH determination and the coefficient of thermal expansion tests were carried out to evaluate the physical properties. Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Aggregate Abrasion Value (AAV), and the Polished Stone Value (PSV) tests were also carried out to determine the slag mechanical properties. In processing tests, magnetic separation, washing and scrubbing recovery for cleanness; acid and pickle liquor treatment tests were carried out to determine aging or maturity attainment of the slag and unsoundness.

Slag samples used for the tests were processed free of furnace brick, wood, incompletely fused fragments, iron and steel blebs, lime and rock after crushing or their presence reduced to the barest minimum. Free lime or magnesia in the slag could result in pavement cracking if ignored FHWA-RD-97-148 report).

RESULTS

The test results are shown in this section.

A, B, C, D

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Figure 1. Photographs of typical DSC slag- (a) flat and smooth lower-face, (b) smooth, undulating lower-face both having tiny netlike cracks containing whitish infillings and coating; (c) showing rough, vesicular surface texture (deep pores) like a volcanic lava, and (d) also showing a very rough, vesicular surface (deep pores) texture with whitish lime infillings and coatings.

Figure 2. Photograph of a typical Jaw crusher produced <14.00mm - 10mm DSC slag showing consistent angular and irregular to sub-rounded shape and rough, vesicular surface texture features with whitish infillings and coatings. The angularity and vesicularity, provides good macadam/tar binding face as an aggregate in the construction and as railway ballast in the transport industry.

Figure 3. Photograph of DSC slag showing consistent physical shape and surface texture characteristics even on consistent grading to the fine, sand size.

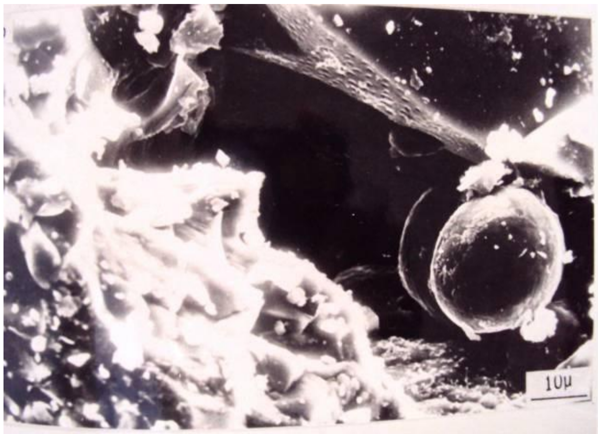

Figure 4 (10µ). Scanning electron microscope (S.E.M.), photomicrograph showing rough surface texture with platy crystalline particles whitish coating on atmospheric exposure with whitish small secondary slag blebs.

Figure 5 (20µ). Scanning electron microscope (S.E.M.), surface texture photomicrograph of DSC slag showing the very rough (deep pores) exposed weathered surface with whitish calcium silicate hydrate (CSH) coatings and infillings.

Tables 1, 2 and show a measure values of the test on physical/mechanical properties

Table 1. Summary of physical/mechanical properties of DSC Slag (mean of fifteen samples)

Physical/mechanical property	Mean	SD.
Flakiness Index	25.8%	0.6
Specific Gravity	3.6	0.07
Bulk Density	1719kg/m^3	1.73
Loss on Ignition	2.29%	0.04
Water Absorption (per cent by mass)	0.02	0.02
Moisture Content (per cent by mass)	0.05	0.04
Porosity (per cent by mass)	2.29	0.04
pH	8.8	0.53
Aggregate Impact Value (AIV)	11.7	5.0

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Aggregate Crushing Value (ACV)	13.7	0.2
Aggregate Abrasion Value (AAV)	3.16	0.005
Polished Stone Value (PSV)	56.0	1.9
Thermal (Vertical) Expansion Coefficient (mV/^{0}C)	6x10^{-4}/^{0}C	6.8x10^{-4}/^{0}C
Washing Recovery	100	0.0
Scrubbing Recovery (sand grade)	97.58%	0.09
Acid Leaching Recovery (i) H_2SO_4 (10%) (ii) HCl (10%)	 99.34% 82.80%	 0.01 1.08
Size Grading on Crushing (i) <14.00mm – 10.00mm (ii) <10.00mm – 2.36 (iii) <2.36mm -	 55.52% 34.51% 9.96%	

Table 2. Grade size analysis of DSC test slag using (a) Coarse and (b) Fine (Sand) grades, (mean %).

