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High-Performance Concrete Using Fly Ash

by A. Camões, P. Rocha, S. Jalali, B. de Aguiar, and R. Delgado

Synopsis: Some of the most recent developments related to the production of concrete have focused on the addition of components which can improve the mechanical, wokability and durability properties of concrete and whenever possible, to solve environmental problems in a simple and economical way. This is research work fits in this field, trying to contribute to the clearing up of the advantages and disadvantages of concrete production with the addition of fly ash (FA).

High-performance concrete (HPC) is usually produced using high quality materials. These constituents drastically increase the initial cost of HPC, thus hindering its more widespread usage. This research work intends to investigate the possibility of producing low cost enhanced performance concrete or even low cost HPC, with 90 day strengths in the range of up to 60 MPa, using low quality fly ash and locally available crushed aggregates.

The effect of the amount of fly ash was evaluated using 0, 20%, 40% and 60% cement replacement with different quantities of total binder of 400 kg/m^3, 500 kg/m^3 and 600 kg/m^3. Workability, mechanical and durability properties were also studied.

The results obtained indicate that it is possible to, produce HPC with up to 60 MPa by replacing up to 40% of cement by fly ash and using local available crushed granite aggregates. Furthermore, it was observed that the workability and the durability, as measured by the chloride-ion diffusion coefficient, increased drastically when fly ash partially replaced Portland cement.

Based on the results obtained, it is possible to conclude that the use of fly ash in concrete is beneficial in terms of the workability and durability properties but was some disadvantages because early strengths are reduced.

Keywords: compressive strength; durability; fly ash; HPC; low cost; workability

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INTRODUCTION

The use and range of applications of high performance concrete (HPC) have increased in the last few years. The growth of this material's usage is due to recent developments in admixtures and additions, namely superplasticizers (SP) and supplementary cementitious materials.

HPC is usually produced using silica fume, high quality fly ash and carefully chosen aggregates. These constituents drastically increase the initial cost of HPC, hence hindering its more widespread usage. In many countries the cost of silica fume is several times the cost of normal Portland cement (NPC). In Portugal, for example, the silica fume is ten times more expensive than NPC and a 10% addition of silica fume would mean doubling the price of the cementitious material. Thus, this research work has focused on the possibility of using locally available fly ash and other aggregates in the production of low cost enhanced performance concrete and low cost HPC.

In order to achieve the aims of the research work, an experimental program was performed which included tests to evaluate the mechanical, workability and durability properties of the proposed concretes. The effect of the amount of cement replacement by mass was evaluated using 0, 20%, 40% and 60% C replacement with different quantities of total binder of 400, 500 and 600 kg/m^3.

The mechanical properties studied were uniaxial compression strength and splitting-tensile strength. Further, three-point bend beam tests were also performed using a closed-loop servocontrolled compression-testing machine. Workability of fresh concrete and binder pastes were evaluated through slump and flow tests for the different mixes studied. The durability of the concretes produced was estimated through capillary water absorption, total open porosity by immersion and apparent coefficient of diffusion using non-steady state chloride migration tests.

MATERIALS AND MIXTURE PORPORTIONS

All aggregates used in the mixes were locally available crushed granite from de same quarry. It is noted that two different crushed sands (D_{max} = 2.38 mm and D_{max} = 4.76 mm) and a crushed coarse aggregate (D_{max} = 9.53 mm) were used as received, this is, without any previous treatment such as washing. The used cement was a normal Portland cement of the Type I, class 42.5R. The used FA was of class F, according to ASTM standards, and was produced by the Portuguese Thermoelectric Power Plant of Pego, with quantities of loss on ignition (LOI) varying between 6% and 9%. The LOI value is more than the maximum allowed by the European Standard EN450 (1) and the ASTM C618 (2), which limit LOI to 5% and 6% respectively. The European norm admits a maximum limit of 7% at national level provided local regulation and arrangements exist. The superplasticizer (SP) used was a naphthalene sulphonate formaldehyde condensates. The quantities of SP used in the mixes were calculated using the results of several tests in pastes and mortars, where it is possible to identify the saturation point (optimum SP solid content dosage) between the values of 0.5% to 1.0% of the binder weight (3). For economical reasons, the value of the SP adopted in this research work was 0.5% by weight of cement.

For more detail of the main characteristics of these materials please refer to references (3-5).

Twelve different kinds of mix proportions were used corresponding to three doses of binder (B = C + FA). The quantities of the binder were fixed at 400, 500 and 600 kg/m^3 and the corresponding water/binder ratio (W/B) at 0.4, 0.3 and 0.25. The amount of the aggregates was estimated using the Faury method (6). The mix design of the studied concretes is presented in Table 1.

The abbreviation mnemonic used has the following meaning: the first number refers to the amount of binder and the number that follows FA represents the percentage of cement replaced by FA.

Cubic (100x100x100 mm^3) and cylindrical (150 mm diameter and 300 mm height) specimens were moulded in order to evaluate the compressive strength gain of the mixes. The splitting-tensile strength was evaluated using cylindrical specimens of 150 mm diameter and approximately 96.5 mm height. The flexural behaviour was assessed using 850x100x100 mm^3 prisms specimens at a span of 800 mm. As far as the evaluation of this aspect is concerned further test results and analysis are presented in reference (7).

