Concrete incorporating High Volume of Industrial by-products

by

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ABSTRACT. Fly ashes and slags are by-products of the energy and steel industry, respectively. They are produced in large quantities and their disposal creates many environmental problems. In the frame of a project by the Greek Secretariat of Research and Technology, the two by-products were used for concrete production. Therefore, a concrete incorporating high volume of local calcareous fly ash and steel slags as aggregates has been manufactured and tested in the laboratory. The characteristics of the two by-products used, as well as the mechanical, elastic and physicochemical properties of this concrete are given in this paper in comparison with conventional concrete. It seems that a concrete with special characteristics, which is particularly suitable for many applications in construction, can be produced with only 5% by mass Portland cement.

Keywords: Calcareous fly ash, Steel slag aggregates, Concrete

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INTRODUCTION

Industrial by-products are marginal materials emanating from industry plants. Depending on the existing utilisation options, they can be either designated as waste or as useful resources. In the former case the by-product needs to be disposed of, which has proven to be not only a financial burden for the production industry, but, most importantly, a cause for considerable environmental problems [1], [2]. On these grounds, successful utilisation possibilities for by-products show great potential for ecologic and economic benefits.

The concrete industry is an important part of the economy and a major consumer of natural resources, and as such it has to face the challenge of sustainability. Since natural resources are scarce, the concrete industry must consider a more efficient use of resources adopting and incorporating alternative materials such as industrial by-products. Fly ash and steel slag form two substitutes for natural resources with great potential for use in concrete manufacturing. High Calcium Fly Ash (HCFA), the solid residue generated by lignite-fired power stations in the production of electricity, is a by-product of the power industry produced in large quantities in Greece (8 million tonnes per year). Steel slags are water-cooled, non-metallic by-products of the steel making process. In Greece the estimated amount of steel slag output reaches the 0.5 million tonnes per year. One important factor is that the properties of industrial by-products vary accordingly to the local conditions and therefore for have to be tested and managed separately. However, research [3], [4], [5], [6] has shown that, generally, HCFA and steel slag have pozzolanic properties and can be used as a binder in concrete manufacturing, providing technical advantages in the durability of concrete. Furthermore, steel slag aggregates can substitute natural aggregates [7], especially in countries such as Greece, which use mainly limestone as conventional aggregate. The scope of this report is to explore the possibility of utilising high volumes of HCFA and granulated steel slag as binder, and steel slag as aggregates to produce a low-cost, durable, and environmentally efficient concrete.

EXPERIMENTAL WORK

Materials

Ordinary Portland cement type CEM I was used in the making of concrete specimens. The steel slag used was from Sidenor S.A. steel industry plant in Thessaloniki, and HCFA from the Greek National Electricity Company power plant in Ptolemaida. The chemical composition of these by-products is given in Table 1. The interoperability of the binders was tested by producing mortars with standard sand (EN 196-1). The development of strength in mortars prepared with slag of fineness <0.075mm can be seen in Table 2.

Table 1 Chemical composition of calcareous fly ash and steel slag

Chemical composition %	FeO	CaO	MgO	Al_2O_3	MnO	SiO_2	K_2O	NaO	SO_3
Calcareous fly ash	4.5	32.5	2.5	14.7	-	30.8	1.5	0.4	4.75
Steel slag	25.0	39.0	4.7	4.6	5.5	16.5	-	-	-

Table 2 Strength development of various mortar mixtures

Binder			Compressive strength (MPa)		Flexural strength (MPa)	
CEM I45 %	Slag %	HCFA%	7 days	28 days	7 days	28 days
70	30	-	31.3	38.4	6.7	7.1
70	15	15	37.1	47.4	7.4	8.4
50	20	30	28.6	39.9	6.0	7.7

Table 3 Properties of river sand, steel slag and crushed limestone aggregate

Property	River sand	Limestone aggregate	Steel slag aggregate
Bulk specific gravity	2.65	2.68	3.33
Water absorption %	1.0	1.2	1.3

Crushed limestone, river sand, and steel slags were used as aggregates. A Los Angeles test was carried out to determine the soundness of steel slag aggregates, which showed loss of 17.14% and 13.86% for maximum aggregate size of 1" and 3/8" respectively, according to AASHTO T96. The natural and steel slag aggregates were tested to determine bulk specific gravity and water absorption. The results are shown on Table 3. All coarse aggregates had a maximum size of 31.5mm and the final mixture of aggregates had grading within the margins shown on Table 4.

