IRONMAKING SLAG – NATURAL SOILS INTERACTION DURING ROAD BASE CONSTRUCTION[1]

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Abstract

It has been demonstrated that all kinds of dumped ferrous slags of iron and steel industry can be used as binding materials for preparing of new concrete-like materials instead of crushed stone, sand and gravel mixtures, etc., in road, airfield, dam and different foundation construction. The materials are produced by mixing of metallurgical slags with natural soils without traditional binders like cement and without heating. Mainly amorphous new formations grow during the hydration and strengthening of slag, with or without activators and mixed with natural soils. Their high properties render these new materials appropriate for the construction of roads and airfield runways, levee cores, industrial and municipal dumps, building foundations, etc. Being binded in new formations slags lost their possibility of heavy metals leaching. The technologies offer numerous advantages and the road base paving cost reduces five-sixfold. Roads with these bases show high performance during over the 30 years in different parts of Russia, including Siberia and the North. Now similar research began in Federal University of Paraná with scientific leadership of the first author of this report with local soils of Curitiba and some metallurgical slags of Brazilian industry, interested in economically more efficient way utilization of their wastes.

Key words: Slag-soil interaction; Resistance; Road base construction; Economical efficiency.

ESCÓRIA SIDERÚRGICA – SOLOS NATURAIS INTERAÇÃO DURANTE A CONSTRUÇÃO DE BASES DE ESTRADAS[1]

Resumo

Demonstrou-se que todos os tipos de escórias siderúrgicas da indústria do ferro e aço podem ser utilizados como ligantes na preparação de materiais similares ao concreto, substituindo misturas de pedras britadas, areia e cascalhos em rodovias, aeroportos, barragens e fundações de edifícios. Os materiais são produzidos com misturas de escórias siderúrgicas e solos naturais sem ligantes tradicionais como cimento e sem aquecimento. Novas formações amorfas ocorrem durante a hidratação e fortalecimento da escória, contendo ou não ativadores e/ou misturas de solos naturais. As boas propriedades destes materiais os tornam apropriados para a construção de rodovias e pistas de aeroportos, núcleo de barragens, aterros industriais e municipais, fundações de edifícios, etc. Sendo ligadas em novas formações, as escórias perderam a possibilidade de lixiviação de metais pesados. A tecnologia oferece inúmeras vantagens e a redução em até seis vezes os custos na pavimentação de bases de rodovias. Rodovias experimentais demonstraram excelente desempenho durante mais de 30 anos em diferentes partes da Rússia, incluindo a Sibéria e a região Norte. Atualmente na Universidade Federal do Paraná, sob liderança científica do autor desse artigo, iniciaram-se estudos utilizando solos naturais de Curitiba e escórias siderúrgicas de indústrias brasileiras interessadas economicamente em métodos eficientes de destinação dos seus resíduos.

Palavras-chave: Interação solo-escória; Resistência; Construção de sub-bases; Eficiência econômica.

1 *Technical contribution to the 3rd International Meeting on Ironmaking, September 22 – 26, 2008, São Luís City – Maranhão State – Brazil*
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1 INTRODUCTION

Mankind has been strengthening natural soils for construction purposes for time immemorial, using a variety of organic and inorganic binding materials for this purpose. The most commonly used some organic spread materials like petroleum, bitumen, pitch, etc. Inorganic binding materials used for this purpose are Portland cement, cement kiln dust or lime,[1,2] water glass or calcium chloride[3], various types of ashes,[4-6] etc.

The accumulation of dump ferrous slag (DFS) from different metallurgical processes is one of the most serious environmental problems in most countries that have a highly developed metallurgical industry. Even in Europe, which has the world's most stringent environmental protection legislation, 35% of the steel slag produced is still dump every year.[7] Some dumps located close to metallurgical plants contain enormous quantities of ferrous slag, up to 180 million tons (Magnitogorsk, Russia).