Crushed sla g size grading	Weight % retained	Grade		
(a) (iv) <14.00mm – 10.00mm (v) <10.00mm – 2.36 (vi) <2.36mm -	55.52% 34.51% 9.96%	Coarse Grade Sand size grade		
(b) Slag (fine) sand size grading	Weigth %	Grade	Total size grade Weight %	Total fine + powder size grade
2.36mm	43.04	Very Coarse		
2.00mm	14.90	Very Coarse	57.94	
1.18mm	22.33	Coarse		
1.00mm	3.13	Coarse	25.46	
600µm	6.79	Medium		
500µm	1.79	Medium		
300µm	3.01	Medium	11.59	
250µm	0.61	Fine		
150µm	1.87	Fine		
125µm	0.45	Fine	2.93	
75µm	1.23	Very fine	1.23	
<75µm	1.11	Powder	1.11	5.57

Total	99.43		99.43	

Table 3. Physical properties of twelve selected DSC slag test samples.

S/No.	Physical property	S A M P L E S											
		N/8	N/9	N/10	N/11	N/12	N/13	N/14	N/15	N/16	N/17	N/18	N/19
01	TEC 6.0x104mv/0c	5.3	6.3	5.6	6.8	5.4	5.8	5.8	5.6	5.8	6.3	6.8	5.8
01	FI wt%	26.5	25.6	25.6	25.6	25.63	24.5	25.6	25.4	25.6	25.6	26.2	26.5
02	BD Kg/m^3	1716	1720	1718	1718	1716	1716	1718	1719	1717	1717	1720	1720
02	SG	3.66	3.66	3.72	3.73	3.65	3.63	3.62	3.65	3.74	3.57	3.69	3.61
03	WA	0.01	0.01	0.04	0.00	0.00	0.01	0.01	0.01	0.00	0.02	0.04	0.04
05	m (%)	0.04	0.10	0.04	0.01	0.01	0.14	0.05	0.04	0.11	0.04	0.00	0.05
07	n (%)	2.23	2.23	2.38	2.40	2.32	2.29	2.29	2.31	2.41	2.24	2.22	2.19
08	pH	8.2	8.5	8.4	8.4	8.5	8.5	8.4	8.3	8.4	8.3	9.4	9.5

*Key to Table 3: FI (Flakiness Index), RD (Relative Density on a surface dried basis, SG (Specific Density), WA (Water absorption) and BD (Bulk density), m (Moisture content), n (Apparent porosity), TEC = Thermal (Vertical) expansion coefficient). Thermal (vertical) coefficient of expansion: The coefficient of thermal expansion was determined using a Linear Variable Differential Transformer (L.V.D.T) with mode of operation as given in the 'Handbook of Measurement and Control' published by the Schaetvitz Engineering Company.

Table 4. Mechanical properties of Twelve (12) selected samples of DSC slag by percentage (%).

S/No	Mechanical property	S A M P L E S											
		N/8	N/9	N/10	N/11	N/12	N/13	N/14	N/15	N/16	N/17	N/18*	N/19*
01	AIV	8.5	12.0	7.3	9.3	8.5	9.8	8.5	8.5	11.0	9.7	24.4	21.5
02	ACV	13.9	13.8	13.8	13.8	13.7	13.6	13.6	13.7	13.8	13.7	13.7	13.7
03	AAV	3.16	3.16	3.16	3.16	3.17	3.16	3.17	3.16	3.16	3.16	3.17	3.16
04	PSV	54.0	57.0	57.0	55.0	54.0	54.0	55.0	56.0	55.0	57.0	59.0	59.0

* vesicular samples

Table 5. Comparison of some physical/mechanical properties of DSC test slag, British steel and blast furnace slags; and of igneous rocks.