The curing of the specimens was done in a wet chamber at a temperature of 21°C and an 80% RH. One day after the moulding, the specimens were removed from the metallic moulds and immersed into water, where they remained until the day of the tests. One end of the cylindrical specimens used for determining the compressive strength was prepared with a sulphur-capping compound. The compressive strength of this compound was tested according to ASTM C617 (8) using a 2-inch cube, having obtained a result in excess of 55 MPa after 2 hours. Other cylinders were divided into three parts with similar dimensions in order to be tested for splitting-tensile strength. The samples used in the durability tests were obtained from the half prisms obtained from the flexural test with approximately 100x100x422.5 mm^3. For each composition six specimens were prepared by wet cutting with the approximate measures of 100x100x50 mm^3. These samples were used for the non-steady state chloride migration test. Three nominally identical cubic specimens with a 100 mm edge were used for the water absorption tests by immersion and capillarity.

PROPERTIES OF FRESH CONCRETE

The workability of the concrete mixtures was determined using the slump test (9) and by the use of the flow table test (10).

In Figs. 1 and 2, the variation of the slump and the flow with the percentage of the FA is presented. The slump and flow classes are also illustrated in accordance ENV206 (11). The results presented are the average values obtained for different mixes.

An analysis of these figures shows that:

- The enclosure of FA considerably improves the workability of the concrete allowing, even, a change of concretes slump class S1 to S4, or from the class F1 to F4 in flow table test;
- The favourable effect of FA is hardly noticeable in mixes with 400 kg/m^3 binder. This feature can be justified by the higher W/B ratio present in such concrete;
- The favourable action of the FA is less significant in mixes with percentage of FA higher than 40%. An explanation for this fact can be found in higher % of FA water demand, which negatively influences the workability opposing the beneficial effect caused by the spherical shape;
- The differences in the consistency of the mixes with 500 and 600 kg/m^3 binder can be considered minor;

- The simultaneous effects of the W/B and the reduction of the amount of binder are more relevant in the improvement of the workability properties up to 20% of FA content. The consistency of the mixes with 40% and 60% substitution by FA is almost independent of the W/B ratio and the corresponding amount of binder.

MECHANICAL PROPERTIES

Compressive Strength

The effect of the addition of FA on compressive strength was evaluated using tests performed by a closed-loop servo controlled compression-testing machine and using a 5 mm field LVDT with a 0.09% precision. The displacement velocity was of 0.36 mm/min.

The evolution of concrete compressive strength with time with a binder content of 500 kg/m^3 and 600 kg/m^3, used cylinders of ϕ150x300 mm^3, and results are presented in Figs.3 and 4. The curves correspond to the application of a numerical model, which predicts the compressive strength with time, proposed by Jalali (12).

The results shown on Figs. 3 and 4 allow the following conclusions:

- Concretes with higher percentage of NPC replacement by FA indicate a smaller rate of strength gain at early ages;
- The percentage FA up to 40% positively influences compressive strength at long curing times, i.e. at about 150 to 200 days;
- Mixes with 60% FA present a significant reduction in strength compared to other mixes, however, in global terms, they achieve values of compressive strength in the range of 60 MPa, given the reduced amount of cement used (200 kg/m^3 in the 500FA60);
- At 90 days, it is possible to produce concretes with FA content up to 40% and with compressive strength measured in ϕ150x300 mm^3 cylindrical specimens in the range of 55 MPa (500 kg/m^3 binder) and 60 MPa (600 kg/m^3 binder).

The above-mentioned conclusions are also valid for results obtained on 100 mm cubic specimens. It is also possible to confirm that the compressive strength on cylinders is about 80% of the results obtained on cubes.

Modulus of Elasticity

The modulus of elasticity in compression (E_c) for the different concrete mixtures was estimated by the compressive strength tests on ϕ150x300 mm^3 cylindrical specimens. A LVDT with 5 mm field and 0.05% of precision was placed in the central area of the sample to register the variation in length of a 60 mm distance. Figs. 5 and 6 present the increase of E_c with curing time for the different mixtures. Each curve represents the average value (E_{cm}) determined on two samples.

An analysis of Figs. 5 and 6 yields the following conclusions:

- The mixtures made without FA present a marginal variation in E_{cm} before the age of 56 days;
- At an age of about 425 days the E_{cm} is similar for all mixtures (approximately 32 GPa for 500 kg/m^3 binder and around 36 GPa for 600 kg/m^3 binder), except for the mixtures 500FA40 and 600FA20, which comparatively present higher values than the expected;
- Despite tending to the same value, the E_{cm} development with time decreased as the FA content increased;
- For a 20% increase of the binder, from 500 to 600 kg/m^3, corresponds to an increase of approx 14% in the E_{cm} at 425 days.

The E_c of the concrete is controlled by the modulus of elasticity of its components, that is, of the hydrated binder paste and of the aggregates. The E_c of concrete can be estimated from empirical expressions related to the compressive strength of the concrete. Such is justifiable on the basis of the influence of the modulus of hydrated binder paste, which depends mainly on the capillary porosity of the paste. In a similar way the capillary porosity influences the compressive strength of the paste (13). In this context, Figs. 7 and 8 show the possible relations between the average compressive strengths, determined in concrete cylinders, f_{cm}, and their E_{cm}. These Figs. also present the curves which result from the application of the suggested expressions by the ACI 363 committee (14), by CEB-FIP (13) and by the Portuguese code REBAP (15). The relationship proposed by the ACI committee 363 is restricted to concretes with compressive strength between 21 MPa and 83 MPa; the CEB-FIP formula is applicable whatever the f_{cm} of the concretes may be and REBAP is applicable for concretes up to 50 MPa characteristic compressive strength (to which correspond a f_{cm} of approximately 58 MPa).

