# Use of cementitious materials for the production of concrete

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ABSTRACT: Shotcrete applications have increased impressively in Greece over the last decade due to large infrastructure projects, in which a great number of tunnels is constructed. Regarding shotcrete mixtures, it could be said that they are very rich in cement which overcharges their total cost. Therefore, the addition of supplementary materials as partial replacement of cement could be very advantageous. Three local cementitious materials of different pozzolanic capacity were used with cement CEM I 42.5 N to form the mixed type binding system of shotcrete mixtures. The cementitious materials used are high calcium fly ash (HCFA) – a by-product of lignite combustion, ladle furnace slag (LFS) and natural pozzolan from the island of Milos. Combinations of them were used for a series of laboratory experiments as well as field experiments by taking cores according to the EFNARC regulations. The results showed that by replacing 50% of the cement in the binding system with cementitious materials there is a 30% decrease of the reference strength with 100% cement in the binding system. Other tests showed that by replacing 20-30% of the cement with slag (LFS) the strength developed in the field was about 20 MPa, which corresponds to 90% of the strength of the reference mixture. Concrete with low 28-day strength of 10 MPa has been achieved by using only cementitious materials in the binding system or with the addition of small quantities of cement. The very low market prices of the cementitious materials make their perspective of their use in shotcrete manufacture very attractive.

## 1 INTRODUCTION

In Greece, the most important supplementary cementitious materials are the natural pozzolan of volcaneous origin from the island of Milos and the industrial by-products, such as calcareous fly ash, emanating from lignite combustion with an annual production of about eleven million tons, and ladle furnace slag produced by the steel industry with the production totaling about fifteen thousand tons annually. Over the last decade, a great effort was made to maximize the utilization of cementitious materials in construction, in the framework of environment protection policies and sustainability requirements.

The objective of the research done was to find if the above mentioned materials can be used in shotcrete applications by replacing part of the portland cement in the binding system, since this type of concrete is considered a very rich in cement mixture. The use of shotcrete, mainly for tunneling and concrete structure repairs, has increased impressively due to the construction of large infrastructure projects such as Egnatia Odos, as well as the reconstruction and reinforcement of existing old concrete structures. Dry and wet-mix processes are used for shotcrete production, with the latter being more preferable in tunnel construction. The addition of cementitious materials in shotcrete is well known in former research [Morgan 1998, Kim 2004, ACI 1990]. The main issues encountered in this research are how much of the cement could be replaced and which would be the strength gained after partial cement replacement.

The pozzolanic capacities of the Milos natural pozzolan and the calcareous fly ash are well known, since these materials have been used continuously over the last twenty years in blended type cement production [Papayianni 1987, Papayianni 1993]. Therefore, the research focused more on the ladle furnace slag (LFS) [Papayianni & Anastasiou 2006]. Laboratory experiments were conducted, as well as in-situ experiments where the wet-mix process was used for casting the shotcrete and the EFNARC regulative framework was used for testing [EFNARC 1999].

## 2 EXPERIMENTAL WORK

### 2.1 *Mixture proportions*

A series of laboratory mixtures was produced to study potential inclusion of the three cementitious materials in shotcrete mixtures. At the first stage the aim was to test them in various combinations with cement to form the final binding system for shotcrete mixtures. The binder content and cement replacement were decided so as to determine the optimum mixing proportions for an economical shotcrete with acceptable strength level. All mixtures were designed for the wet process spraying technique, thus with high binder content (>450 kg/m$^3$). Workability was tested by the flow test, aiming at a certain extension of 45-50cm at the flow table measurement. Specimens produced from the mixtures were tested, measuring their 28-day compressive, split tensile and flexural strength.

At the second stage of laboratory testing another series of mixtures was produced to test the use of ladle furnace slag as a substitute for portland cement in shotcrete mix design. Ladle furnace slag had a nominal size of 0-500μm (LFS-500) and was used in 20% replacement of portland cement. To increase its pozzolanic properties though, ladle furnace slag was sieved down to 0-100μm (LFS-100) nominal size and further trial mixtures were carried with LFS-100 replacing 30% of the portland cement in the control mixtures. Specimens produced from the mixtures were tested for their 7-day and 28-day compressive strength.

A large scale production of shotcrete with 20% cement replacement by ladle furnace slag (LFS-100) took place at the construction plant of a tunnel of Egnatia Odos. The shotcrete was cast using the wet mix process and laboratory tests were carried out on a large number of drilled cores, measuring 7-day, 28-day, and 90-day strength, as well as the 90-day split tensile strength.