Mixture Design

The parameters for the mixture design were:

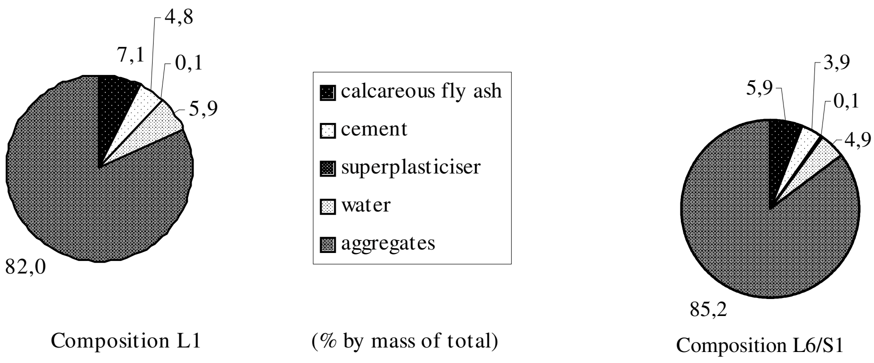
- The replacement of cement with HCFA and/or granulated steel slag in the binding system
- The use of steel slag aggregates in partial (coarse aggregates) and total replacement of natural aggregates.

The concept of the compositions was that of a concrete with binder content of 280 kg/m^3, low w/c ratio (~0.50) and high specific gravity for use in massive concrete applications such as pavements, dams, covering of radioactive sources or heavy precast concrete products. Superplasticiser at a ratio of 2% by mass of binder was used to ensure good workability and compaction of concrete.

Table 4 Aggregate grading used in the produced concrete

Sieve opening, mm	Percent passing
31.5	100
16	70-87
8	45-68
4	30-52
2	18-40
1	10-30
0.5	5-20
0.25	2-13

Figure 1. The composition of some of the concrete mixtures tested



A total of 8 compositions were manufactured to test the properties of concrete with variable amounts of by-products against conventional concrete, according to Table 5. The first 6 (compositions L1 to L6) were carried out in the laboratory while compositions S1 and S2 were carried out in larger scale on-site, based on the findings of the laboratory tests. Some of the concrete mixtures are shown in Figure 1.

For each composition, concrete cylinders 150mm in diameter and 300mm high were cast to determine unit weight, compressive strength, split tensile strength, and the modulus of elasticity. Beam specimens 100x150x700mm were cast to measure the flexural strength and 100x400x400mm specimens were cast to determine abrasion resistance according to ASTM C779. Some cubic 150x150mm specimens were also cast to measure resistance to wet-dry cycles, the dynamic modulus of elasticity, and exposure in outdoor conditions. The compressive strength in mixtures S1 and S2, cast on-site was determined by crushing a big number of cube specimens. These specimens were prepared by a ready-made concrete industry during the course of a relevant demonstration project for production of concrete. The concrete produced was used for the making of blocks for jetty construction and also as a test part of a highway. A modified Vebe test was carried out in the laboratory to measure workability of fresh concrete with a target Vebe time of 20 seconds, while in the on-site mixtures a slump test was used with a required 0-2 cm slump. The specimens were compacted using a vibrating table where possible and with equivalent manual compaction in all other cases.