The results show that the values of E_{cm} are in general lower than those obtained by the application of the codes. So for the mixes studied the applicability of the proposed expressions whether by ACI 363, by CEB-FIP or by REBAP, underestimates the E_{cm} value. The equation that comes closer to the experimental results is the one by the ACI 363. However, the CEB-FIP suggests the adoption of a coefficient, which translates the influence of the type of

- The favourable result of increasing the binder quantity becomes unimportant for mixes with 500 kg/m^3 or more. This is even more obvious in compositions without FA.

Water Absorption Tests by Immersion and by Capillarity

The capillary water absorption tests followed the LNEC specification E393 (17), which is based on the RILEM CPC11.2 draft recommendation. This test consists of registering the increase in mass of a specimen at given intervals of time when permitted to absorb water by capillary suction. The specimen is usually placed on saturated sand or is in contact with water along one surface. The values of the coefficient of capillarity absorption, S_{ca}, shown in Figs 13 and 14, correspond to the slope of the curves representing the water absorbed by unit area versus square root of time, during the initial four hours of testing (18).

The results presented in Figs 13 and 14 show that:

- The addition of FA causes a reduction in S_{ca};
- An increase in the quantity of binder, in conjunction with the reduction of W/B ratio, leads to a decrease in S_{ca}, particularly in mixes with up to 500 kg/m^3 of binder;
- The S_{ca} does not seem to change significantly when binder content is increased from 500 to 600 kg/m^3.

Water absorption by immersion tests according to LNEC specification E394 (19), based on the RILEM CPC 11.1 recommendation, were also performed and led to identical conclusions.

CONCLUSIONS

For the Type of concrete mixtures studied, the mixture containing 500 kg/m^3 of binder revealed better potential for usage as HPC, as they presented an important gain in performance compared to mixes with 400 kg/m^3 of binder and small difference with mixture with 600 kg/m^3 of binder.

Generally speaking at long curing times, mixtures with FA contents up to 40% seem to improve all the properties studied in this research work. Thus, considering the economic factor, the 40% FA mixture indicate a better performance.

Adding 60% FA renders concrete with considerably lower mechanical characteristics, in comparison with other mixes studied here. However, given the low quantities of cement these mixtures demonstrate good economic performance.

When evaluating the durability of concrete through the chloride ion diffusion coefficient, the coefficient of capillary absorption and the water absorption by immersion, the addition of FA is beneficial, leading to more durable concrete. This effect is particularly noticeable with a substantial decrease in the chloride-ion diffusion coefficient, indicating its special aptitude for environments that promote degradation of reinforced concrete due to chloride ion penetration.

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Table 1 – Concrete mix proportions

Concrete	W/B	C kg/m^3	FA kg/m^3	Sand 1 kg/m^3	Sand 2 kg/m^3	Coarse aggregate kg/m^3
400FA0	0.4	400	0	613.56	233.55	857.45
400FA20	0.4	320	80	591.96	262.38	878.58
400FA40	0.4	240	160	552.99	284.75	875.65
400FA60	0.4	160	240	503.44	300.96	855.01
500FA0	0.3	500	0	502.92	308.43	865.61
500FA20	0.3	400	100	461.85	334.01	869.82
500FA40	0.3	300	200	406.91	349.01	847.11
500FA60	0.3	200	300	364.24	373.70	848.70
600FA0	0.25	600	0	377.30	367.85	850.73
600FA20	0.25	480	120	326.57	399.51	856.01
600FA40	0.25	360	240	271.28	407.93	832.76
600FA60	0.25	240	360	223.26	421.23	824.23

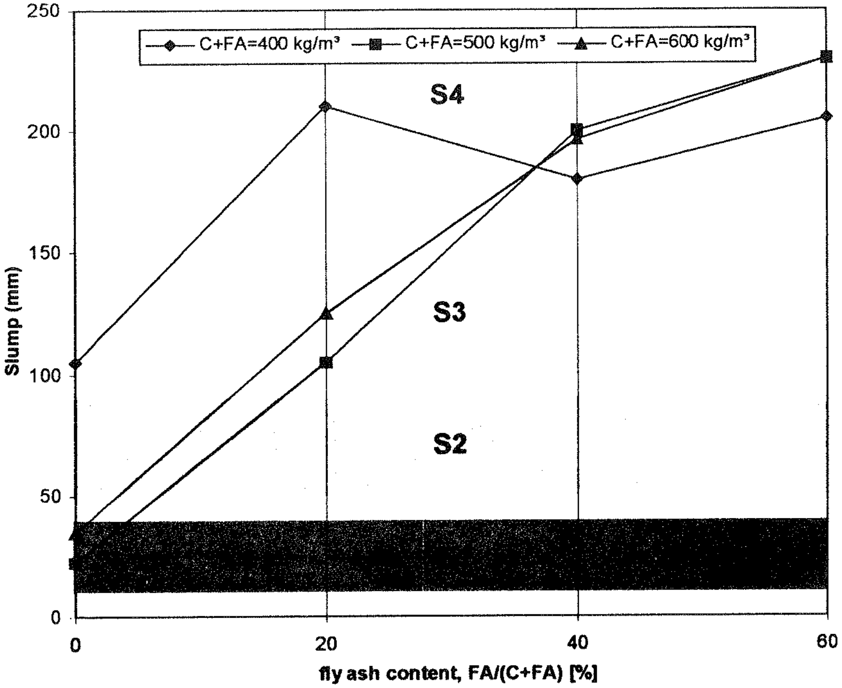


Fig. 1 – Slump versus fly ash content.