### 2.2 *Laboratory work*

#### 2.2.1 *First stage*

The constituents of the control mixture were ordinary portland cement CEM I42.5 N, river sand, water, and superplasticizer. In the various mixtures cement was replaced at varying ratios by Greek high calcium fly ash (HCFA), ladle furnace slag, or natural pozzolan. Ladle furnace slag originally had a maximum grain size of 500μm (LFS-500), which was reduced by sieving to 100μm (LFS-100). The main characteristics of the cementitious materials are given in Table 1.

Table 1. Technical characteristics of cementitious materials.

| Materials | Density | Pozzolanicity index (EN 196-1) | Fineness (% retained in 45μm sieve) |
|---|---|---|---|
| HCFA | 2.41 | 95% | 19% |
| Natural Pozzolan | 1.90 | 85% | 10% |
| LFS-500 | 2.52 | 76% | 33% |
| LFS-100 | 2.59 | 85% | 21% |

One mixture was produced using only CEM IV32.5 B with 50% HCFA included in the clinker. For the first three trial mixtures the constant parameters were binder content of 450 kg/m$^3$ and workability (45-50 cm extension at the flow table test method). The first three laboratory mixtures are shown on Table 2.

Table 2. Laboratory mixtures L1-L3.

| Mixture | L1 | L2 | L3 |
|---|---|---|---|
| CEM I42.5 N (kg/m$^3$) | 450 | - | 225 |
| CEM IV32.5 B (kg/m$^3$) | - | 450 | - |
| HCFA (kg/m$^3$) | - | - | 90 |
| LFS-500 (kg/m$^3$) | - | - | 90 |
| Natural Pozzolan (kg/m$^3$) | - | - | 45 |
| Sand (kg/m$^3$) | 1635 | 1635 | 1580 |
| Water (kg/m$^3$) | 245 | 245 | 250 |
| Superplasticizer (% b.w. of binder) | 0.6 | 0.6 | 0.8 |
| W/Cm | 0.54 | 0.54 | 0.56 |
| Flow (cm) | 44 | 44 | 44 |

For the following two mixtures the binder content was increased to 500 kg/m$^3$ to achieve mixtures richer in binder and also to achieve larger inclusion of cementitious materials. Workability was kept constant as with the previous mixtures (Table 3).

Four more mixtures were produced in a similar way, increasing the total binder content to 575 kg/m$^3$, and keeping the workability same as with the previous mixtures. For demonstration purposes, one mixture (L9) was produced without any portland cement (Table 4).

Table 3. Laboratory mixtures L4-L5.

| Mixture | L4 | L5 |
|---|---|---|
| CEM I42.5 N (kg/m$^3$) | 200 | 250 |
| CEM IV32.5 B (kg/m$^3$) | - | - |
| HCFA (kg/m$^3$) | 150 | - |
| LFS-500 (kg/m$^3$) | 100 | 150 |
| Natural Pozzolan (kg/m$^3$) | 50 | 100 |
| Sand (kg/m$^3$) | 1455 | 1438 |
| Water (kg/m$^3$) | 270 | 275 |
| Superplasticizer (% b.w. of binder) | 0.6 | 0.6 |
| W/Cm | 0.54 | 0.55 |
| Flow (cm) | 45 | 45 |

Table 4. Laboratory mixtures L6-L9.

| Mixture | L6 | L7 | L8 | L9 |
|---|---|---|---|---|
| CEM I42.5N(kg/m$^3$) | 287 | 230 | 287 | - |
| CEM IV32.5 B (kg/m$^3$) | - | - | - | - |
| HCFA (kg/m$^3$) | 115 | 173 | - | 345 |
| LFS-500 (kg/m$^3$) | 115 | 115 | 115 | 115 |
| Natural Pozzolan (kg/m$^3$) | 58 | 57 | 173 | 115 |
| Sand (kg/m$^3$) | 1315 | 1315 | 1302 | 1301 |
| Water (kg/m$^3$) | 297 | 293 | 308 | 322 |
| Superplasticizer (% b.w. of binder) | 0.5 | 0.6 | 0.5 | 1.5 |
| W/Cm | 0.52 | 0.51 | 0.54 | 0.56 |
| Flow (cm) | 44 | 45 | 45 | 43 |

### 2.2.2 *First stage test results*

Six 15x30 cm cylinder specimens and three 10x10x40 cm prisms from each mixture were cast and cured for 28 days in a laboratory chamber in conditions of 20°C temperature and 95% relative humidity. Then three of the cylinders were tested for their compressive strength, three were tested for their split tensile strength and the three prisms were tested for their flexural strength. The results are shown on Table 5.