There is a plethora of international literature on many different ways of using metallurgical slag as cementing material.[8] The largest consumers of slag as an alternative inert material replacing crushed natural stone, gravel and sand mixtures are road constructors.[9-11] Another widespread form of using slag is in the production of Portland cement.[12,13] There are the well-known technologies of slag-wool production for thermal and acoustic isolation, for technical glasses, as fertilizer for agriculture purposes, for the stabilization of shores,[7] etc. Some authors even propose the use of slag as coating for environmentally dangerous materials.[14]

Unfortunately, most of the reports concentrate on the use of granulated ferrous slags, which are not strictly industrial wastes, but intermediate products of Portland cement production.

The method developed by[14-17] and described herein allows for the use of dump slags as binding materials for different natural soil strengthening applications.

The method was developed by the first author of this report in the Federal University of Moscow (MGU) and Russian People Friendship University, Russia. Now similar research began in Federal University of Paraná with local soils of Curitiba and some metallurgical slags of Brazilian industry, interested in economically more efficient way utilization of their wastes.

2 MAIN RESEARCH PURPOSES

1. Study the real possibility of different natural soils strengthening by ground cooled metallurgical slags after theirs many years being in open air conditions (in rains, snows, etc);
2. Study the processes of new formations strengthening during chemical interaction of DFS with different natural soils and main mechanical properties of these new construction materials without some activation;
3. Study the processes of new formations strengthening during chemical interaction of DFS activated by small (2%) additions of Portland cement with different natural soils and main properties of these new construction materials;
4. Propose economically attractive and environment friendly technologies of developed slag-soil materials application for road, airport, dam, etc. construction.

3 RESEARCH OBJECTS

The most typical ferrous metallurgy dump slags (blast furnace, open-hearth, converter and electric steel smelting) were studied for the strengthening of a variety of most spread in Russia natural soils (light and heavy loams, fine and medium sands, loess and loess-like loam). The main components of the chemical composition of these materials are given in Table 1.

The significant differences in the chemical compositions of the slags under study (Table 1) are explained by the substantially divergent metallurgical processes and applications for the final metal produced. The greatest difference is found between the compositions of blast furnace and converter slags, especially insofar as the content of SiO_2, CaO, Al_2O_3, MnO, FeO+Fe_2O_3, and common S are concerned. Open heart and electrical steel slag compositions, on the other hand, are more similar to each other (except the amount of Al_2O_3 and FeO +Fe_2O_3) and are intermediate between the first two slags.

Table 1. Main components of the chemical composition (%) of dumped ferrous slags and natural soils under study.

n°	Slags & Soils	SiO_2	MgO	CaO	Al_2O_3	MnO	FeO + Fe_2O_3	SO_3 common	M_a
1	blast furnace	35.2	3.5	36.1	10.6	2.0	4.0	3.7	0.69
2	open hearth	17.5	18.1	26.7	6.1	2.0	22.1	0.2	1.85
3	converter	19.5	1.8	56.1	2.1	6.7	11.0	0.1	2.67
4	electric steel	18.4	16.5	29.6	10.9	4.2	16.2	0.5	1.57
5	light loam	73.2	2.3	3.7	8.8	0	3.2	0.0	-
6	heavy loam	59.1	2.2	8.0	13.4	0	4.6	0.2	-
7	loess-like loam	56.7	2.1	17.4	14.3	0.1	4.4	0.5	-
8	loess	59.1	1.9	6.8	14.5	0	5.8	0	-
9	medium sand	92.7	0.1	0.2	2.3	0	4.1	0	-

Where: modulus of alkalinity $M_a = \dfrac{CaO + MgO}{SiO_2 + Al_2O_3}$

These divergent chemical compositions of slags lead to different values of modulus of alkalinity, Ma, which is one of the most important indicators of the binding properties of inorganic materials. Converter slag has the best Ma while furnace slag has the worst. Maximal SiO_2 content occurs naturally in all types of natural soils, but especially in medium sand (item 9 of Table 1).

Small amounts (2%) of Portland cement were used to activate the slags' binding properties and accelerate the chemical interaction of slag-soil mixtures.