Mechanical property	DSC slag	Other Steel slag *	Blast furnace slag*	Igneous rocks *
Specific Gravity	3.61-3.73	3.1 – 3.5	2.38 -2.76	3.23
Water Absorption (per cent by mass)	0.00-0.04	0.2 – 2	1.5 – 5	
Aggregate Impact Value (AIV)	7.3 – 24.4	18 – 24	21 – 42	13 – 16
Aggregate Crushing Value (ACV)	13.6-13.9	12 – 25	25 – 39	16 – 17

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Aggregate Abrasion Value (AAV)	3.16-3.17	3 – 4	5 – 31	4 – 5.4
Polished Stone Value (PSV)	54-59	53– 72	56 – 63	56– 60

*Source: Lee (1974) and Mineral Dossier No 19 (1976).

Figure 6(a-4μ). Scanning electron micrographs (back scattered mode) untreated slag samples showing silicate fracture infillings.

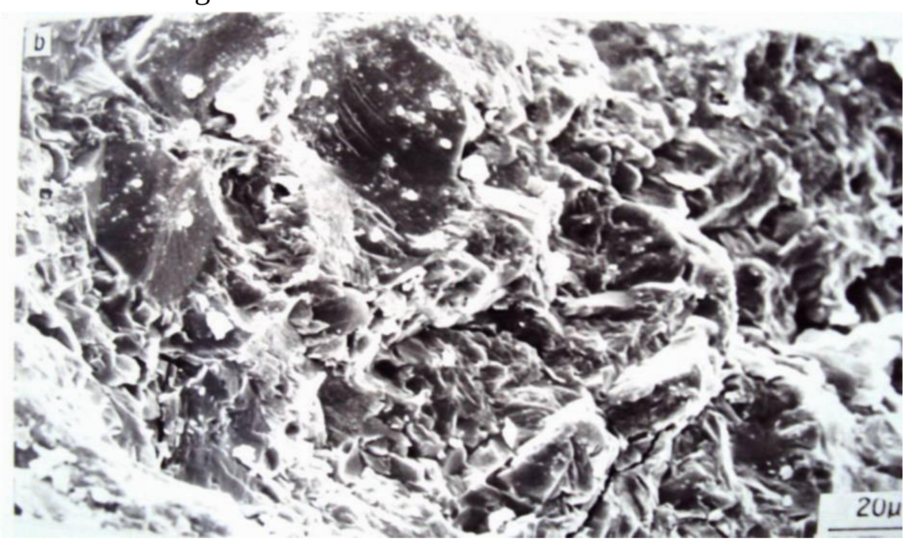

Figure 6(b-20μ). Scanning electron micrograph of pickle liquor activant (H_2SO_4) treated typical DSC slag sample showing a well developed and multiple oriented dicalcium silicate mineral.