### 2.2.3 *Second stage*

At the second stage of the laboratory work the mixture parameters were the total binder content (varying from 450kg/m$^3$ to 650 kg/m$^3$) and the replacement of portland cement with ladle furnace slag (20% replacement when the coarser slag LFS-500 was used and 30% replacement when the finer slag LFS-100 was used). Thus, nine more trial mixtures (B1-B9) were produced as shown on Tables 6-8. Workability was also measured by the flow test and kept constant to 50±5 cm

Table 5. Laboratory mixtures L6-L9.

| Mix. | Binder Content | 28-day Compr. Strength | 28-day Splitting Tensile Strength | 28-day Flexural Strength |
|---|---|---|---|---|
| | kg/m$^3$ | MPa | MPa | MPa |
| L1 | 450kg/m³ | 22.5 | 1.69 | 3.55 |
| L2 | 450kg/m³ | 18.8 | 1.27 | 2.91 |
| L3 | 450kg/m³ | 14.2 | 1.21 | 2.37 |
| L4 | 500kg/m³ | 16.4 | 1.23 | 2.33 |
| L5 | 500kg/m³ | 14.5 | 1.25 | 3.15 |
| L6 | 575kg/m³ | 17.8 | 1.23 | 3.70 |
| L7 | 575kg/m³ | 17.1 | 1.26 | 2.71 |
| L8 | 575kg/m³ | 15.4 | 1.35 | 3.66 |
| L9 | 575kg/m³ | 10.8 | 0.64 | 2.07 |

Table 6. Mixtures with binder content of 450 kg/m$^3$

| Mixture | B1 | B2 | B3 |
|---|---|---|---|
| CEM I42.5 N (kg/m$^3$) | 450 | 360 | 315 |
| LFS-500 (kg/m$^3$) | - | 90 | - |
| LFS-100 (kg/m$^3$) | - | - | 135 |
| Sand (kg/m$^3$) | 1743 | 1647 | 1635 |
| Water (kg/m$^3$) | 180 | 180 | 202 |
| Superplasticizer (% b.w. of binder) | 0.5 | 0.5 | 1.0 |
| W/Cm | 0.40 | 0.40 | 0.45 |
| Flow (cm) | 54 | 47 | 50 |

Table 7. Mixtures with binder content of 550 kg/m$^3$

| Mixture | B4 | B5 | B6 |
|---|---|---|---|
| CEM I42.5 N (kg/m$^3$) | 550 | 440 | 385 |
| LFS-500 (kg/m$^3$) | - | 110 | - |
| LFS-100 (kg/m$^3$) | - | - | 165 |
| Sand (kg/m$^3$) | 1563 | 1432 | 1423 |
| Water (kg/m$^3$) | 194 | 220 | 220 |
| Superplasticizer (% b.w. of binder) | 0.5 | 0.5 | 0.5 |
| W/Cm | 0.35 | 0.40 | 0.40 |
| Flow (cm) | 51 | 49 | 49 |

Table 8. Mixtures with binder content of 650 kg/m$^3$

| Mixture | B7 | B8 | B9 |
|---|---|---|---|
| CEM I42.5 N (kg/m$^3$) | 650 | 520 | 455 |
| LFS-500 (kg/m$^3$) | - | 130 | - |
| LFS-100 (kg/m$^3$) | - | - | 195 |
| Sand (kg/m$^3$) | 1356 | 1211 | 1200 |
| Water (kg/m$^3$) | 208 | 247 | 227 |
| Superplasticizer (% b.w. of binder) | 0.5 | 0.5 | 0.5 |
| W/Cm | 0.32 | 0.38 | 0.35 |
| Flow (cm) | 51 | 50 | 51 |

### 2.2.4 *Second stage test results*

Six 15x30 cm cylinder specimens from each mixture were cast and cured for 28 days in a laboratory chamber in conditions of 20°C temperature and 95% relative humidity. Then three of the cylinders were tested for their compressive strength at 7 days and three were tested for their compressive strength at 28 days. The results are shown on Table 9.

Table 9. Test results for mixtures B1-B9.

| Mix | Compressive Strength 7-day | 28-day | % of control |
|---|---|---|---|
| | MPa | MPa | |
| B1 | 27.6 | 35.3 | - |
| B2 | 18.3 | 24.9 | 70.5 |
| B3 | 18.3 | 25.1 | 71.1 |
| B4 | 33.4 | 41.4 | - |
| B5 | 23.1 | 28.1 | 67.9 |
| B6 | 30.1 | 37.5 | 90.5 |
| B7 | 37.0 | 45.7 | - |
| B8 | 34.4 | 40.6 | 88.8 |
| B9 | 38.6 | 44.8 | 98.0 |

## 2.3 *Field experimental work*

### 2.3.1 *Mixture proportions*

The in-situ tests were carried out at an Egnatia Odos plant, where part of a new tunnel was constructed as a pilot project using shotcrete with ladle furnace slag as a binder. Three batches were designed and tested, the first being the concrete mixture commonly used by the company in other tunneling works, with 100% portland cement as a binder. The other two batches were designed with 20% and 30% replacement of portland cement with ladle furnace slag. The slag used was that of nominal size 0-100μm, the cement type was CEM II42.5 N, and the sand crushed limestone. Two types of admixtures were used; a superplasticizer to aid flowability through the nozzle of the spraying equipment and a hardening accelerator which is essential for the wet-mix spraying process. The three mixtures are presented on Table 10.