4 RESEARCH METHODS

A wide range of traditional and novel methods of mutually complementary research were used to study the initial slag compositions and their temporal changes during hydration. These methods included the definition of the limit strength under uniaxial compression, temporal changes of moisture and of linear deformation, water and frost resistance, XRD analyses by the powder method, the amount of bonded water and carbonate content, using TGA and DTA, scanning electron microscopy and chemical analysis (free CaO, SiO_2, Fe_2O_3, Al_2O_3, non-bonded SO_3, pH and others), infra-red spectroscopy, X-ray-spectral analysis by "Cameca", "Edax" and "Link-System", and laser micro-mass analysis by "LAMMA-1000". Presenting the

results of all these methods here would be impossible owing to space limitations; nonetheless, they have been taken into consideration in the description of the materials strengthening process.
Samples of the materials were compacted for 1 min under a 10 MPa pressure in a cylindrical mold with a 5 cm diameter and height under conditions of optimal humidity (10-12%). The hardening occurred under a condition of 98% humidity.

5 RESEARCH RESULTS

5.1 Strengthening of Natural Soils by Non-activated and Activated DFS

The mechanical properties of slag-soil materials depend mainly on their chemical (Table 1) and mineralogical compositions, their ratios, dissolution properties and interaction in alkaline pore solutions. Most non-activated soil-slag materials showed (Table 2) very low uniaxial resistance strength, water resistance values, and all of them failed the frost resistance tests. Only the samples of mixture 5 (medium sand + open hearth slag) did not show spontaneous destruction by the end of the frost resistance tests. The aforementioned lack of SiO_2 in the chemical composition of open hearth slag was compensated for by the addition of medium sand, which may explain the significant improvement of the slag-soil samples' properties. However, its Cf value (0.42) allows this material to be used only as road base substratum for Russia's climatic conditions.

Table 2. Mechanical properties of the developed materials.

Composition of materials, weight %				Strength (MPa) after (days)			Water and Frost Resistance			
№	Type of soil	Type of slag	P.C.	28	90	360	R w	Cw	Rf	Cf
1	Light loam	Blast furnace	0	0.9	1.3	1.0	0.6	0.4	0	0
2			2	2.9	2.6	3.6	2.5	0.96	2.1	0.84
3	Heavy loam		0	0.6	0.3	1.3	0.1	0.4	0	0
4			2	2.5	3.1	6.0	2.9	0.96	2.3	0.79
5	Medium sand	Open hearth	0	0.1	0.8	3.9	1.3	1.71	0.7	0.4
6			3	1.5	3.0	5.6	3.4	1.04	4.1	1.16
7	Light loam		0	0.3	0.2	0.5	0.1	0.24	0	0
8			3	1.1	1.9	7.0	1.7	0.93	1.5	0.86
9	Loess-like loam	Electric steel	0	2.3	4.0	9.5	4.0	0.84	0	0
10			2	5.8	12.0	14.4	14.0	1.13	11.1	0.81
11	Heavy loam	Conver-ter	0	1.4	3.4	7.4	3.1	0.93	0	0
12			2	2.1	3.7	8.6	4.3	1.14	3.3	0.78

A small addition (2-3%) of Portland cement drastically changed the mechanical properties of slag-soil materials. The strength of the 90-day-old materials varied from 2.6 MPa (composition 2) to 12 MPa (composition 10). The water and frost resistance of all the slag-soil materials tested (Table 3) also improved considerably in response to activation and, by the 90th day, the value of Rw ranged from 1.5 to 11.1 MPa, the Cw varied from 0.93 to 1.16, the Rf from 1.5 to 11.1 MPa, and the Cf from 0.78 to 1.16. After their activation, all these materials can be recommended as road base materials, in accordance with the aforementioned Russian construction standards.

5.2 Structural Formation of Activated Slag-soil Materials

The hardening processes of the natural soil-dump ferrous slag-activator mixtures were studied with every possible instrumental detail, in accordance with paragraph 4 “Research methods.” Table 3 presents the main physicochemical strengthening parameters obtained for the “heavy loam - blast furnace slag - 2% Portland cement” system.

Table 3. Changing of the indices of heavy loam strengthen by activated blast furnace slag.