Table 5 Mix design parameters for concrete compositions

mix	w/c	binder (% by mass)			aggregates	
		cement	HCFA	slag	fine	coarse
L1	0.50	40%	60%	0%	natural	natural
L2	0.58	40%	60%	0%	natural	steel slag
L3	0.50	40%	30%	0%	natural	steel slag
L4	0.50	40%	30%	30%	natural	natural
L5	0.56	40%	60%	30%	natural	steel slag
L6	0.59	40%	60%	0%	steel slag	steel slag
S1	0.66	40%	60%	0%	steel slag	steel slag
S2	0.63	50%	50%	0%	natural	steel slag

Table 6 Test data for concrete specimens prepared with cement, HCFA, steel slag, crushed limestone aggregate, and river sand

Binder	C+F	C+F	C+F+S	C+F+S	C+F	C+F	C+F	C+F
Aggregates	L	L+S	L+S	L	L+S	S	S	R+S
Test	L1	L2	L3	L4	L5	L6	S1*	S2*
Unit weight, kg/m^3	2398	2535	2544	2348	2681	2887	2796	2674
Compressive strength, MPa								
7 days	20.5	13.8	14.4	7.4	18.1	14.4	-	-
28 days	26.8	22.5	16.7	15.9	22.4	21.1	16.0	22.2
Split tensile strength, MPa, 28 days	3.46	2.75	2.39	1.73	4.72	2.13	3.16	2.38
Flexural strength, MPa, 28 days	8.24	6.38	5.22	3.26	6.62	10.6	7.17	5.22
Modulus of elasticity, GPa	33.59	23.88	29.07	31.66	49.85	38.94	39.58	26.12
Dynamic modulus of elasticity, GPa	102.8	90.1	86.5	87.4	111.5	94.3	81.6	91.6

C: Cement, F: HCFA, L: Limestone, S: Slag, R: River sand (0-4mm)
* characteristic values (according to conformance criteria)

RESULTS AND DISCUSSION

The properties of concrete produced with cement, HCFA, steel slag and crushed limestone aggregate are summarised in Table 6. Results are discussed in detail in the following subsections.

Unit Weight

The unit weight of the concrete increased from 2348 kg/m^3 for a composition with only natural aggregates to 2535-2674 kg/m^3 for compositions with fine natural and slag coarse aggregates and to 2887 kg/m^3 for a composition with only slag aggregates. The high specific gravity of steel slag aggregates resulted in the significant increase in the unit weight of the produced concrete, which is advantageous in some concrete applications.

Mechanical Properties

Compressive strength

The compressive strength reduced from 26.8 MPa for concrete with cement and fly ash as binder (L1) to 15.9-16.7 MPa for concrete with cement, fly ash and slag as binder (L4). This significant decrease led to the continuation of experiments with steel slags only as aggregates. Concrete with substitution of all natural aggregates with slags also decreased compressive strength from 26.8 MPa to 16.0-21.1 MPa. However, substitution of coarse natural aggregates with steel slag in 3 compositions resulted in compressive strength of 22.2-22.5 MPa, achieving an 83% of the strength of the reference concrete. This result shows the potential of coarse steel slag aggregates, along with their compatibility with fly ash as binder. Furthermore, 12 cubic specimens 150x150mm from each one of S1 and S2 mixtures were tested in compressive strength and gave average of 28.77 MPa and 27.13 MPa respectively.

These results along with the fulfilment of relevant criteria give to the concrete mixtures S1 and S2 a strength category of C16/20, accomplished with the use only 5% cement by mass. The compressive strength development of the different concrete mixtures can be seen in Figure 2.

Split tensile strength

The split tensile strength also decreased from 3.46 MPa to 1.73-2.39 MPa, when steel slag was used as binder compared to concrete with cement and fly ash as binder. The importance of good compaction led to variability from 2.38 MPa to 4.72 MPa for concrete with coarse steel slag aggregates, however this type of concrete is still the closest to the reference fly ash concrete.

Flexural strength

The flexural strength of concrete made only with steel slag as aggregates compared to the reference fly ash cement indicates that steel slag aggregates might have an advantage in this test. While in compression and split tensile strength compositions with all slag aggregates show a slight decline of strength compared to the fly ash-cement with natural aggregates compositions, in flexural strength the compositions show similar values.

