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HIGH PERFORMANCE CONCRETE FOR PAVEMENTS WITH STEEL SLAG AGGREGATE

by

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ABSTRACT

Steel slag in different grain sizes, coming from local industry, was tested as aggregate for concrete of specific applications such as industrial concrete pavements. The low Los Angeles value and the higher resistance to abrasion were the desired properties for its selection as pavement material. In addition, ladle furnace slag was also added as cement replacement and two types of concrete were developed; one of zero slump that could be placed by using roller drums and one of 5-6 cm slump that could be placed by using conventional equipment. An adequate number of samples were prepared for testing compressive, splitting tensile and flexural strength, as well as abrasion resistance. Some measurements concerning durability, such as wetting-drying cycles were also carried out.

Based on the results, it seems that concrete with steel slag by-products is a cost effective and advantageous material for pavement construction. Strength of 40-60 MPa and high resistance to abrasion can be achieved, improving considerably pavement performance.

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1 INTRODUCTION

The construction of industrial concrete pavements has been spectacularly increased in the logistic center areas of the cities, where large metallic store houses are built on concrete ground slabs. The main requirements for the concrete pavements, apart from strength, are abrasion resistance and durability. The available choice is usually high cost concrete which is finished after treatment with a specific technique in order to become adequately hard. However, many failures often occur because of inappropriate treatment timing and this means loss of money due to delays in the project schedule and repair works [1]. In pavement construction intended for industrial use there are often requirements for improved mechanical properties, resistance to abrasion or chemical attack, which may form basic parameters of the concrete's design [2]. Big load transportation, impact from heavy objects, movement of wheel-bearing apparatus, leaking of many types of liquids (water, lubricants, fuel, acids, etc.) as well as cleaning with chemical agents is common in such spaces. All these actions cause multiple problems in concrete pavements such as cracking, spalling and scaling [3]. The use of industrial by-products could provide economically and technically viable solutions for the construction of such pavements [4] and also to contribute to the sustainability of the construction industry [5].

The purpose of this report is to propose a durable, low-cost concrete as an alternative to common practice, without requiring specific concrete producing equipment. The proposed concrete should be capable of forming a pavement for industrial use without organic (resin) or inorganic (cementitious) finishing layers.

The industrial by-products intended for use in the concrete pavement mixture were metallurgical slags from the steel industry. More specifically, the selected industrial by-products were Electric Arc Furnace steel slag (EAF slag) and Ladle Furnace steel slag (LF slag), which are both produced in different stages of the steel production process. LF slag is a by-product generated at the second phase of treatment of scrap for the production of steel and has a different chemical composition compared to EAF slag which is produced at the first phase of the previous process and can be used as aggregate [6]. Taking into account the physicochemical properties of the materials it was decided to use EAF slag as aggregate and LF slag as a binder, replacing part of the cement in the concrete mixture. EAF slag aggregates were used either as coarse aggregates or as both fine and coarse aggregate, while the LF slag Portland cement replacement rate was 30%.

2 MATERIAL PROPERTIES

In order to incorporate the new materials in concrete properly it is necessary to determine some of their physical properties. The suitability of steel slags as aggregates had already been tested at the Laboratory of Building Materials A.U.TH. [7].

2.1 Aggregates

The aggregates used in concrete mixtures were EAF slag, crushed limestone and river sand. The fine aggregates used were tested for their content in fines, fineness modulus, water absorption, and apparent specific density (Table 1). The coarse aggregates used were tested for bulk density, apparent specific density, absorption, resistance to fragmentation (Los Angeles test) and resistance to polishing (Table 2).