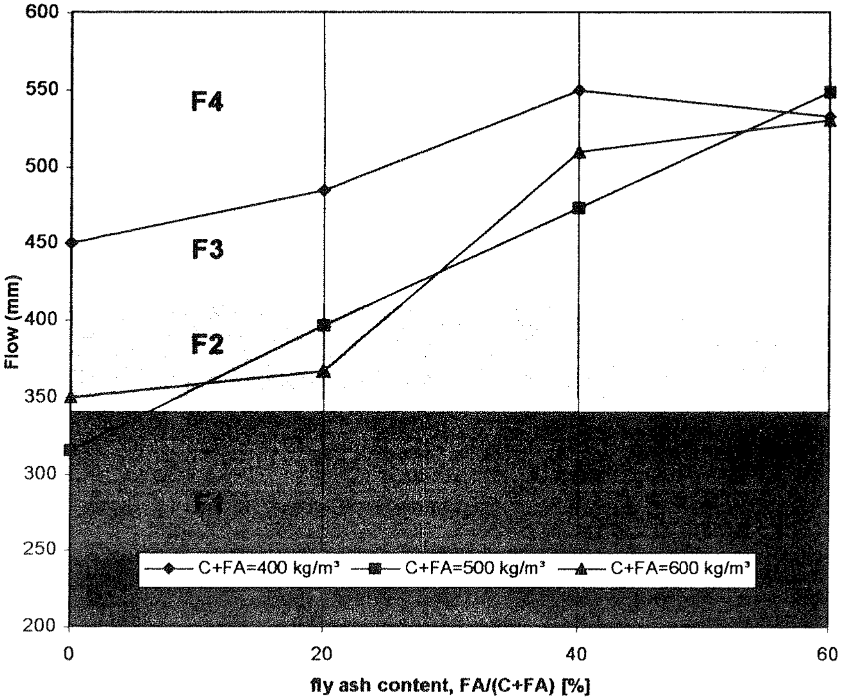


Fig. 2 – Flow versus fly ash content.

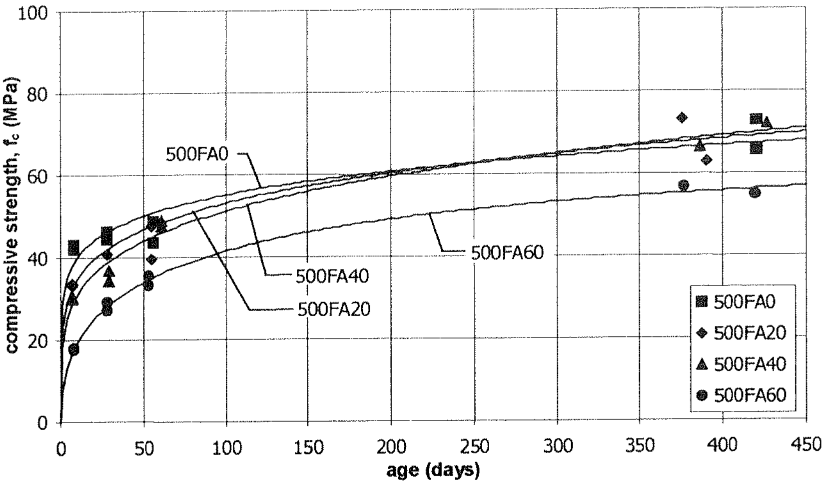


Fig. 3 – Compressive strength development with time (B=500 kg/m^3).

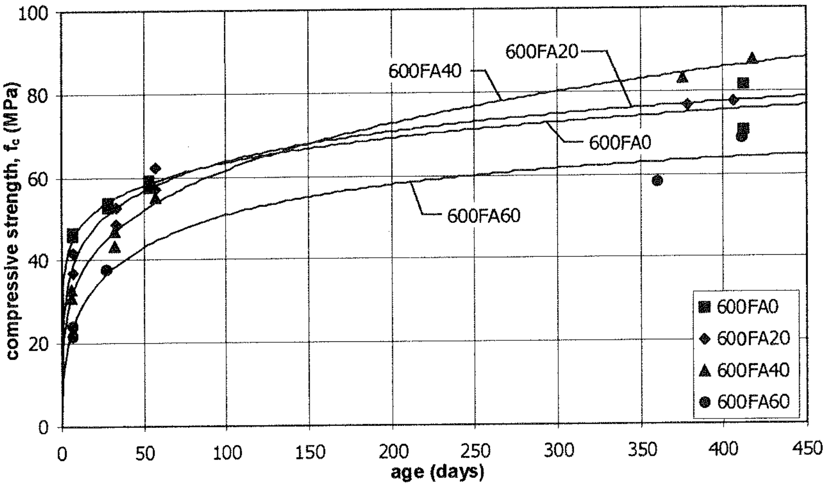


Fig. 4 – Compressive strength development with time (B=600 kg/m^3).