Abrasion Test

The abrasion resistance was measured using a modified ASTM C779 test. Three specimens from composition S1 with steel slag coarse aggregates were tested, giving an average gauge depth of 1.71mm, and three from composition S2, made only with steel slag aggregates, giving an average gauge depth of 2.51mm (Figure 3). In other words, abrasion resistance of concrete increased 31%, by substituting limestone aggregates with slag aggregates. This special feature of the steel slag aggregate concrete is of great importance in concrete pavement construction.

Figure 2. Compressive strength development of different concrete mixtures

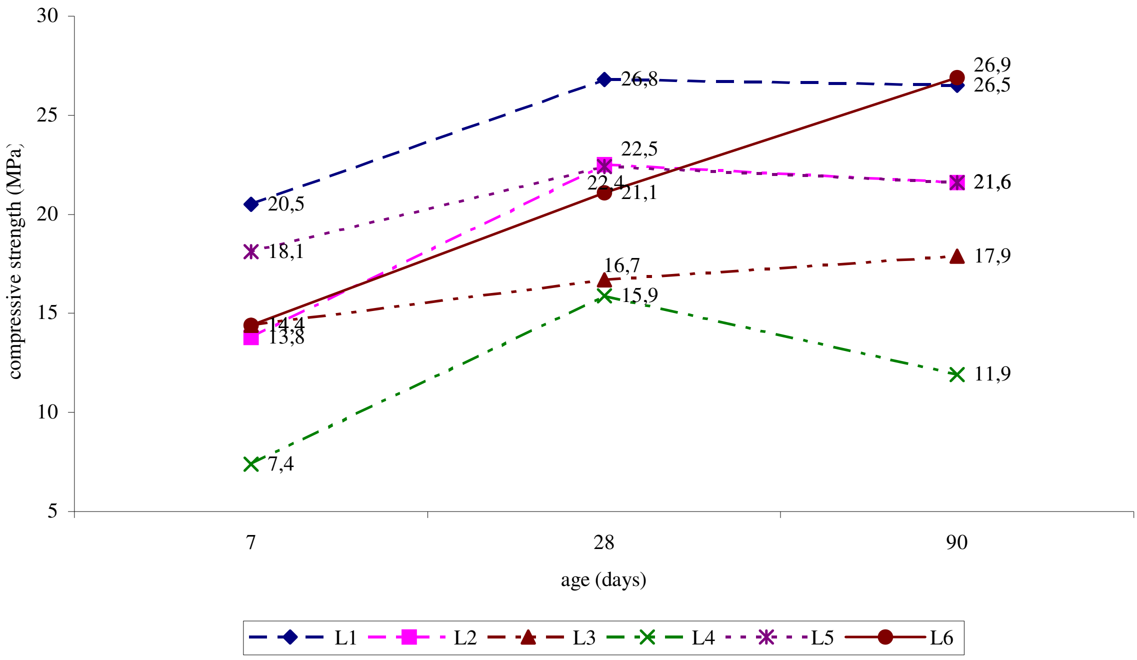
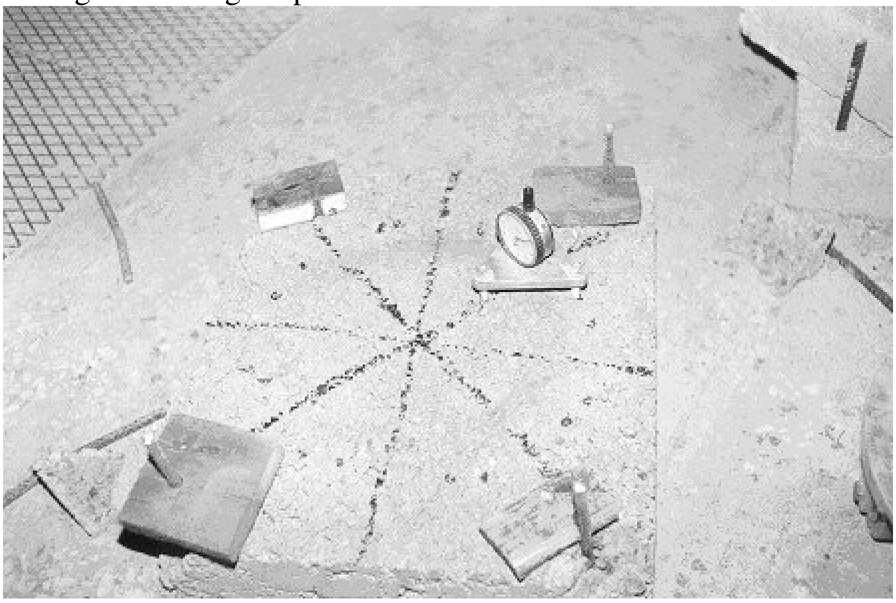


