



Admixture tuning for high-performance concrete for the production of novel precast pre-stressed long-span girders for highway overpasses

Paulo Fernandes¹  | Helena Pala² | Eduardo Cavaco³  | Paulo Tiago⁴ | Eduardo Júlio⁵

¹CERIS, DEC, Escola Superior de Tecnologia e Gestão do Instituto Politécnico de Leiria, Leiria, Portugal

²DEA, Escola Superior de Tecnologia e Gestão do Instituto Politécnico de Leiria, Leiria, Portugal

³CERIS, DEC, Faculdade de Ciências e Tecnologia da Universidade NOVA de Lisboa, Almada, Portugal

⁴DEC, Instituto Politécnico de Coimbra. Instituto Superior de Engenharia de Coimbra, Coimbra, Portugal

⁵CERIS, DEC, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Correspondence

Eduardo Cavaco, CERIS, DEC, Faculdade de Ciências e Tecnologia da Universidade NOVA de Lisboa, Almada, Portugal.
Email: e.cavaco@fct.unl.pt

Abstract

The improvements observed in concrete technology in the last decades, namely the production of Portland cement CEM I 52.5 R, the development of third generation super-plasticizers, and the commercialization of additions with high pozzolanic properties, turned possible the development of new concrete products using high performance concrete (HPC). Nevertheless, their implementation in the production process of the conservative precast concrete industry is not yet a reality. In this paper, the development and characterization of a HPC exhibiting high workability in the fresh state and high compressive strength in hardened state is presented. This HPC aims at producing, on a competitive basis, precast pre-stressed long-span girders for highway overpasses. For this reason, the main goal was to maximize the abovementioned properties but using the constituents available at the concrete precast company supporting the research. A set of different commercial admixtures was gathered and their influence on both compressive strength and workability of concrete was experimentally investigated. Results show that the compatibility between the admixture and the cementitious material is of paramount importance. By selecting the best type of the considered super-plasticizers and by optimizing its dosage, it was possible to increase the workability from class S1 to S5 and, simultaneously, increase the compressive strength in circa 50%, up to 120 MPa, at 28 days of age.

KEYWORDS

admixture, compressive strength, high-performance concrete, super-plasticizer, workability

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1 | INTRODUCTION

In the last 20 years, Portugal made a considerable modernization effort. A notable example of this is the highway network, originally totalizing a length of just circa 20 km, and nowadays extended to more than 2,400 km. In addition, important investments are also being devoted to the

widening of existing highways with significant volumes of traffic. This has represented a very significant market for the national precast concrete industry and a motivation to invest in innovation. Considering the improvements observed in concrete technology during the same period, namely the production of Portland cement CEM I 52.5 R, the development of third generation super-plasticizers, and the commercialization of additions with high pozzolanic properties, the authors identified the opportunity to develop new precast pre-stressed long span beams, using high-performance concrete (HPC), that can compete with steel alternatives from both the economical and structural points of view. This idea was proposed to Prégia, a Portuguese precast concrete company, that agreed in funding a project to make the proof of concept and build and test four prototypes.

The main goal of the project was to develop pre-stressed concrete beams that could be an economical alternative to steel girders on the construction of long span highway overpasses. Also, important, and since significant investments are expected to be devoted to the cross-section widening of several highways, the pre-stressed concrete beams to be developed should exhibit similar slenderness to the competing steel girders, due to minimum gabarit requirements. In particular, and considering the cross section widening from 2×2 to 2×3 carriageways, the pre-stressed elements, aimed to be produced, should have a span of 40 m and a height/span ratio of 1/40, which corresponds approximately to one third reduction in slenderness, in comparison to widely used pre-stressed concrete girders (1/30).

In view of the above, and to achieve such an ambitious purpose, it was considered to be crucial to reach high mechanical properties to significantly reduce the cross-section of the beams and thus to reduce both the production costs and the deadweight, the latter also leading to a reduction in transportation costs, as well as to increase the productivity of the company, due to the high compressive strength obtained at early ages, allowing shorter curing times. It should be highlighted that, in order to be cost-effective, the HPC mixture should be designed using current constituents, that is, available at the industrial plant where the prototypes were going to be produced. Based on the expected traffic loads, span on the height/span ratio a compressive strength higher than 100 MPa was defined as target.

Finally, and considering the reduced thickness and dimensions of the cross-section of the structural elements to be produced, the HPC should exhibit enhanced rheological properties in fresh state. A consistency class ranging from S4 to S5 was defined for the fresh mixture workability. Regard that this has obvious advantages for the precast concrete company, such as better finishing

and noise reduction, both associated with the decrease of vibration need, the latter being quite relevant in terms of labor conditions required by the workers unions.

In the present paper, the first part of the project referred to is described, aiming at setting the type and dosage of the super-plasticizer leading to an HPC with the adequate compressive strength and workability, for a reference mixture designed with the constituents available at the industrial plant.