Table 1. Test results for fine aggregates used

Material	Fines content (%)	Fineness modulus	Water absorption (%)	App. specific density (kg/m^3)
Crushed Limestone	4.5	3.4	0.71	2650
River sand	2.0	2.8	1.35	2680
EAF slag	0.5	4.2	3.16	3358

Table 2. Test results for coarse aggregates used

Material	Bulk density (kg/m^3)	App. specific density (kg/m^3)	Resistance to fragmentation (%)	Resistance to polishing (PSV) (%)
Crushed Limestone	1448	2650	20.04	-
EAF slag	1532	3333	13.32	64

The EAF slag fine aggregate shows an increased fineness modulus which means that it is rather coarse. Using very coarse fine aggregates could cause cohesiveness problems in the concrete mixtures, so EAF slag fine aggregate was mixed with natural sand in order to obtain an overall fine-aggregate fineness modulus equal to that of crushed limestone (3.4). Furthermore, the steel slag fine aggregates need more water to reach the saturated-surface-dry condition, so the concrete mixture needs to be properly designed.

2.2 Binders

The cement used was CEM I42.5 N, according to EN 197-1, with a specific gravity 3140 kg/m^3. Some of the mixtures where prepared with LF slag replacing 30% of the total binder conctent. The chemical composition and some physical properties of LF slag are given in Table 3.

Table 3. LF slag properties

Chemical composition	(%)
Na_2O	0.34
K_2O	0.04
CaO	54.1
MgO	5.55
FeO	1.72
Al_2O_3	2.50
SiO_2	32.5
Cl^-	0.03
NO_3^-	Not detected
SO_4^-	0.21
Physical properties	
Loss on ignition (950°C) (%)	3.19
Loss on ignition (550°C) (%)	2.62
Fineness (by sieving)	<75μm
App. specific density (kg/m^3)	2590

3 CONCRETE MIXTURES

The basic parameters for the design of concrete mixtures were low content of cement (≤300 kg/m^3), low water/cement ratio (≤0.50) and maximum aggregate size 31.5mm. Firstly, two test mixtures were prepared; Mixture A with crushed limestone aggregates and Mixture B with steel slag aggregates. Both mixtures had 300 kg/m^3 cement content and water/cement ratio 0.40, while workability was very low (1 cm slump) and was measured with the Vebe time test method. The concrete mix proportioning and some properties of the fresh concrete are listed in Table 4. It was obvious that this concrete should be applied by using roller drums as roller compacted concrete.

Table 4. Mixture A and B proportioning and concrete properties

Material	Mixture A (kg/m^3)	Mixture B (kg/m^3)
Cement (I 42.5 N)	300	300
River sand	-	452
EAF slag fine aggregate	-	452
Crushed limestone sand	626	-
Coarse limestone	1461	-
EAF slag coarse aggregate	-	1607
Water	120	120
Superplasticizer	2.1	3.0
Properties of fresh concrete		
w/c	0.40	0.40
Superplasticizer (% b.w. of the binder)	0.71%	1.00%
Workability (Vebe time)	17s	15s
Properties of hardened concrete		
Compressive strength (MPa)	51.8	68.2
Split tensile strength (MPa)	4.44	3.92
Unit weight (kg/m^3)	2552	2824

An adequate number of cubes (15x15x15 cm) and cylinders (15x30cm) were cast from concrete mixtures A and B and were cured at 20˚C and 95% RH conditions until testing. At 28 days of age the specimens were tested for compressive strength, split tensile strength, and unit weight (Table 4). The results showed more than adequate strength development. It is worth mentioning that strength of conventional industrial pavement is commonly of C20/25 f_{ck} category. The compressive strength of mixture B was higher than 50 MPa so it was possible to design a more economic mixture by reducing the cement content to 270 kg/m^3 and also to produce a mixture (mixture E) by replacing 30% of the cement with LF slag. Therefore, it was decided to produce three more concrete mixtures, decreasing the cement content to 270 kg/m^3 and increasing the water/cement ratio to 0.52. In order to improve consistency, it was decided to use only coarse steel slag aggregate in the three new concrete mixtures (C, D, and E) as described in Table 5. Concrete mixture E had a 30% cement replacement with LF slag. All mixtures had a desired workability of ~10s Vebe time which was achieved by adjusting the amount of superplasticizer in the mixture.