Figure 3. Gauge depth measurement in abrasion resistance test



Wet-Dry Cycles

The objective of this test is to examine any colour or volume change in concrete after cyclical exposure to cycling wet-dry conditions. Concrete specimens from mixtures L1, L2, and L3, were tested in 3-day wet-dry cycles for a total period of 60 days. The results showed that substitution of cement with granulated steel slag might increase the water absorption rate of concrete (Figure 4). On the other hand, substitution of limestone with steel slag aggregates showed no significant change in the rate of water absorption. No leaching, change in volume or colour was observed in the specimens after the completion of the test.

Figure 4. Water absorption of concrete exposed in wet-dry cycles

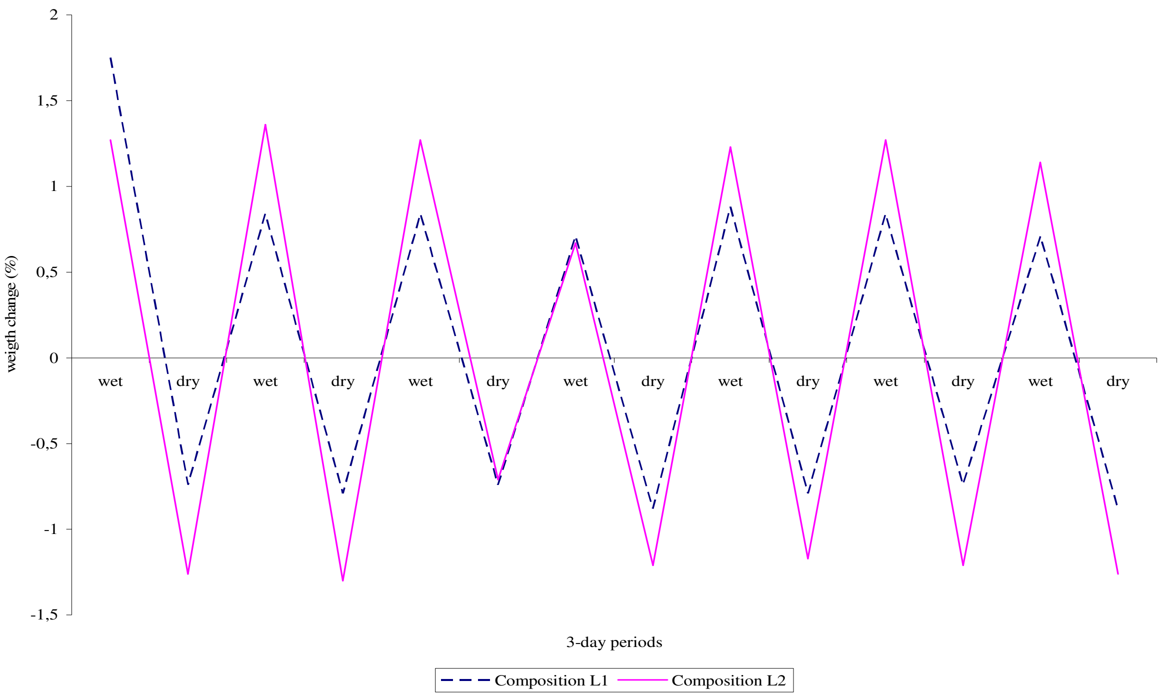
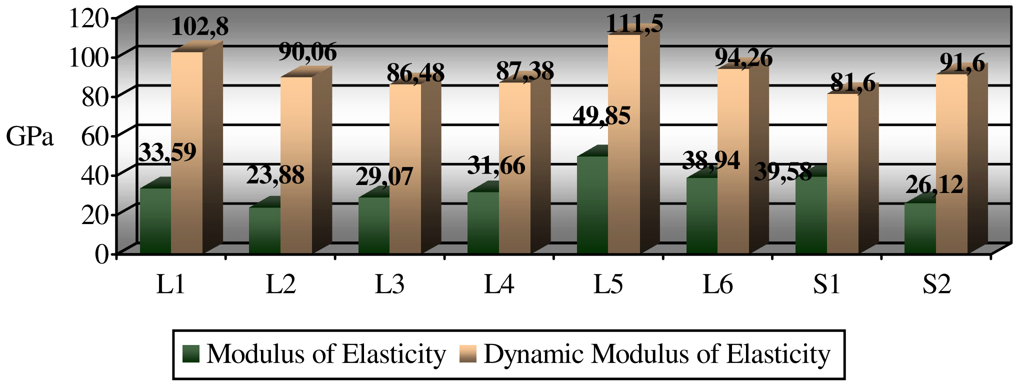