2 | LITERATURE REVIEW

In recent years, the production in Portugal of Portland cement CEM I 52.5 R and additions with pozzolanic properties, such as silica fume, made possible the design of HPC.¹

In previous studies,² concrete mixtures with compressive strengths up to 100 MPa were designed, using river siliceous sand, granitic crushed aggregates and organic polymers or synthetic resins type super-plasticizers. However, it was experienced a major difficulty in reaching this strength assuring, simultaneously, an acceptable workability, corroborating the conclusions of other researchers.^{3,4}

In the last decade, new admixtures were developed, commonly known as “third generation super-plasticizers”, exhibiting a significant influence on the rheological properties of fresh concrete and allowing large water reductions.⁵⁻⁷ Therefore, with these new admixtures it became technically possible to produce HPC with fluid consistence in fresh state and exhibiting high compressive strengths. However, a number of studies⁸⁻¹⁰ underlines the undesirable effect of high dosages of super-plasticizer associated with low relation water/cement on fresh concrete rheology: high workability only for a short period of time. Another problem related to some super-plasticizers consists on retarding concrete hardening by restraining the hydration process, caused by a surfacing mechanism of cement particles.^{3,11} These studies emphasize the need of testing the compatibility between the binder and the super-plasticizer adopted, even in the case of materials with the same normative classification (type and class of cement and additions).

More recently, concretes exhibiting ultra-high compressive strengths, circa 150 MPa and more, have been developed.¹² Nevertheless, these comprehend a very high cement and silica fume dosage that do not lead to a real advantage, neither from a structural point of view, nor from an environmental perspective.

For the reasons previously pointed out, it was decided to focus the study herein described on the influence of the type and dosage of current super-plasticizers on the rheology in fresh state and mechanical properties of

TABLE 1 Cement chemical analysis

Item	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O
% of mass	19.04	5.28	3.51	63.39	1.76	3.36	1.10
Item	Na ₂ O	TiO ₂	P ₂ O ₅	MnO	SrO	Cl ⁻	S ²⁻
% of mass	0.11	0.27	0.04	0.05	0.08	0.01	0.03

HPC, adopting current constituents, since the main goal was to produce precast pre-stressed long-span beams for highway overpasses that could be considered a real cost-effective alternative for the traditional products in the market.

3 | MATERIALS AND METHODS

3.1 | Challenges

In straight cooperation with the precast company, the authors set the goal of producing an HPC with a compressive strength higher than 100 MPa at 28 days of age, subjected to the following two restraints¹: the HPC constituents had to be the materials currently available at the precast company facilities; and² its consistence in fresh state had to be at least S4, due to the reduced thickness of the adopted I cross-section, also aiming at both obtaining well finished surfaces and reducing the vibration need.

Preliminary tests showed that the objective could be reached but the admixture needed to be carefully selected and its dosage tuned to optimize the HPC properties. Therefore, five of the most commonly used commercial super-plasticizers were selected and, based on the Faury method, several mixtures were designed using increasing dosages of the adopted admixtures. The workability of fresh concrete was assessed by measuring its consistence with the slump test and the compressive strength of hardened concrete at 3, 7 and 28 days of age was determined using standard cubic specimens. Microscopic analysis of cement suspensions and cement plus addition suspensions, with or without admixture, was performed in order to clarify the admixture effect on the behaviour of the binder particles.

3.2 | Experimental investigation

3.2.1 | Concrete constituents

Portland cement classified as “CEM I 52.5 R”, according to EN 197-1,¹³ produced by Cimpor in Alhandra, Portugal, was adopted. The chemical composition is presented in Table 1.

A densified dry powder micro silica, commercially designated as “Sikacrete HD”, was used as pozzolanic addition. According to the manufacturers' technical data sheet, fine silicon dioxide particles (more than 90% of SiO₂) in a non-crystalline form, with a diameter of less than 1 μm, constitute this addition.

Current aggregates, from North of Portugal, were used: granitic crushed aggregates, with 17% of Los Angeles coefficient, and river siliceous sand. The characterization of the aggregates is given in Table 2.

The tested admixtures are classified as “super-plasticizers” and/or “high range water reducers” by EN 934-2.¹⁴ According to the suppliers, the admixtures are modified polycarboxylate polymers (Ad₁, Ad₂, Ad₃) or modified carboxylates ether polymers (Ad₄, Ad₅), but no further information is given, namely the polymers' structure. Other properties of these admixtures are summarized in Table 3.