Indices	Initial	Time of hardening							
		Days					Years		
		7	28	60	90	180	1	2	3
Compression resistance, MPa	-	1.3	2.5	3.2	3.1	4.4	6.0	5.7	7.5
Coefficient of lineal deformation, %	-	0.74	1.04	1.13	1.22	1.37	1.35	1.70	1.83
Common losses of weight, (TG), %	-	10.33	10.73	11.50	11.33	11.45	11.67	11.74	13.83
Contain of CO_2, (TG), %	-	1.00	1.00	1.00	1.33	1.33	1.34	1.52	1.83
Losses of bounded water, (TG), %	-	9.33	9.73	10.50	10.00	10.12	10.33	10.22	12.00
pH	10.90	8.41	8.25	8.21	8.34	8.45	8.31	8.02	7.70
Content of mobile SiO_2, %	0.23	0.60	0.62	0.62	0.65	0.70	0.70	1.15	1.40

Similar data were also obtained for all the compositions of soil – activated slags, but are not given here due to space limitations.

Table 3 indicates the following: the fastest increase in the system’s values occurred during the first 7 days. There was a clearly defined synchronization between the samples changes in compressive strength and bonded water losses over the 3-year period under study. These changes coincided with the value of pH up to the 60th day and thereafter overlapped up to the 3rd year. The values of the coefficient of linear deformation and the CO_2 and SiO_2 content increased steadily throughout the period under study, but in the first 60 days (i.e., 5.5% of this 3-year period) they rose to 61.7%, 54.6 and 39%, respectively, of their final values.

The XRD images showed no new peaks of newly formed crystals during the entire period. SEM, however, revealed many gel-like new formations that completely covered the sample’s surface.

All the above data can be explained by the corrosion (leaching) of the solid surfaces of soil and slags by alkaline (pH=10.90) pore solution, which causes all the ions of the dissolved parts to be carried into this solution, and the gradual transformation of sol solutions into a more dense gel.

Part of the alkaline Ca and Mg ions are bonded in very different complex compounds of new formations and part are bonded by the CO_2 of air in the carbonates. However, the carbonization process takes place very gradually (Table 3 – CO_2 quantity), reaching the value 2.3% of $CaCO_3$ with the conversion of CO_2 content on the 60th day, 3.0% at 1 year and 4.2% at 3 years. Such small amounts of all carbonate forms (calcite, dolomite, siderite, etc.) are hardly sufficient for their peaks to be fixed by powder XRD method (sensitivity close to 3-5%).

The fact that the samples’ strength reached almost 7.5 MPa, although no new crystal peaks appeared on the XRD curve, can be attributed to only two possible reasons:

1. The growth of some crystal phases, each in a very small quantity that was undetectable by the sensitivity of the XRD method. However, the results of SEM rule out this possibility, since all the surfaces of the materials are covered only by specific amorphous-like new formations without any similarity to crystal bodies;
2. The growth of amorphous new formations and their gradual transformation into a stone-like condition.

It is possible to surmise, that the density of the pore solution is rather low at the beginning of the hydration process, but it increases over time. Moreover, it appears that the density of the new formations around the solid surfaces of the slag after the first year becomes sufficiently high to prevent future strong erosion of the slag's particles by alkaline pore solutions. Due to cracks caused by gel syneresis, the liquid phase of the alkaline pore solution approaches the surface of solid slag particles and starts leaching them out once more. During the 90 to 180-day period, the cracks are closed by more freshly generated amorphous gel new formations.

The amorphous nature of the new formations are confirmed by:

1. The absence of new peaks on the XRD until the samples reach the age of 6 years, except for very small carbonate peaks; 2. The aforementioned absence of crystal-like forms in SEM and the presence of large amounts of specific amorphous-like new formations without any similarity to crystal bodies, and by the presence of syneresis-related cracks and their eventual filling up and closing by new portions of gel; 3. The presence of wide exothermic areas ranging from 50° to 750°C on the DTA curves of all ages; 4. The results of laser micro-mass analysis . All the spectra of the chemical compositions of new formations obtained at points as close as possible reveal quite different combinations and quantities of isotopes (intensity of the peaks); Similar results were obtained by X-ray spectral analysis using the "Edax" and "Link-System".

The phenomenon of the amorphous structure of new formations agrees with Groth-Fedorow's crystal-chemical law on the growth of crystal structures from solutions. According to this law, the crystal structure system (syngony) tends to decrease as the complexity of the chemical solution increases. From the point of view of Groth-Fedorow's law, no crystal bodies are expected to grow in solutions as complex as mixtures of DFS with natural soils and Portland cement; hence, they can only be amorphous.