Figure 5. Elastic properties of different concrete mixtures



Exposure In Outdoor Conditions

Same as above, concrete specimens from mixtures L1, L2, and L3 were left in outdoor conditions for a period of 360 days, to observe possible leaching, colour change, or any other deformation. After the completion of the test there was no leaching or any other visually noticeable change in any of the specimens.

Elastic Properties

The modulus of elasticity and the dynamic modulus of elasticity were measured in each of the concrete mixtures and the results are presented in Figure 5. The substitution of natural aggregates with slag clearly increases both of these properties.

Retention Of Heavy Metals

The objective of this test was the determination of heavy metals released by leaching and was carried out in carrot specimens taken from concrete with steel slag aggregates (the percentage of aggregates in total concrete being 80% by mass) and the content of heavy metals was determined after oxidation and leaching. The same test was carried out in the steel slag aggregates before their incorporation in the concrete mixture. The results of these tests are given in Table 7.

Table 7 Determination of heavy metals in steel slag aggregates and in concrete prepared with >80% steel slag aggregates, (in mg/lt)

	Fe	Ni	Cu	Mn	Zn	Cr	Cd	Pb
Steel Slag	17.3	0.28	2.42	6.00	6.25	0.46	1.00	3.04
Concrete + steel slag	16.3	0.25	0.03	0.70	0.03	0.24	0.10	0.19