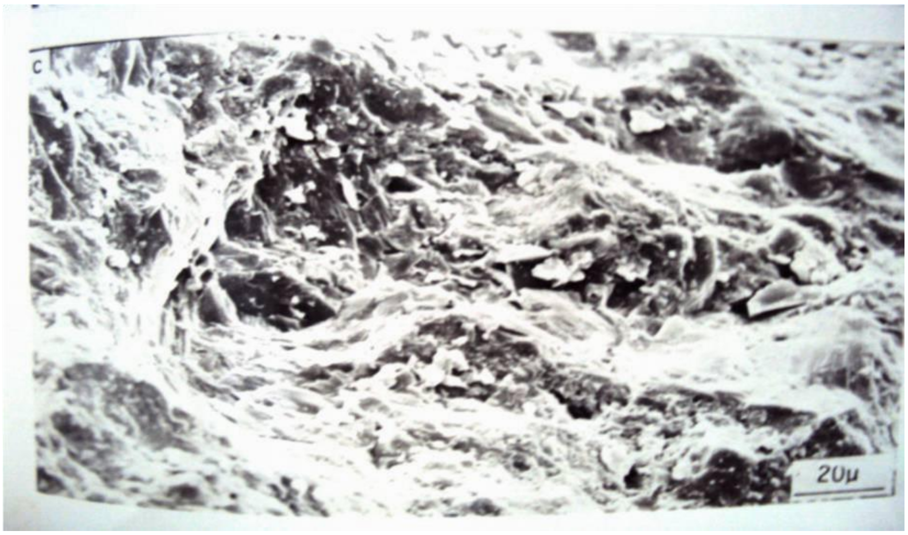

Figure 6(c-20µ). Scanning electron microscope (SEM) micrographs of $Na_2(CO3)$ activant treated typical DSC slag sample showing better developed and oriented lath shaped dicalcium silicate hydrate (CSH) honey comb structure.

DISCUSSIONS

Morphological, physical/mechanical and other properties of the slag

The slag was observed to be sub-angular to irregular, sub-rounded in shape and of low sphericity and sharp edged, the same for the bulky, crushed coarse and fine, (sand) grade sizes. The basal face of the bulk dump slag was almost flat, sometimes undulating with tiny netlike cracks which had whitish infillings and coatings. The cracks are attributable to a more rapid cooling contraction on contact between furnace de-slagged ladle hot slag and cooler dump surface assisted by water sprayed on to aid fast cooling of this slag (Figures 1, 2 and 3).

Typically, the surface of the slag had a very rough or vesicular texture (deep pores) and also with whitish material linings, (Figure 1). Vesicularity or rough texture is attributable to escape of volatiles from the free upper surface. Deep pores can increase the susceptibility of this slag aggregate to differential drying and potential retention of moisture when used in a hot mix asphalt. Moisture retention by the aggregate coupled with the presence of expansion potential, hydratable hydroxides presence, could result in volumetric instability (ASTM D4792-95, FHWA-RD-97-148). The general colour of the slag varied from dark grey (vesicular slag) to bluish grey (non-vesicular slag). Some samples had thin coatings of brownish to whitish coloured powder which easily rubbed off. The coatings were due to weathering and lime/silicate hydration products suggesting the presence of free lime (CaO) and magnesia (MgO), indicating possible unsoundness of this slag when used as a construction, transportation and building aggregate.

Figure 4 and Figure 5, show the presence of calcium silicate hydrate, an indication that the slag had attained maturity (aging) having been exposed in the dump for at least three (3) or four (4) months at the time of test reducing susceptibility to unsoundness (Pajgade and Thakur, 2013). The slag is suitable for macadam binding or asphalt mix for surfacing in road construction (NSA 181-14; Smith. 1972,).

PHYSICAL PROPERTIES

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The physical properties test results in Table 3, show strong indications for the subconclusions made under each test.

Thermal (vertical) coefficient of expansion

The slag had a low coefficient of thermal expansion of $6x10^{-4}mV/^{0}C$. The slag was subjected to $100^{0}C$ experimental temperature which was much higher than the maximum $31^{0}C$ attainable atmospheric temperature recorded of the Delta area of Nigeria at the time of this investigation. Besides, the minimum $23^{0}C$ attainable atmospheric temperature in the steel plant area is higher than the $21^{0}C$ – $26^{0}C$ laboratory temperature to which the slag fell to without development of contraction cracks even with rapid water cooling. In the laboratory, it took the slag samples of size 8cm x 3cm about 20 minutes to cool slowly from $100^{0}C$. The slow cooling is a qualitative indication that the slag has a high specific heat and that it can be a good insulator. The results generally show resistance to even higher changes in temperature (thermal expansion), coupled with stability to heating, can make the slag a good road construction aggregate, as expansive reaction due to temperature changes are very unlikely. The heat retention characteristics of this slag can be advantageous for hot mix asphalt repair work during cold weather (, JEGEL, 1993; FHWA-RD-97-148).