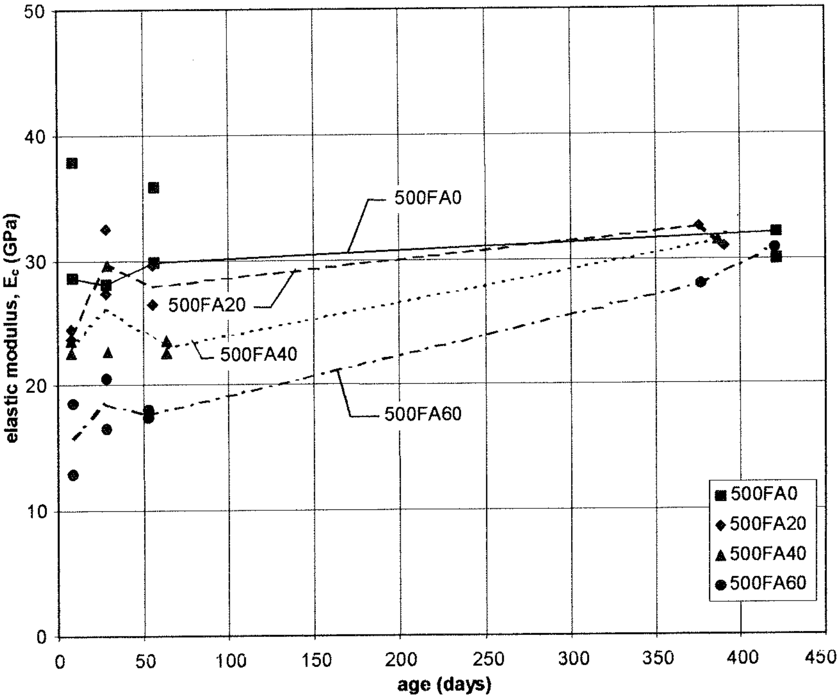


Fig. 5 – Elastic modulus development with time (B=500 kg/m^3).

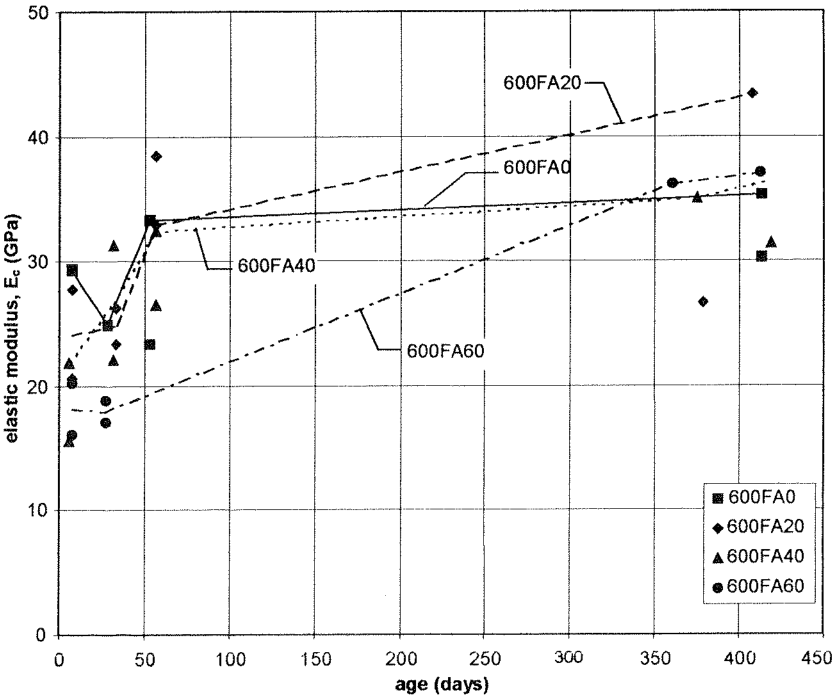


Fig. 6 – Elastic modulus development with time (B=600 kg/m^3).

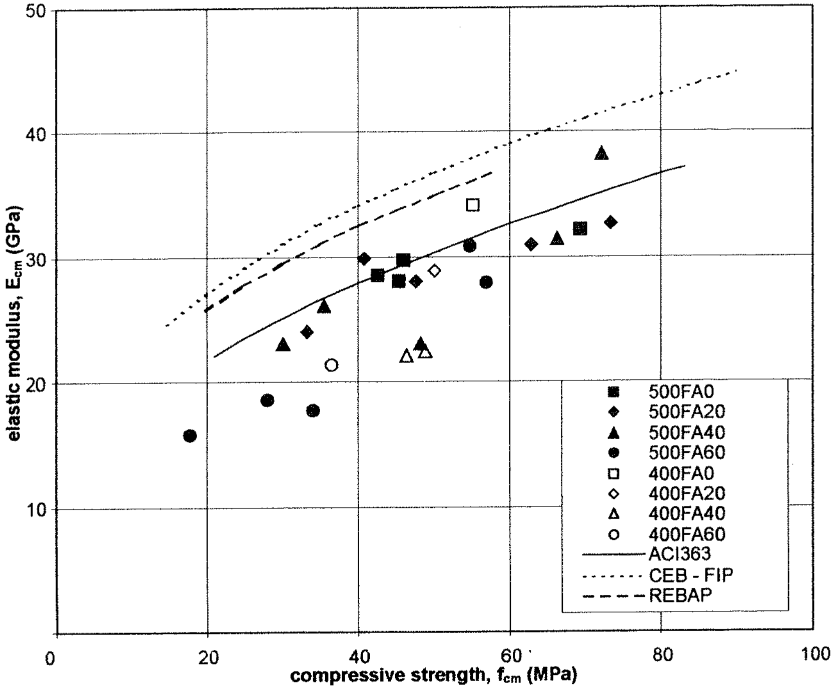


Fig. 7 – Relation between compressive strength and elastic modulus ($B = 400$ kg/m^3 and $B = 500$ kg/m^3).