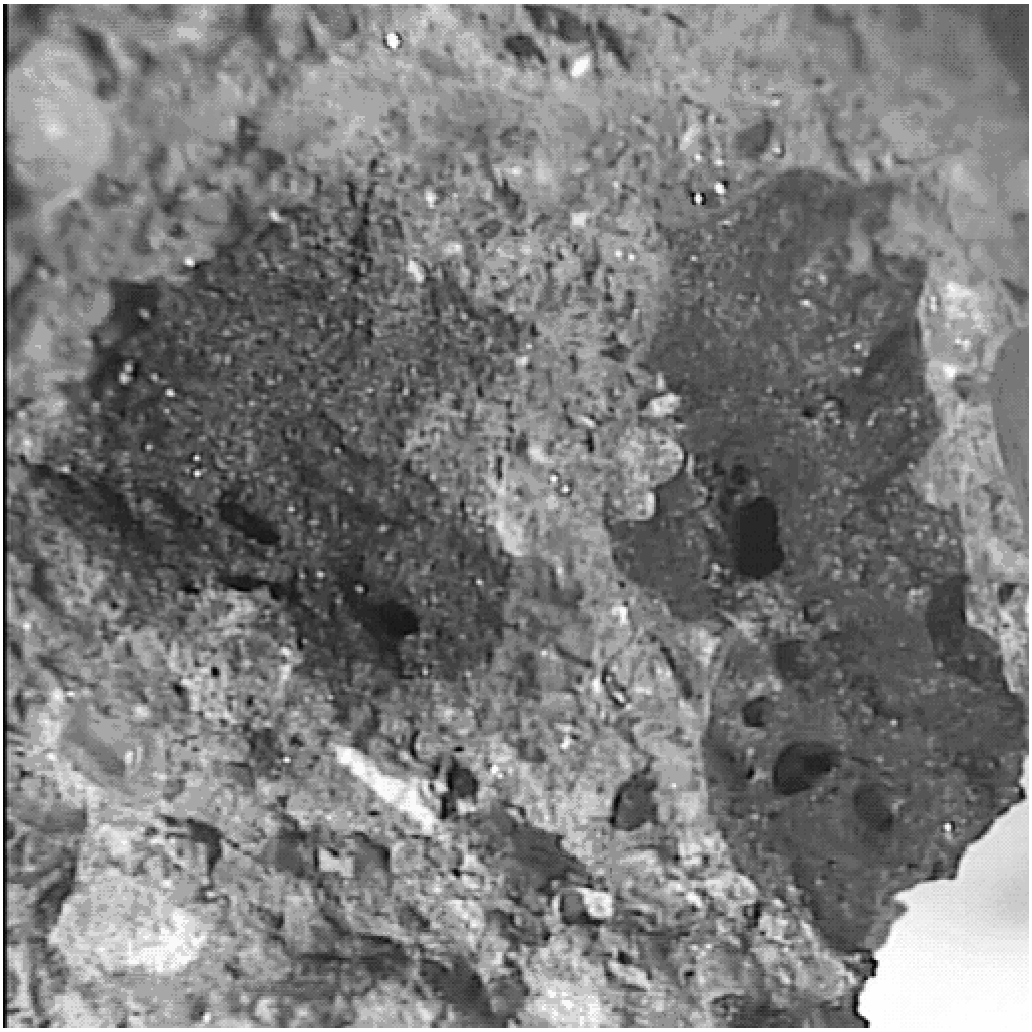
Discussion

The contribution of the fine portion of steel slag to the development of strength has been shown in Table 2 and it seems that its pozzolanicity is lower than that of fly ash, but steel slag cooperates with cement and fly ash.

The use of steel slag as aggregates in concrete shows some advantages, because:

- the concrete produced has a high unit weight, a desirable property in certain applications;
- the concrete produced has improved abrasion resistance compared to ordinary concrete;
- the transition zone of the matrix-aggregate is enforced, as can be seen in Figure 6 and this also might be the reason for the improvement in flexural strength of concrete with steel slag aggregates;
- the leaching of heavy metals from steel slag aggregates that are embodied in concrete is small compared to that of land-filling applications.

Figure 6. Matrix-aggregate transition zone in concrete with steel slag aggregates



CONCLUSIONS

The research undertaken has shown that it is possible to produce on-site a concrete with high volume of fly ash and steel slag aggregates. Cement, fly ash, and steel slag aggregates are compatible materials and can be incorporated together in concrete mixtures without hindering the strength development process. Category C16/20 concrete can easily be produced commercially. Compared to conventional concrete, the concrete tested is:

- Low-cost concrete (only 5% by mass cement is used).
- Advantageous in certain technical properties (abrasion resistance, unit weight).
- Environmentally friendly due to the conservation of natural resources achieved and the incorporation in the construction industry of undesired by-products. Especially, the proposed concrete encloses two by-products, fly ash and slag, which are embodied in concrete with very low cement content. Considering pavement applications, for which large quantities of concrete is usually required, the proposed concrete seems to be very advantageous from technical, economical and environmental aspects.

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