Flakiness Index

The result on flakiness index of 25.4 - 26.5 % is low, indicating the non flaky nature of the slag. This combined with the rough surface texture can make this slag excellently resistant to striping of asphalt cement from the aggregate particles. Also, weathering exposure had no adverse flakiness effect on it making it suitable for use as an aggregate (FHWA-RD-97-148).

Bulk density

The bulk density result of $1716kg/m^3$ - $1720kg/m^3$ is high. The slag is very hard and can be abrasion resistant and thus displays good durability with resistance to weathering and erosion.

Specific gravity

The specific gravity of 3.61 - 3.73 for the slag is high when compared to values obtained from other steelmaking slag of 3.1 – 3.5. This high value is attributable to the high iron content in the slag. This high density can confer on the slag physical force stability which outweighs the disadvantage of high cartage cost for use as aggregate. The bulk density value

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obtained 1719kgm^3 agree with the very high density (S.G.) of the slag. The effect of weathering on the relative density of the slag is insignificant. The slag aggregate with this typical relative specific gravity, can yield a higher density product compared with that of conventional mixes (Emery, 1982).

Water Absorption (WA)

Moisture content (m) and Apparent porosity. Water absorption of 0.00 - 0.04 and moisture content of 0.01 – 0.05 are very low despite the deep holes rough surface texture. This can make the slag very resistant to chemical/hydration reactions and volumetric instability when used as road and pavement aggregate. The porosity is 2.19 to 2.41, which is low. This must be due to a thin acidic gel coating the surface of slag resulting in low water penetration (Heaton, et al, 1976) and low absorption. There is low water retention resulting in less water being available for hydration reactions, minimizing hydration reactions to cause slag aggregate unsoundness.

pH.

The pH of the slag ranged from between 8.8 to 9.6, indicating alkalinity resulting from its free lime content reaction with water due to long time dump exposure. The pH 8.8 to pH 9.6 was less than that of recycled concrete base course material and cement-stabilized soil. The soils in the Niger Delta and Ovwian-Aladja, Warri area are generally acidic. The alkali components that dissolve from the slag when used as aggregate may be absorbed and neutralized by the soil. However, when water that contacts the slag does not pass through the soil but may flow directly to the outside, then it is necessary to take steps such as creating an embarkment of soil alkali-absorption capacity (JIS K0058-1) to reduce alkalinity.

From Table 3, the physical properties confer on the slag favourable characteristics, relative density, bulk density/specific density, permeability, and porosity for its use as an aggregate.

MECHANICAL PROPERTIES

The results in Tables 4 and 5 confirm the mechanical property aggregate use potential of the slag based on AIV, ACV, AAV and PSV when compared to other steel slag, blast furnace and natural igneous rocks that have been used as aggregates. The results obtained are favourable for the slag use as an aggregate (Earle, 1974; Eggleston, 1970, 1981, 1985, 1980, Emery, 1976, 1977, 1979, 1982, NSA Spec Data, 1967, 1968; Rossini-Lake et al, 1995).

Aggregate Impact Value (AIV)

The AIV result of 7.3 - 24.4 is high, indicating that the slag is generally more resistant to sudden impact than other quoted steel slags (18.0 - 24.0), blast furnace slags (21 - 42), (igneous rocks- (13 -16) (Lee, 1974). This confirms its suitability for use as aggregate for road base in road construction (NSA, 1967).