3.2.2 | Concrete mixture

The concrete mixture was designed using the Faury Method,^{15,16} based on the following reference curve:

$$\begin{cases} p(d) = Y \frac{\sqrt[5]{d} - \sqrt[5]{0.0065}}{\sqrt[5]{D_{\max}/2} - \sqrt[5]{0.0065}} & \Leftrightarrow 0.0065 \leq d \leq \frac{D_{\max}}{2} \\ p(d) = Y + (100 - Y) \frac{\sqrt[5]{d} - \sqrt[5]{D_{\max}/2}}{\sqrt[5]{D_{\max}} - \sqrt[5]{D_{\max}/2}} & \Leftrightarrow \frac{D_{\max}}{2} < d \leq D_{\max} \end{cases} \quad (1)$$

with

$$Y = A_F + 17 \sqrt[5]{D_{\max}} + \frac{B_F}{0.25} \quad (2)$$

where A_F is a parameter that depends on the type of aggregates and consistence of concrete; B_F is a parameter that depends on the energy required for compacting concrete; and D_{\max} is the maximum aggregate size, given by the expression:

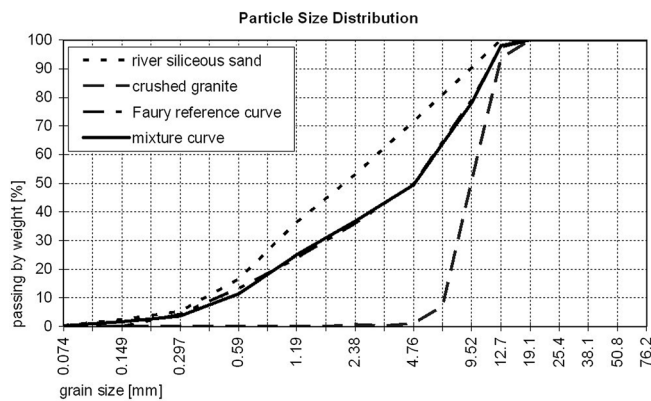
$$D_{\max} = d_1 + (d_1 - d_2) \frac{x}{y} \quad (3)$$

TABLE 2 Aggregates characterization

Aggregate	Fineness modulus	ρ (kg/dm ³)
Crushed granite	6.47	2.65
River siliceous sand	4.24	2.60

TABLE 3 Admixture characterization

Admixture	ρ (kg/dm ³)	pH	Recommended dosage rate (% in weight of binder)
Ad ₁	1.08 ± 0.02	4.3 ± 0.5	0.2–2.0
Ad ₂	1.06 ± 0.02	4.3 ± 1.0	0.4–2.0
Ad ₃	1.06 ± 0.01	5.0 ± 1.0	0.3–3.0
Ad ₄	1.02 ± 0.02	8.0 ± 0.8	1.0–1.9
Ad ₅	1.05 ± 0.02	7.0 ± 1.0	0.7–2.6

**FIGURE 1** Particle size distribution

being d_1 the dimension of the first sieve retaining aggregates; d_2 the dimension of the next sieve; x the percentage of particles retained by sieve d_1 ; and y the percentage of particles retained by sieve d_2 .

The following values were assumed¹⁵: $A_F = 32$ (for river sand, crushed coarse aggregate and fluid consistence) and $B_F = 1.5$ (for medium compacting energy).

The Faury reference curve and the adopted parameters were chosen to fulfill what was considered to be the best compromise between the compressive strength and the workability required.^{3,11} Figure 1 shows the particle size distribution of aggregates, the Faury reference curve and the adopted mixture curve.

The following relevant ratios were adopted in the concrete mixture design:

- (Water + Admixture)/(Cement + Addition) equal to 0.28;
- (Water + Admixture)/(Cement) equal to 0.31;

- (Addition)/(Cement) equal to 10%;
- (CA)/(FA) equal to 1.0;

being, CA the volume of coarse aggregates, defined as the sum of the absolute volume of the particles with dimension larger than 4.76 mm; and FA the volume of fine aggregates, defined as the sum of the absolute volume of the particles with dimension smaller than 4.76 mm.

In Table 4 are indicated the constituents ($/m^3$) of the concrete mixture adopted to serve as reference in this study. For each tested concrete mixture, the volume of admixture was deducted from the total volume of water (154 L) in order to maintain constant and equal to 0.28 the ratio (water + admixture)/(cement + addition). It is worth to mention that, considering the reduced water/binder ratio of the mixture, it is of paramount importance to control aggregates humidity in the precast plant due to the influence on both the fresh concrete workability and the hardened material's compressive strength.

3.2.3 | Characterization of concrete mixtures

To classify the workability of fresh concrete, its consistence was measured using the slump test (Figure 2a), according to EN 12350-1¹⁷ and EN 12350-2.¹⁸ This test was adopted mainly for its simplicity and because it is fast to perform.

Apart from admixture's type and dosage, the experimental conditions adopted to produce the concrete mixtures were exactly the same.¹⁹ All concrete mixtures were prepared for 20 min in a concrete mixer with 100 L capacity.