A larger numder of 15x15x15 cm cubes, 10x10x40 cm prisms, 10x40x45 cm slabs and 15x30 cm cylinders were cast from concrete mixtures C, D and E and were cured at 20˚C and 95% RH conditions until testing.

Table 5. Mixture C, D, and E proportioning and fresh concrete properties

Material	Mixture C (kg/m^3)	Mixture D (kg/m^3)	Mixture E (kg/m^3)
Cement (I 42.5 N)	270	270	190
Ladle furnace slag	-	-	80
Crushed limestone sand	614	702	698
Coarse limestone	1433	-	-
EAF slag coarse aggregate	-	1,638	1630
Water	140	140	140
Superplasticizer	1.35	1.80	2.15
Properties of fresh concrete			
w/c	0.52	0.52	0.52
Superplasticizer (% b.w. of the binder)	0.50%	0.67%	0.80%
Workability (Vebe time)	10s	12s	9s

4 LABORATORY TEST RESULTS

The concrete specimens from mixtures C, D and E were tested at 28 days. Compressive strength, split tensile strength, flexural strength and resistance to abrasion were measured. In addition, toughness of the C and D mixtures was measured according to RILEM 50-FMC draft recommendation [8]. The results are given in Table 6. Early cracking in pavement is related to heat of hydration [9]. Therefore, under semi-adiabatic conditions such as insulating boxes, the heat of hydration was measured for mixtures C, D and E for 24 hours after casting. 10x40x45 cm slabs were used and the heat changes at the lower side of the specimens are shown in Figure 1. From this figure it is clear that the use of LF slag in the binder system contributes to reduced maximum concrete temperature.

Table 6. Fracture toughness measurements on mixtures C, D and E

Mixture	Max. bending load (kN)	Displacement (mm)	Fracture energy (Nm)
C	10.70	0.112	0.555
D	12.63	0.155	0.931
E	11.55	0.245	1.402

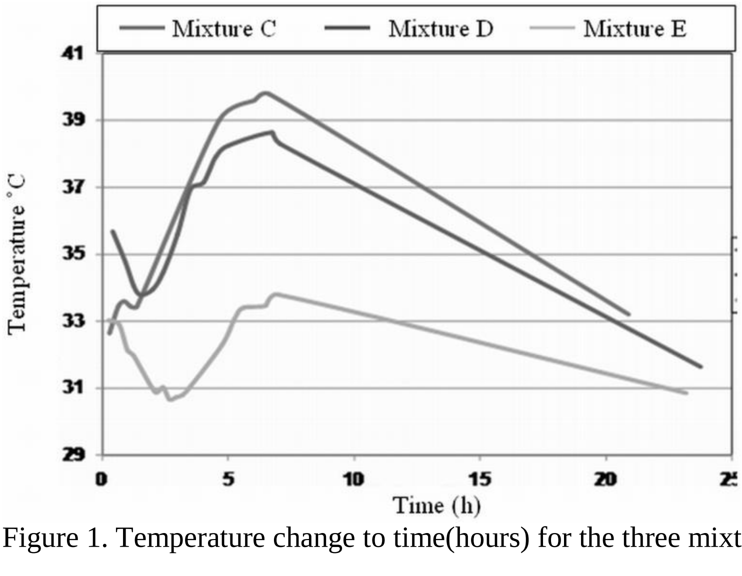

Figure 1. Temperature change to time(hours) for the three mixtures

4.2 Physical and mechanical properties

Cubic specimens were used to measure compressive strength, cylindrical specimens for split tensile strength and prisms for flexural strength. All tests were carried out at 28 days and the results are shown in Table 7. The use of EAF slag as coarse aggregate leads to a significant increase of all mechanical properties (over 40%). Furthermore, the cement replacement with LF slag leads to the production of a concrete with the same strength as the reference mixture C.

Resistance to abrasion was also tested according to modified specification ASTM C779-00 (Figure 2) [10]. The test was carried out on 10x40x45 cm slabs which were subjected to 20΄ of steel-rod abrasion and the depth of the gauge created was measured (Figure 3) and is presented in Table 7.