Aggregate Crushing Value (ACV)

The ACV value of 13.6 – 13.9 is relatively low when compared to other steel slag (12 - 25), blast furnace slags (25.39) - and igneous rocks (16 - 17) (Lee, 1974, Mineral Dossier N0 19, 1976). This shows that the test slag has high resistance to compressive load. It is suitable as road surface aggregate (Gutt and Nixon, 1972; Heaton et al, 1976; Hosking, 1968).

Aggregate Abrasion Value (AAV)

The Aggregate Abrasion Value (AAV) of 3.16 – 13.17 is low. The slag has high resistance to wear and abrasion when compared to other steel slags (3 - 4), blast furnace slags (5 - 31) and igneous rocks (4 - 5.4). This show of superior wear and abrasion resistance provides a reason for its use as aggregate for asphalt concrete and road surfacing (Heaton, 1979; Hegmon and Ryan, 1969; Kandahl and Hoffman, 1982).

Polished Stone Value (PSV)

The Polished Stone Value of 56 – 59 is high. The value is comparable with that of good grit stones and other steel slags (53 - 72), blast furnace slags (50 – 63) and igneous rocks (56 – 60) (Lee, 1974, Mineral Dossier No 19, 1976) and lie at the top of the quoted range for slags. This makes it resistant to abrasion and polishing and for this reason can be used as an anti skid aggregate on roads (Hegmon and Ryan, 1969, Kandahl and Hoffman, 1982; JEGEL, 1993).

The results particularly of the high PSV and low AAV, confirm that this slag exhibit superior frictional resistance for highway pavements (Emery, 1982). The possible high frictional resistance, as well as the abrasion and impact resistance gives it the advantage for applications in such areas as industrial roads, intersections, and parking areas subjected to heavy traffic. The results also indicate that this slag aggregate is very hard and abrasion resistant and can be very durable with resistance to weathering and erosion. These properties combined with the morphological properties of the slag confirm the slag as suitable for use as a railroad ballast.

PROCESSING TESTS

Table 6 presents results of processing, physical washing and scrubbing recoveries and chemical/activant (H_2SO_4 and HCl, Na_2CO_3) treatment leaching recovery.

Washing and scrubbing recovery

The slag had both good washing recovery (100%) and good scrubbing recovery (97.58%). This confers on the slag good binding properties with macadam as there were no or minimal surface impurities to form impediment with bitumen/macadam binding activity when slag is used for aggregate in road surfacing (Heaton et al, 1976).

Acid/pickle liquor treatment

The acid/pickle liquor treatment results are presented in Table 6 and shown on Figures 6 (a, b and c). Reflected light Scanning Electron Microscope (SEM) back scattered mode photomicroscopy studies of the rough surfaces and polished thin sections respectively, show a well developed mineral structure (honey comb- (Figures 6 (a) & (b)) well, better developed and oriented lath shaped calcium silicate hydrate (Figures (b) & (C). This shows that pickle liquor and sodium carbonate aqueous solutions accelerate aging and thus contribute to early maturity and strength development. However, the possible dicalcium silicate or lime (CaO) or periclase (MgO) hydration as indicated by the presence of brownish to whitish colour of rough surface (deep pores) infillings can lead to slag deleterious volume expansion when used as aggregate. But the show of maturity attainment on long time exposure to hydration of the CaO and MgO on acid and activant treatment, confirm that there was no or a minimal danger of possible expansion when the slag is used as an aggregate. This is also confirmed by the low coefficient of linear expansion of the slag.

CONCLUSION

Conclusions that can be drawn from the results of the investigation are that DSC slag is of high quality for use as aggregate in the construction, building and transport industries including coastal landfills in the delta area. This can be in response to the increasing economic and environmental pressures to conserve natural resources and energy and the continuing demand for high quality aggregates in Nigeria. The slag use will contribute to conserving natural resources and help to reduce land and water pollution and promote environmental aestheticity. Steelmaking slag should continue to be produced due to its proven usage benefits.

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