For each of the admixtures tested, successive dosage increases of 0.5% in weight of binder mass were considered, until the fresh concrete reached the S5 consistence class. The reference concrete (without admixture) has also been tested to serve as reference.

For Ad₁, four mixtures with dosages from 0.5 to 2.0% were tested. For Ad₂ to Ad₅, seven different mixtures were tested, for each one, with dosages varying from 1.0 to 3.5%.

The compressive strength of concrete was evaluated with cubic specimens (150 mm) at 3, 7 and 28 days of age (Figure 2), according to EN 12390-1,²⁰ EN12390-2²¹ and EN12390-3.²²

3.2.4 | Microscopic analysis

Suspensions were prepared considering the cement and the addition dosages given in Table 4 for the reference

TABLE 4 Proportioning of reference concrete mixture

Cement (CEM I 52.5R)	Addition (silica fume)	Aggregate 1 (crushed granite)	Aggregate 2 (river siliceous sand)	Water
500 kg	50 kg	538 kg	1,124 kg	157 L

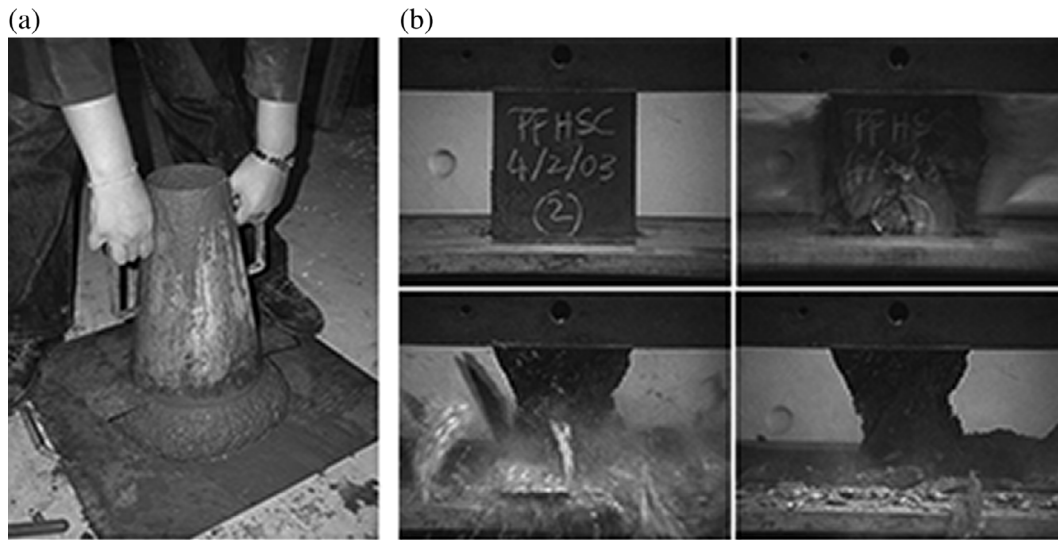


FIGURE 2 (a) Slump test (left); and (b) compressive strength test (right)

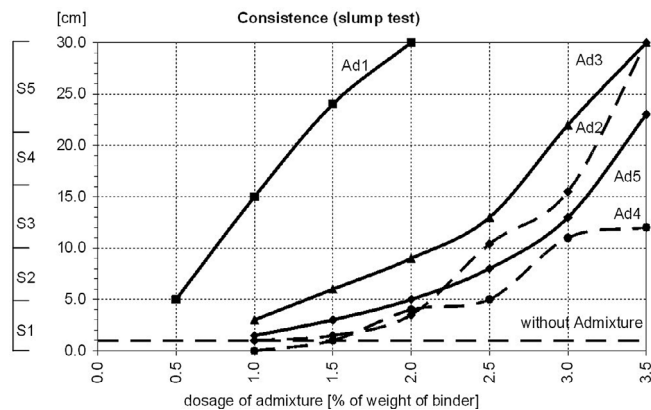


FIGURE 3 Consistence versus type and dosage of admixture

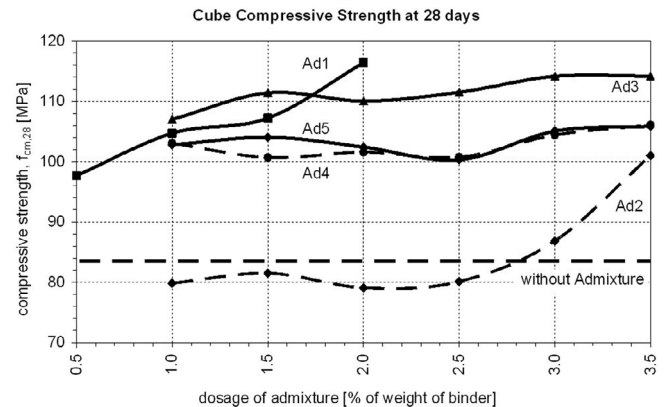


FIGURE 4 Compressive strength at 28 days of age versus type and dosage of admixture