Table 7. Mechanical properties of mixtures C, D and E

Mixture	Compressive strength (MPa)	Split tensile strength (MPa)	Flexural strength (MPa)	Abrasion resistance (mm)
C	42.2	3.35	6.95	2.401
D	60.1	4.58	9.40	1.002
E	45.5	3.67	6.98	1.199


Figure 2. Abrasion test.

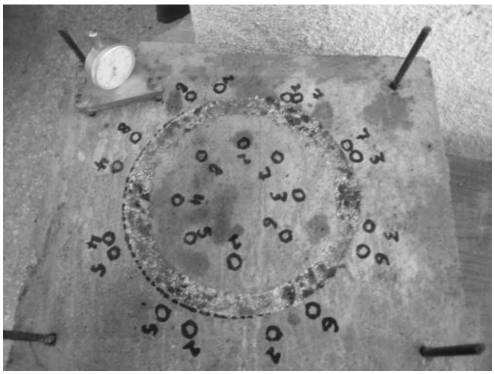
Figure 3. Gauge depth measurement

From the results of the abrasion resistance test it seems that EAF slag aggregates improve by more than 50% the abrasion resistance of concrete and the addition of LF slag does not differentiate much this benefit. This was expected because the resistance to abrasion depends mainly on coarse aggregate.

Microscopic observation of concrete specimens from the Mixtures D and E was carried out in order to check their microstructure. EAF slag aggregate concrete showed good homogeneity and cement paste-aggregate bonding seemed strong (Figure 4). Some surface spots, as well as some salt concentration in the pores of steel slag aggregates were observed on the concrete specimens after exposure in repeated wetting-drying cycles (Figure 5). The pores were generally in a small percentage (1-3%) with a diameter of 700-900μm.

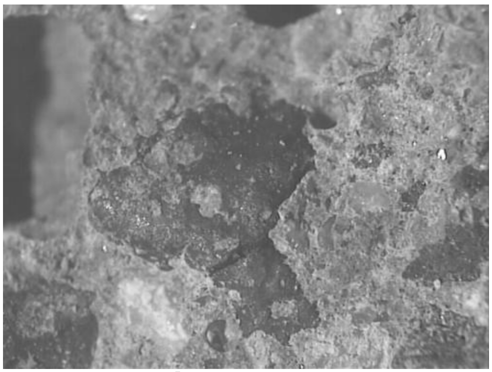

Figure 4. Good cement paste-aggregate bonding

Figure 5. Salt concentration is slag aggregate

5. DISCUSSION

This research work aimed at the proposal of an alternative mixture for industrial concrete pavement construction using EAF slag aggregates and LF slag as binder. The use of slag compared to limestone aggregates showed a significant increase in the mechanical strength of the produced concrete. The use of coarse LF slag aggregates increased compressive and flexural strength by more than 40%, compared to the reference concrete with limestone coarse aggregates. Also, the abrasion resistance of concrete with EAF slag aggregates increased by more than 50% compared to the reference concrete. These properties can be attributed to the higher strength and resistance to fragmentation of slag compared to limestone aggregates.

The combined use of EAF slag aggregate and LF slag as 30% of the total binder in mixture E produced a concrete with strength level equal to that of the reference concrete mixture C, while the use of high volume of industrial by-products suggests a concrete of reduced cost and environmental impact.

Concrete mixture E showed significantly lower heat of hydration when compared to the reference concrete mixture with 100% cement as binder. The lower heat of hydration could be attributed to the slower reaction rate of LF slag and is a desirable property in concrete pavement construction (less thermal cracking due to temperature changes).

In conclusion, it could be said that when LF slag binder and EAF slag aggregate are combined, it is feasible to produce a concrete of adequate strength for concrete pavement production (compressive strength >40MPa) by using a very low amount of cement (190 kg/m^3). The low cement content of the proposed concrete reduces cost significantly, while the use of high volumes of industrial by-products is a step towards preserving natural resources and producing concrete of reduced environmental impact.

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