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Production of high-strength concrete using high volume of industrial by-products

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ABSTRACT

The production of a high-strength, high performance concrete using high volumes of industrial by-products is tested in laboratory mixtures. The by-products used are high-calcium fly ash and ladle furnace slag as binders and electric arc furnace slag as aggregates. Fly ash is used as 50% by mass of the total binder and ladle furnace slag as 30% by mass of the total binder. Slag aggregates are used in replacement of coarse aggregate or in replacement of both fine and coarse aggregates. In the mixtures containing both supplementary cementitious materials and slag aggregates the produced concrete shows high-strength (>70 MPa), good abrasion resistance and fracture toughness.

1. Introduction

The increased natural resource consumption has evolved into a major international problem with severe environmental, social and financial consequences. In order to reduce resource depletion from the construction sector, an effort to use recycled and secondary materials in concrete production has been noted over the past decades [1,2]. The use of secondary materials in concrete is still largely limited to low-strength concrete products such as base courses for roads and 80% of the produced fly ashes and slags end up in low-value applications [3]. However, some industrial by-products show some excellent properties as construction materials, which means that they could be used in concrete production not only for resource preservation but also to improve the mechanical properties and durability of the final product [3]. However, industrial by-products as construction materials may show different properties compared to conventional materials. In order to safely use them in concrete production they should undergo thorough quality control testing and their properties must be taken into account in the concrete mixture design.

In the present report, the use of industrial by-products in concrete production regards both binder and aggregate substitution. High-calcium fly ash (HCFA) or ladle furnace slag (LF slag) were used as alternative binders and electric arc furnace (EAF slag) as alternative aggregates. Greek HCFA is being successfully used for the production of blended cements for over 20 years [4] and could find numerous other applications as a binder [5]. The potential of Greek HCFA to substitute more than 60% of cement in the total binder content of concrete mixtures has been demonstrated through research and applications [6,7]. LF and EAF slags are both steel slags, by-products of the steel manufacturing industry. EAF slag is produced at an early stage of the steel production process, where the cooling of melt slag gives dense, coarse particles, showing good properties as aggregates [8,9]. LF slag is produced at a later stage of the steel production process and gives a fine material, which shows some pozzolanic properties and could be used as a supplementary cementing material [10,11]. Also its performance could be improved with suitable treatment [12]. Earlier work has shown that ground LF slag can substitute cement at percentages up to 30% in the concrete mixture [13].

In order to produce a concrete with high volume of industrial by-products, cement substitution with alternative binders (HCFA or LF slag) is combined with the use of EAF slag as aggregate. EAF slag is an aggregate of high density with excellent properties [14–16] but its use in concrete is limited due to risk of expansion [17]. Research and testing of EAF slag in concrete applications has demonstrated that it shows minimal risk of expansion when free CaO and MgO content are limited and the material is subjected to weathering in outdoor conditions for a period longer than 9 months [18,19].

2. Experimental programme

2.1. Materials

2.1.1. Binder properties

Cement type CEM I42.5 N was used as reference binder in all mixtures. Greek HCFA or LF slag was used as supplementary cementing material in the test concrete mixtures. Cement and both supplementary cementing materials used were tested for density, fineness, specific surface, initial setting time, expansion and pozzolanic-

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Table 1
Physical properties of binders used.

	Test method	CEM I42.5 N	HCFA	LF slag
App. density (kg/m^3)	EN 196-1	3140	2420	2650
Fineness (% retained at 45 μm)	Particle size analysis	11	19	22
Specific surface (m^2/g)	Particle size analysis	0.962	0.938	0.660
Initial setting time (min)	EN 196-3	125	145	180
Expansion (mm)	EN 196-3	–	1.50	0.49
28-day pozzolanicity index (%)	ASTM C311-02	100	96	92

ity index and the results are shown in Table 1. The chemical composition of the binders used was also determined (Table 2) and a DTA–TG analysis was carried out on LF slag, in order to determine its magnesium content.

The fineness of LF slag was increased by grinding while HCFA was processed by grinding and hydrolysis. Pozzolanicity index, initial setting time and expansion values were satisfactory for both supplementary cementing materials. Although HCFA has similar fineness compared to LF slag, it shows significantly higher specific surface, shorter initial setting time and increased pozzolanicity index.

Regarding the chemical composition of the supplementary cementing materials, HCFA shows adequate reactive SiO_2 content and the sulfate and free lime contents are just below 5% and 3% respectively. On the other hand, LF slag has a reactive SiO_2 content of 20.4%, which could explain its weaker pozzolanic character. The free lime content of LF slag is low, but the magnesia content is 4.25%. A DTA–TG analysis carried out on LF slag (Fig. 1), which showed that 0.11% and 0.75% of the total MgO content are in the form of $Mg(OH)_2$ and $MgCO_3$, respectively. This, along with the 0.49 mm expansion value, shows that the risk of LF slag expansion due to free magnesia and free lime content is small.

2.1.2. Aggregate properties

The coarse aggregates used for the production of the concrete mixtures were either crushed limestone or EAF slag. Both aggregates were tested for density, percentage of voids, water absorption, resistance to fragmentation, freeze–thaw resistance and magnesium sulfate soundness and the results are shown in Table 3. To ensure minimal risk of expansion, EAF slag aggregates were also tested for expansion according to EN 1744-1. The fine aggregates used were crushed limestone, EAF slag and river sand. Water absorption, fines content and fineness modulus were determined for all of the fine aggregates and the results are shown in Table 4.