concrete mixture. However, water addition was significantly higher in order to allow microscope observation. Three admixtures were tested (Ad₁, Ad₃ and Ad₄) with dosages 1.0, 2.0 and 3.5%. Cement or cement plus addition suspensions with no admixtures were used as control assays. These admixtures were selected according to the workability of fresh concrete mixtures (Figure 4). After preparation, the suspensions were immediately analyzed to avoid the sedimentation of the solids; the suspensions were maintained under continuous stirring. A drop of the suspensions was placed in the microscope slides and

analyzed in an optical microscope (Nikon, model Eclipse E200) equipped with a digital camera Coolpix 995. The same magnification (×10) and lightning were used throughout the work in order to obtain comparable results. Preliminary assays revealed that this magnification made focusing and image acquiring easier, providing better images.

Each sample (cement, cement + Ad_n, cement + addition, cement + addition+Ad_n) was tested twice. A set of six microscope slides was prepared and analyzed

for each suspension. Good image reproducibility was found between the results.

4 | RESULTS AND DISCUSSION

4.1 | Workability/consistence

Figure 3 shows the relationship between the slump and the type and dosage of admixture. The results demonstrate the high efficiency of Ad₁ in comparison with the remaining super-plasticizers. With only 1.0% dosage, S4 consistence class is reached. With Ad₄ this consistence is never achieved for the tested dosages. The remaining admixtures require dosages between 2.5 and 3.5% to reach a similar consistence.

In terms of workability, Ad₃ seems to be more efficient than Ad₂ and this more efficient than Ad₅.

It is significant the evolution of workability with dosage, observed with all admixtures, presenting Ad₁ an approximately linear correlation between these parameters. In opposition, Ad₃ and Ad₅ present correlations that can be considered bilinear: lower influence in slump, for low admixture dosages, and higher influence for dosages above 2.5%. Ad₂ and Ad₄ show an irregular increase of workability with admixture dosage.

The activation dosage of Ad₂ and Ad₄ for this concrete (above 2.0%) is considerably higher than the recommended minimum dosage indicated by the manufacturers of these admixtures, respectively 0.3 and 1.0%.

4.2 | Compressive strength

Figure 4 shows the results of the concrete compressive strength assessed at 28 days of age with cubic specimens, versus the type and dosage of the tested admixtures. The compressive strength of the concrete without admixture is also plotted.

Ad₁ and Ad₃ are the most efficient admixtures in terms of compressive strength. Nevertheless, different performances were exhibited: for Ad₁, with a small increase in dosage, an accentuated increase in compressive strength is observed whilst, for Ad₃, the corresponding increase is significantly lower.

With Ad₄ and Ad₅, the admixture dosage does not exhibit a significant influence on the achieved compressive strength of concrete (100–105 MPa).

The worst results were obtained with some dosages of Ad₂, presenting values of the concrete compressive strength even lower than those obtained without admixture. Nevertheless, some gain on strength was observed for dosages above 3.0%.

Apart from Ad₂, all the super-plasticizers tested have shown a positive influence on the compressive strength of concrete when compared with the result of the concrete mixture without super-plasticizer.

In Figures 5 and 6 the results of the concrete compressive strength assessed with cubic specimens at 3 and 7 days of age for increasing dosages of the admixtures tested and for the reference mixture (without admixture) are presented, respectively.

At early ages (3 days), Ad₃, Ad₄ and Ad₅ are the most efficient super-plasticizers, providing a gain of 10–20 MPa, comparatively to the compressive strength achieved without admixture. Ad₁ does not demonstrate a significant influence on concrete strength at early ages. Ad₂ exhibits a negative influence on the compressive strength at early ages, which limits the use of this admixture when a high compressive strength at early ages is required. This behaviour is explained by the restraining of the hydration process, caused by the surfacing mechanism of the cement particles, previously referred.^{3,11}