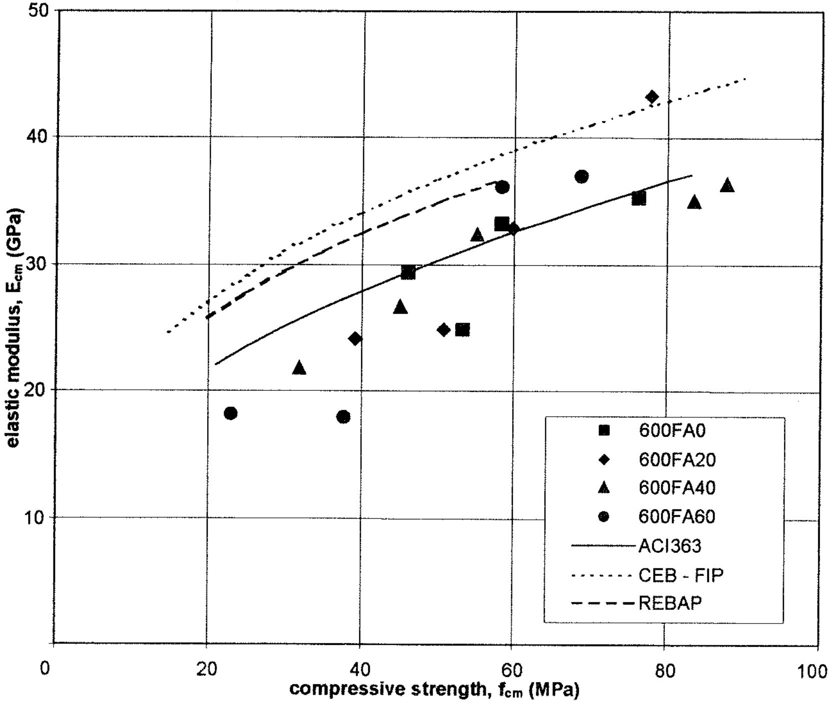


Fig. 8 – Relation between compressive strength and elastic modulus ($B = 600$ kg/m^3).

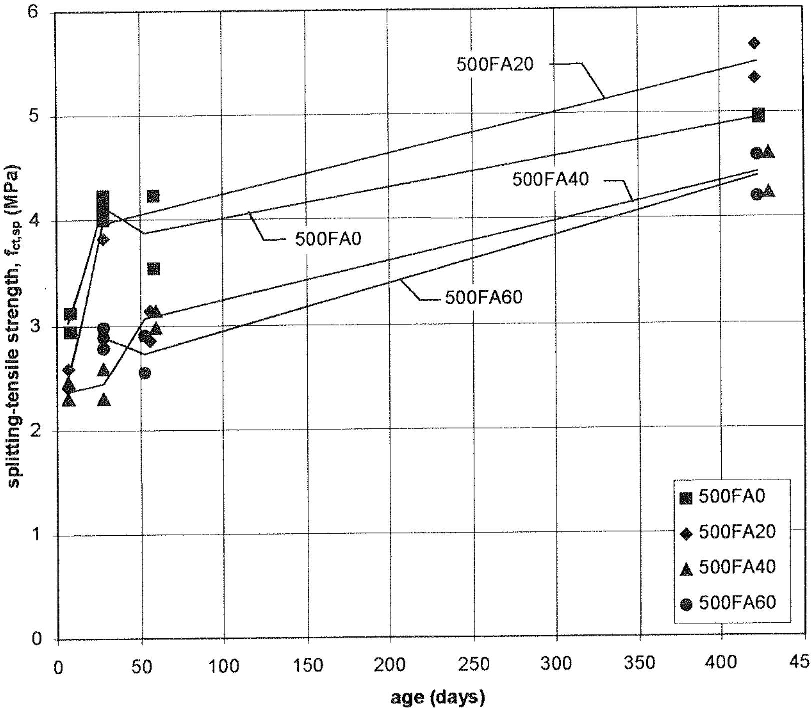


Fig. 9 – Development of splitting-tensile strength with time (B = 500 kg/m^3).

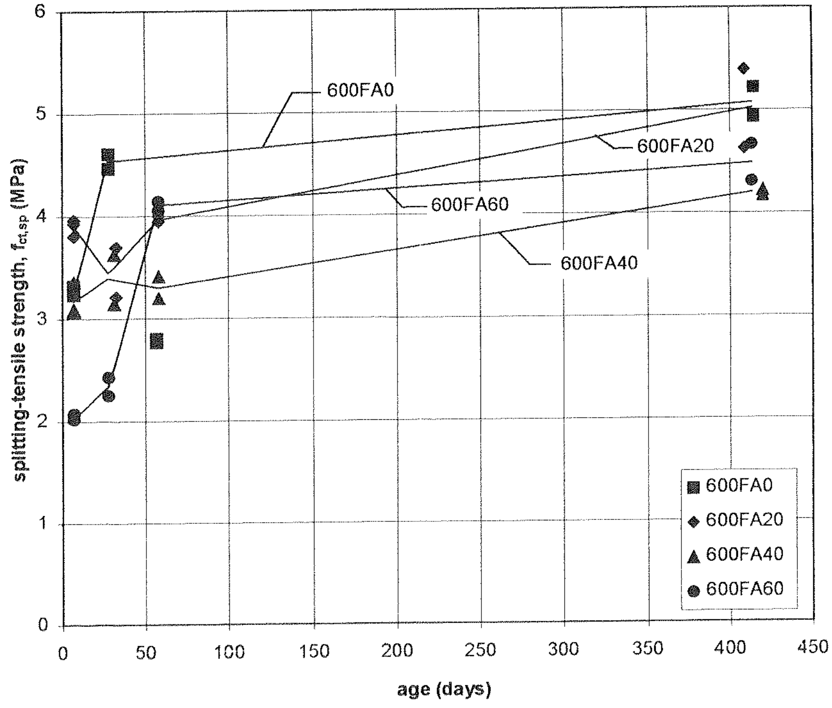


Fig. 10 – Development of splitting-tensile strength with time (B = 600 kg/m^3).