Coarse EAF slag aggregates compared to crushed limestone aggregates show increased density and water absorption, while resistance to fragmentation and flakiness index are significantly improved. The higher density of EAF slag aggregates could lead to a heavyweight concrete and the increased water absorption must be taken into account at the design of the concrete mixture. The higher resistance to fragmentation and flakiness index of EAF slag could give a concrete with increased resistance to mechanical wear. The results of the durability tests (freeze–thaw resistance and magnesium sulfate soundness) are similar for both types of aggregate. The EN 1744-1 test for the expansion of EAF slag showed a value of 0.14%, which is considerably small and shows that the use of these aggregates poses minimal risk of expansion. Overall, EAF slag aggregates fulfill the requirements of the European Standards tested and seem suitable for use as concrete aggregates [20].

Regarding the fine aggregates used, EAF slag sand has very low fines content – a sign of good quality aggregate – but is also very coarse. In order to improve the gradation for the concrete mixture when EAF sand was used, 50% of the fine aggregate was replaced with natural river sand.

2.2. Concrete mixtures

Concrete mixtures were prepared in the laboratory in order to test cement substitution with cementitious materials (HCFA or LF slag) and limestone aggregate substitution with EAF slag aggregate. Six different concrete mixtures were produced, as shown in Table 5. The common characteristics of these mixtures were 400 kg/m^3 total binder content, maximum aggregate size of 12 mm, water to cementitious material ratio 0.35 and low workability (10–20 s Vebe time), adjusted with the use of a superplasticizer. The different water absorption of the aggregates used was taken into consideration and in order to ensure a constant *w*/*c* ratio, water content was calculated on a saturated-surface-dry basis for all the aggregates. The aggregate gradation curves of the concrete mixtures are shown in Fig. 2 and the proportioning of the concrete mixtures is shown in Table 6.

The concrete specimens cast from the mixtures were 150 × 150 × 150 mm cubes, 100 × 100 × 400 mm beams and 100 × 400 × 450 mm slabs. All specimens were cured at 20 °C and 95% RH until the time of testing.

Table 2
Chemical composition of binders used.

	CEM I42.5 (%)	HCFA (%)	LF slag (%)
CaO	66.8	42.1	37.4
CaO_{free}	–	2.89	0.80
SiO_2	19.6	32.6	50.1
$SiO_{2,reactive}$	18.9	26.0	20.4
FeO	2.16	6.60	2.37
Al_2O_3	2.40	10.6	1.62
MgO	3.91	1.50	4.25
SO_3	1.24	4.60	0.20
Na_2O_{eqv}	1.28	0.73	0.39
L.O.I.	1.91	4.60	2.06

2.3. Concrete properties

The concrete specimens produced were tested for unit weight, compressive strength, splitting tensile strength, flexural strength and fracture toughness. Water penetration under pressure, abrasion resistance, freeze–thaw resistance, porosity and microstructure, were also tested, in order to assess the durability of the produced concrete.

Fracture toughness was measured by three-point bending tests in notched beam specimens, according to RILEM 50-FMC Committee Draft Recommendation [21]. In order to test the depth of water penetration, three specimens from each mixture were subjected to water under pressure of 500 kPa for a period of 72 h, according to EN 12390-8. After the completion of the test the specimens were split and the depth of water penetration was measured.

Three concrete specimens from each mixture were subjected to freezing and thawing cycles in 3% NaCl solution, according to DD CEN/TS 12390-9. The abrasion resistance test was carried out on 40 × 45 × 10 cm slabs, according to ASTM C779. The test specimens were subjected to 20 min of abrasion and the depth of the gauge produced was measured.

Open porosity was measured according to RILEM CPC 11.3 Recommendation [22], based on water absorption under vacuum. Also, microstructure was observed using a Leica Wild M10 stereoscope under 10× magnification. The results of the above testing programme are discussed below.

3. Results and discussion

3.1. Unit weight and mechanical strength of concrete mixtures

Table 7 shows some of the properties of the test concrete mixtures. The unit weight of the crushed limestone aggregate concrete (K1) was 2330 kg/m^3 and the unit weight of the EAF slag aggregate concrete varied from 2574 to 2750 kg/m^3, increasing with the proportion of the slag aggregate in the mixture. The use of large volumes of EAF slag, which is a high-density aggregate, seems to produce heavyweight concrete (2750 kg/m^3 unit weight).

The 28-day compressive strength of crushed limestone aggregate concrete (mixture K1) was 64.2 MPa. When coarse EAF slag was used as coarse aggregate (mixture K2), the compressive strength was 70.3 MPa, showing an increase of 9.5%. Furthermore, when both coarse and fine EAF slag aggregates were used (mixture K3), compressive strength increased to 77.9 MPa, which is 21.3% higher than the reference concrete mixture K1. The combined use of LF slag binder and EAF slag aggregate (mixture K4) gave a 28-day compressive strength of 64.3 MPa, which is of the same level with the reference mixture. On the other hand, when HCFA was used as a binder in combination with EAF slag (mixtures K5 and K6) the produced concretes had 28-day compressive strength higher than 70 MPa, showing an increase of more than 10% compared to the reference mixture.