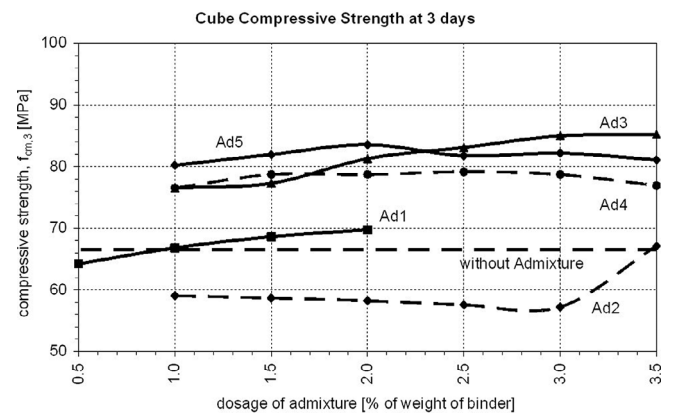


FIGURE 5 Compressive strength at 3 day versus type and dosage of admixture

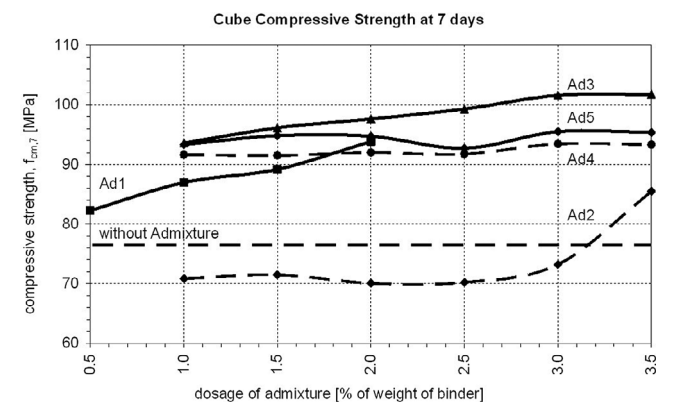


FIGURE 6 Compressive strength at 7 days versus type and dosage of admixture

Results at 7 days of age are a clear transition between those obtained at early ages (3 days) and those obtained at 28 days of age.

4.3 | Microscopic analysis

Figures 7–9 show the images obtained during the microscopic analysis of suspensions containing cement particles or cement + addition particles, with different types and/or dosages of admixtures.

It can be seen that a very good dispersion of the binder was obtained, independently of the type or dosage of the admixture used. This effect is also described in other studies^{23–25} and explained as the result of both electrostatic repulsion and steric effects caused by the admixture effective adsorption on the binder surface. It is responsible for the improvement observed in the presence of all the admixtures on the consistence/workability of the

mixtures (Figure 3) as well as on the compressive strength of concrete in hardened state at 28 days of age (Figure 5). In fact, this intensive dispersant effect allows both an extreme water reduction in the mixtures, without reducing its workability in fresh state, and a better arrangement of concrete constituents during concrete hardening, thus contributing to a better internal cohesion of the material and consequently higher compressive strength.^{26,27}

It is also known that the chemical nature of the admixture influences mostly the effect of dispersion and the chemical hydration of the binder.^{23–25} This might explain the different development in workability and compressive strength observed with the admixture's type and dosage. In general, the relative importance of electrostatic and steric effects in particle-particle repulsion depends on the composition, molecular structure (main backbone and side chains), and molecular weight of the polymer, whereas the chemical phenomena resulting from the interaction between the admixture and the

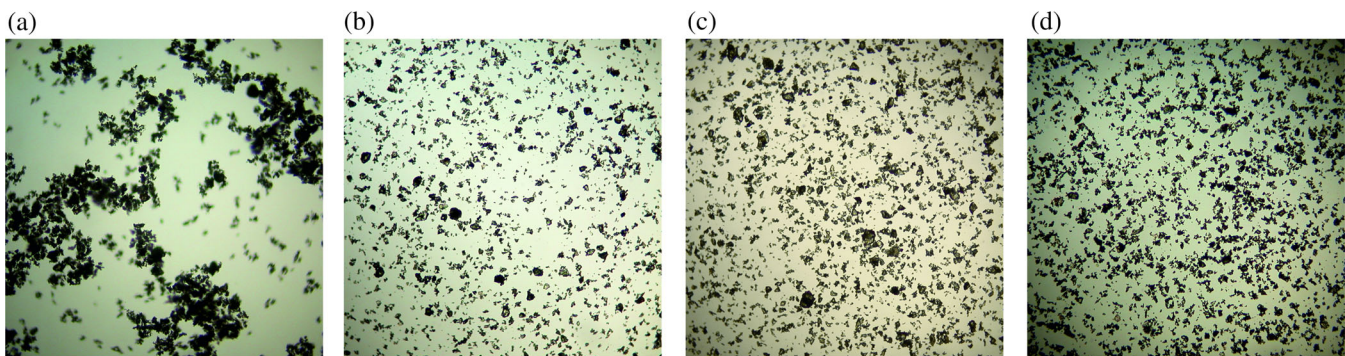


FIGURE 7 Microscopic analysis of suspensions containing Cement particles and: (a) no admixture, (b) 3.5% Ad₁, (c) 3.5% Ad₃, (d) 3.5% Ad₄