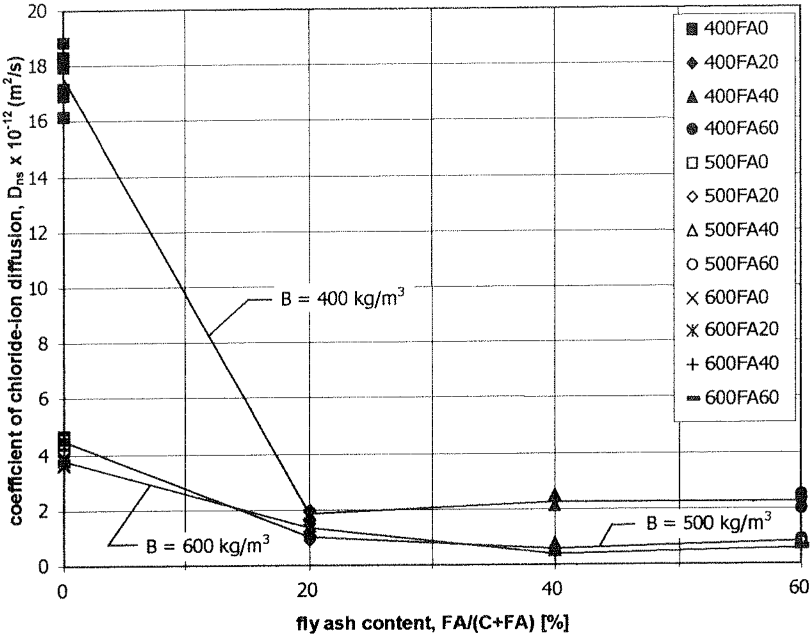


Fig. 11 – Relation between coefficient of chloride-ion diffusion and fly ash content.

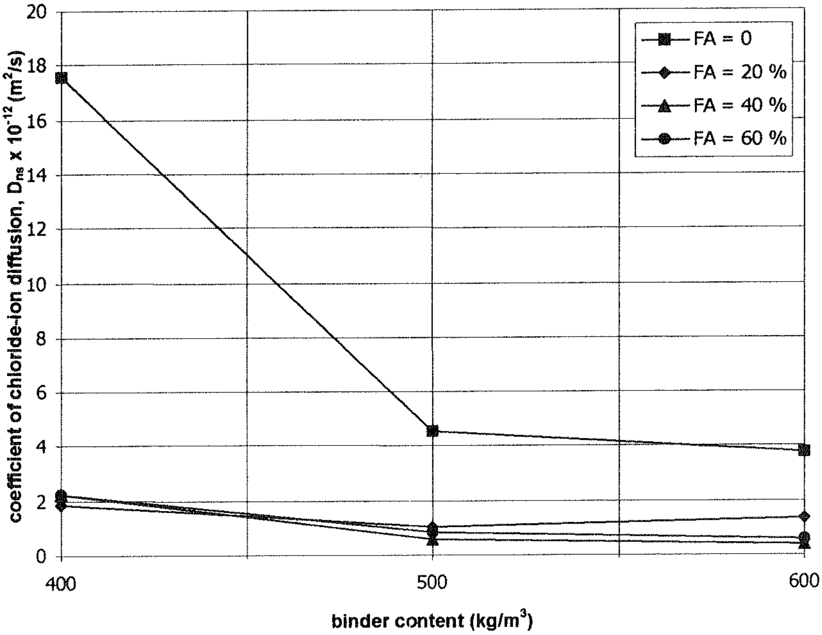


Fig. 12 – Relation between coefficient of chloride-ion diffusion and binder content.

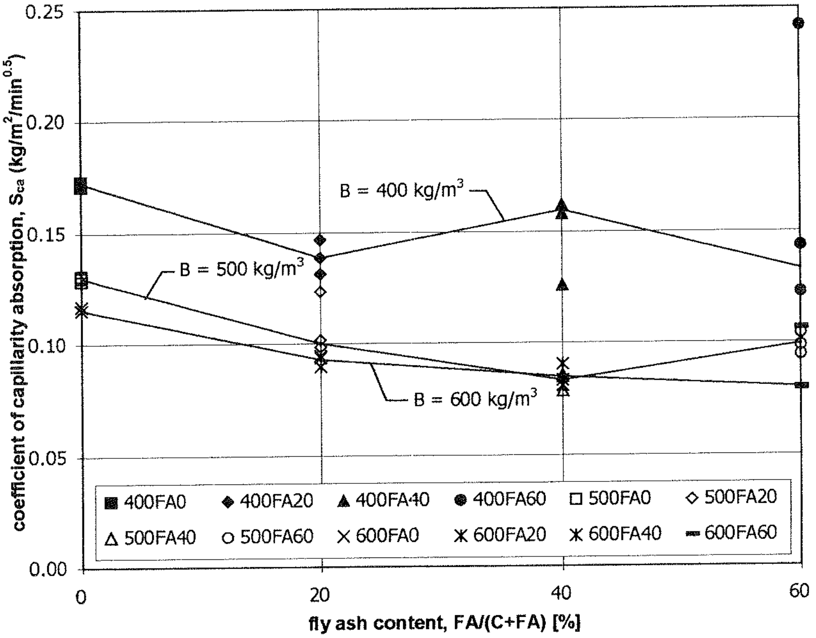


Fig. 13 – Relation between coefficient of capillarity absorption and fly ash content.