These amorphous formations can be very stable, occurring in amorphous minerals (e.g., hisingerite, limonite, etc.) or in sedimentary rocks such as flint, opoka, tripolite, etc., that have existed in amorphous form over geological epochs.

After 90 days, the strength, water and frost resistance of all activated slag-soil materials met the standards' requirements for the second (2-4 MPa) and third (1-2 MPa) grades of reinforced soils.

Further increases of the materials' resistance from 4.4 to 6.0 MPa in the period of 180 days to 1 year, in our opinion, can be explained by the synthesis of the gel of new formations at the bottom of the cracks produced by gel syneresis. The increase of new gel augments the amount of bonded water from 10.12 to 10.33%. The alkaline corrosion of the slag's fresh surfaces at the bottom of the cracks causes the quantity of all ions to increase, including alkaline Ca and Mg, raising the pH. But the changes in pH value are not clearly synchronous with the resistance and bonded water content.

The same simultaneous oscillation was observed in the periods of 1-2 and 2-3 years, with the total growth of these two parameters. This is ascribed to the total increase of gel formation with no significant linear deformation of the samples, due to the equal growth of this gel density. Such gluing of solid slag and soil grains by gel formation accompanied by the growth in density explains the effect of equal increases in the samples' strength and other mechanical properties, such as water and frost resistance.

6 APPLICATIONS OF THE MATERIALS

Leaching tests of the materials in acid, alkaline and neutral solutions were conducted by two independent and competent groups of medical and sanitary experts. The value of leachability was found to be well below the requirements of Russian standards.(18)

The results of the leaching tests and the high value of the main mechanical properties of slag-soil activated materials permit their recommendation as road base construction materials to replace crushed stone, gravel, sand, etc.

The first constructions of experimental stretches of roads of different technical categories using these slag-soil materials demonstrated their excellent cost efficiency and exploitation properties, even in the extremely harsh climatic conditions of northern Russia and Siberia. Subsequently, almost 300 km of road were built with different structures. A comparison of traditional and proposed road structures is given in Fig. 1. Two layers (crushed stone and sand) are replaced by one layer of the activated slag-soil mixture.

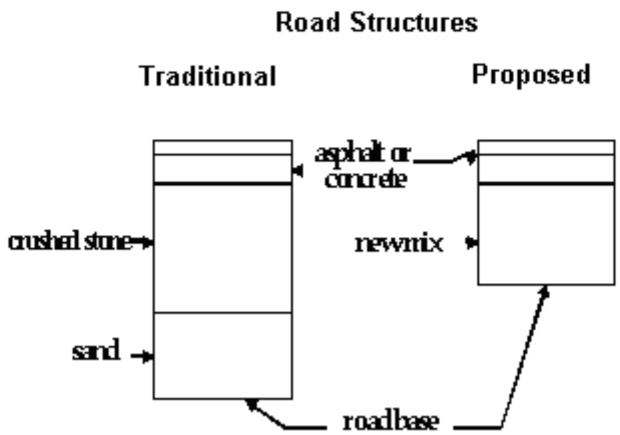

Figure 1. The comparison of the simplest schemes of traditional and proposed road structures.

These road base layers were built by mixing natural local soils with DFS, activator and water directly on the road (*in situ*). The mixture can also be prepared in stationary mixers.

7 CONCLUSIONS

1. The strengthening of the "slag-natural soil-activator" system has clearly expressed amorphous nature, similarly to strengthening to hydrated DFS. But because natural soils adsorb a substantial part of the alkaline ions Ca and Mg, the alkaline excitement of the solid parts of slag takes place at a comparatively low intensity, resulting in the weaker synthesis of amorphous new formations. As a result, the highest strength of this system at 1 year is only 14.4 MPa.
2. Activated slag-soil materials can be used for the construction of road bases, airfields, municipal and industrial dumps, as dam core, etc. Almost 300 km of roads

have been built with such bases in different regions of Russia, including regions with rigorous climates in northern regions of Russia and Siberia. These roads have all displayed many advantages, evidenced by their high indices of cost effectiveness, and technological and ecological efficiency compared to the traditional forms of road construction around the world.

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