Table 10. In-situ mixtures E1-E3 with total binder content of 440 kg/m$^3$.

| Mixture | E1 | E2 | E3 |
|---|---|---|---|
| CEM II42.5 N-B (kg/m$^3$) | 440 | 352 | 308 |
| LFS-100 (kg/m$^3$) | - | 88 | 132 |
| Sand (kg/m$^3$) | 1540 | 1540 | 1540 |
| Water (kg/m$^3$) | 250 | 250 | 250 |
| Superplasticizer (% b.w. of binder) | 1.0 | 1.6 | 1.0 |
| Accelerator (% b.w. of binder) | 5-6 | 5-6 | 5-6 |
| W/Cm | 0.57 | 0.57 | 0.57 |
| Flow (cm) | 48 | 51 | 50 |

### 2.3.2 *Test results*

The three mixtures were sprayed on different parts of the tunnel surface and core specimens were drilled from the surface within 24 hours from the casting. Thus, a large number of drilled cores; cylindrical specimens with 10 cm diameter and 20 cm height were produced and cured in the laboratory in conditions of 20°C temperature and 95% relative humidity. Compressive strength was measured at 7, 28, and 90 days, while split tensile strength was also measured on 90 days. The results are shown on Table 11.

Table11. Test results for mixtures E1-E3.

| | Compressive strength (average of 12) | | | | Split tensile strength (average of 6) |
|---|---|---|---|---|---|
| | MPa | | | | MPa |
| Mix | 7d | 28d | % of control (28d) | 90d | 90d |
| E1 | 15.6 | 23.1 | - | 29.1 | 2.42 |
| E2 | 11.6 | 21.6 | 93.5 | 26.3 | 2.23 |
| E3 | 13.4 | 21.1 | 91.3 | 25.6 | 2.16 |

## 3 RESULTS AND DISCUSSION

Based on the results of the first stage of the laboratory work, where 50% of the portland cement type I 42.5 N was replaced by a combination of cementitious materials consisting of 20% HCFA, 20% LFS, and 10% Natural pozzolan, the drop in 28-day strength ranges from 30% to 40% depending on the total binder content and the percentage of HCFA, which contributes to strength development more than the other cementitious materials. The mixture L2 with the CEM IV 32.5 B composite cement –in which HCFA constitutes 50% of the clinker– has developed 28-day strength with more than 80% of the strength of the reference mixture. By comparing L3 with L4 it can be derived that the increase of the HCFA percentage in the mixture is obviously beneficial. It could also be said that the large amount of binder content contributes to higher strength. The L9 mixture was prepared only with supplementary cementitious materials (without any cement) developed 28-day strength of around 10 MPa while the other mixtures (L2-L8) showed a 28-day strength range from 15 to 17.5 MPa.

The second laboratory stage showed that the finest fragment of the LFS (LFS-100) is more reactive and can replace cement in higher percentages. The 28-day strength achieved by the mixtures with 30% LFS-100 was from 90% to 98% of the reference mixture with 100% CEM I42.5 N, while the corresponding strength with 20% LFS-500 ranged from 70% to 88% of the reference, with the higher values presented at the mixtures of higher total binder content. The level of 28-day strength achieved was from 25 to 45 MPa, while the 7-day strength ranged from 18 to 38 MPa.

The results from testing core specimens taken from the field production of shotcrete according to the EFNARC regulations indicated that 20% or 30% LFS (LFS-100) replacement for cement (CEM I 42.5 N) does not decrease final strength more than 10% and a strength level of 25 MPa is achieved at 90 days. This is very encouraging, taking into account the very good cohesiveness of the fresh mixtures with slag and its relatively very low price.

In conclusion, it seems that the cementitious materials tested cooperate with cement in shotcrete mixtures without any problem in strength development. Their contribution to strength depends on their pozzolanic index, their fineness, and the total binder content in the mixture. According to the proportioning of concrete mixtures, a strength level from 10 to 40 MPa can be achieved with a total binder content of 340 kg/m$^3$. Consisting of 70% cement and 30% LFS, strength of 20 MPa was achieved on site by using the wet-mix process of spraying. Considering the very low price of cementitious materials which is actually their transportation cost and the environmental benefit resulting from their absorption in construction that eliminates their deposit in the ground the results of the work is of great interest for the construction.

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