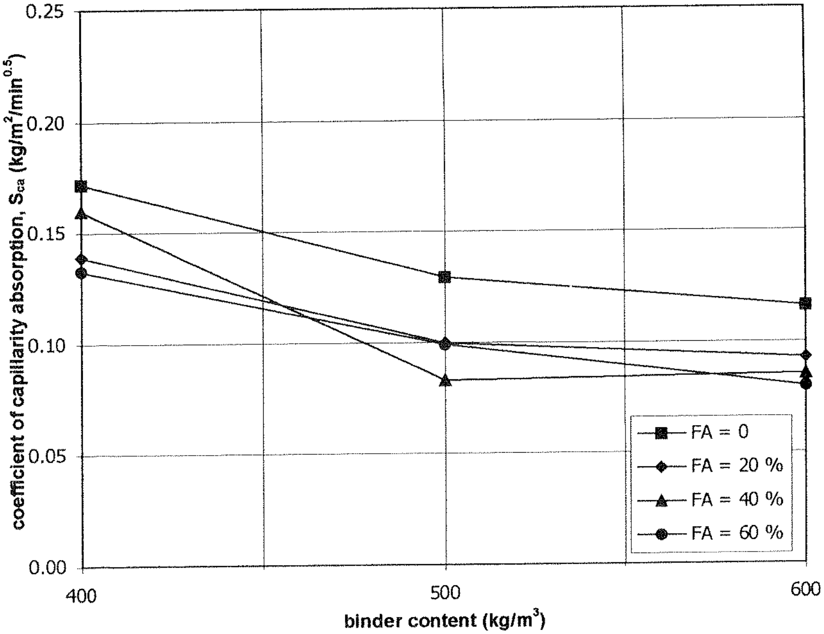
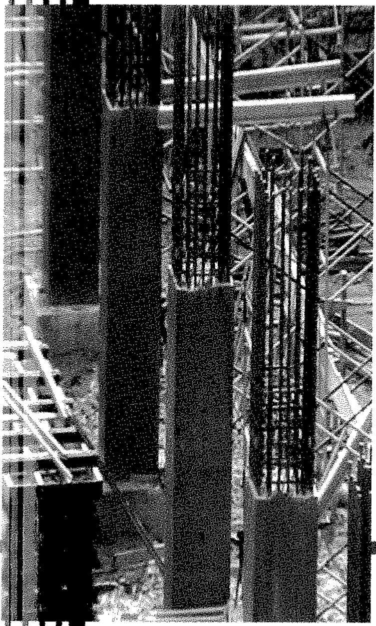


Fig. 14 – Relation between coefficient of capillarity absorption and binder content.

High-Performance Concrete

Performance and Quality of Concrete Structures



Proceedings
Third International Conference
Recife, PE, Brazil, 2002

Editors:
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Armando Carneiro

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SP-207

PREFACE

The first conference on the subject of High-Performance Concrete (HPC), and Performance and Quality of Concrete Structures was held in Florianopolis, Brazil in 1996 as a result of the initiative of Prof. Luiz Roberto Prudêncio and Prof. Paulo Helene of Brazil, supported by Dr. Mohan Malhotra and Prof. Kumar Metha from Canada and the U.S.A., respectively. The second conference on this subject was held in Gramado, Brazil in 1999, organized by Prof. Denise dal Molin, with more than 350 participants worldwide. The success of these International Conferences is recognized by the ABCP-Brazilian Cement Industry Association (IBRACON), Brazilian Concrete Institute, and the academic and professional communities. A significant number of the participants in the HPC conferences were young researchers. Conferences are really contributing to the best engineering and holistic vision of Brazil's concrete professionals for tomorrow.

Brazil has a huge experience in concrete structures design and construction since the beginning of the 1900s. In spite of this experience of more than 90 years, there have been few opportunities to show and to share this experience with ACI and other important worldwide organizations.

The Guinle Building, a 7-floor concrete office tower (28-m high) was inaugurated in 1916 in São Paulo, and is still functional. In 1929, the Martinelli concrete tower (106-m high), reached the world record in high-rise buildings, and is still in good condition. Also, in Rio de Janeiro, the Night Building was one of the highest concrete buildings in the world for many years.

In addition, many other concrete structures, like Itaipu Dam (largest in the world) and 13-km large Rio-Niteroi Bridge, are important concrete structures. Since the 1980s, new concrete structures using high-performance concrete have been built. In 1997, the highest concrete building in Brazil, 180-m high United Nations Towers, used 30,000 m^3 of high-strength concrete (HSC) with $f'_c = 50$ MPa. This year the e-Tower Building with HSC $f'_c = 125$ MPa in columns is a new record in the world.

To make sure of the safety of the above developments, major research projects were undertaken in the Brazilian universities, and important exchanges of information with well-known researchers and institutions in the world was necessary. The Third Conference demonstrates the significance of these exchanges. More than 90 papers were received and 30 were accepted by the ACI review panel for publication in the ACI Special Publication, SP-207, as the proceedings of this conference. The Organizing Committee decided to publish many of those submissions that could not be included in the Special Publication as supplementary papers. In addition to the papers that have been published in the proceedings and supplementary volume, a number of other papers were also presented in the Conference.

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