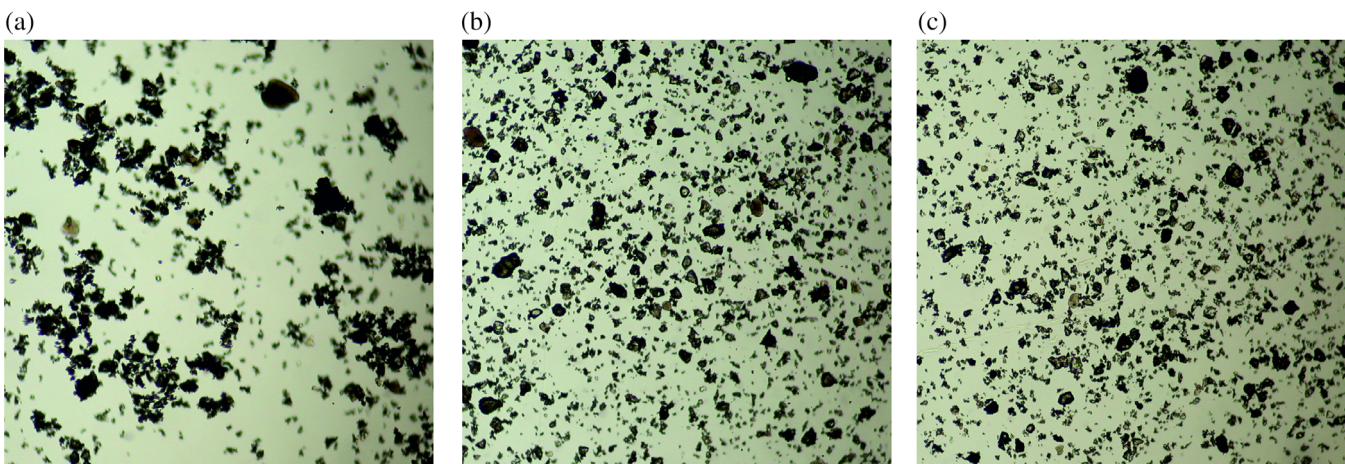


FIGURE 8 Microscopic analysis of suspensions containing Cement particles + Addition and: (a) no admixture, (b) 3.5% Ad₁, (c) 3.5% Ad₄

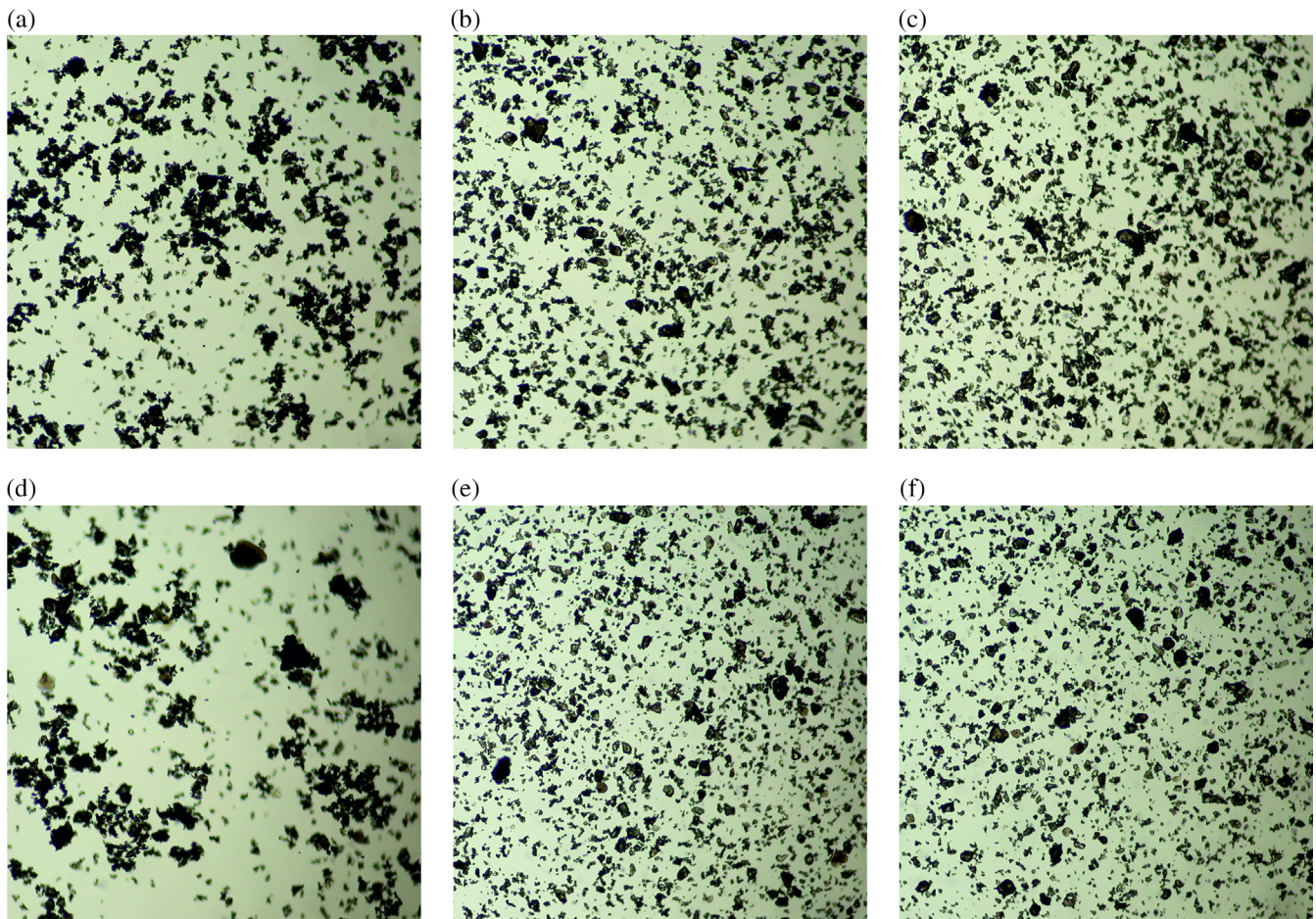


FIGURE 9 Microscopic analysis of suspensions containing: Cement particles and (a) no admixture, (b) 1% Ad₁, (c) 3.5% Ad₁; Cement particles + Addition and (d) no admixture, (e) 1% Ad₁, (f) 3.5% Ad₁

binder lead to different hydration rates thus contributing (Ad₁, Ad₃ – Ad₅) or not (Ad₂) to an accelerated strength development and to an excellent compressive strength at early ages and later.

Since, in this study, commercial admixtures were tested, and given that these are supplied without detailed information on their nature, further interpretation of the obtained results cannot be performed.

5 | CONCLUSIONS AND PROPOSED FUTURE DEVELOPMENTS

Aiming at developing an HPC with the adequate compressive strength and workability to produce an innovative precast prestressed beam for highway overpasses, the research study herein described was conducted. The goal of the latter was to select the type and dosage of the super-plasticizer that maximizes both the compressive strength and the workability on fresh state of a reference

concrete mixture, designed using the constituents available at the industrial facilities of the precast concrete company leading this project.

From the results analysis, it is possible to draw the following conclusions:

1. The compatibility between the selected admixture and the cement type is of utmost relevance;
2. Microscopic analysis of suspensions containing both the cementitious material and the admixture showed that the surface properties of the cement particles are modified due to the presence of the admixture thus allowing a better dispersion of the particles and consequently a better arrangement of the concrete constituents during hardening;
3. The type and dosage of *third generation super-plasticizers* have a significant influence on both the workability of fresh concrete and the compressive strength of hardened concrete;
4. By optimizing the type and dosage of the tested “new generation super-plasticizers” it was possible to

design, for the adopted constituents, an HPC with approximately 120 MPa compressive strength at 28 days of age and S5 consistence class; it should be mentioned that the corresponding values of the reference mixture (without admixture) were, respectively, 80 MPa and S1;

5. For concrete mixtures, such as the one adopted in the present study, with low water/binder ratio (0.28), the minimum dosage recommended by some of the admixtures manufacturers is beneath the corresponding activation value;
6. When, as in the case of pre-stressed elements, the concrete compressive strength at early ages is most relevant, the type and dosage of the admixture must be carefully selected avoiding the negative effect of some super-plasticizers of delaying concrete hardening, by retarding the hydration process; it should be noted that, in this study, the most efficient admixture in terms of compressive strength at 28 days of age (Ad_1) was not the most efficient at early ages (Ad_3).

The dispersion effect resulting from the adsorption of the admixture on the surface of the binder does not explain, alone, the influence of the different admixtures on the properties of concrete in fresh and hardened states; therefore, it is proposed to conduct a more in depth study on the chemical nature of the admixtures in order to fully explain the physical/chemical interaction between these polymers and the mixtures' constituents.

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ORCID

Paulo Fernandes  <https://orcid.org/0000-0002-5644-8889>

Eduardo Cavaco  <https://orcid.org/0000-0001-6413-4217>

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AUTHOR BIOGRAPHIES



Paulo Fernandes,
CERIS, DEC, Escola Superior de
Tecnologia e Gestão do Instituto
Politécnico de Leiria, Leiria,
Portugal



Helena Pala,
DEA, Escola Superior de Tecnologia
e Gestão do Instituto Politécnico de
Leiria, Leiria, Portugal



Eduardo Cavaco,
CERIS, DEC, Faculdade de Ciências
e Tecnologia da Universidade
NOVA de Lisboa, Almada, Portugal



P. Tiago,
DEC, Instituto Politécnico de
Coimbra. Instituto Superior de
Engenharia de Coimbra, Coimbra,
Portugal



Eduardo Júlio,
CERIS, DEC, Instituto Superior
Técnico, Universidade de Lisboa,
Lisboa, Portugal

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