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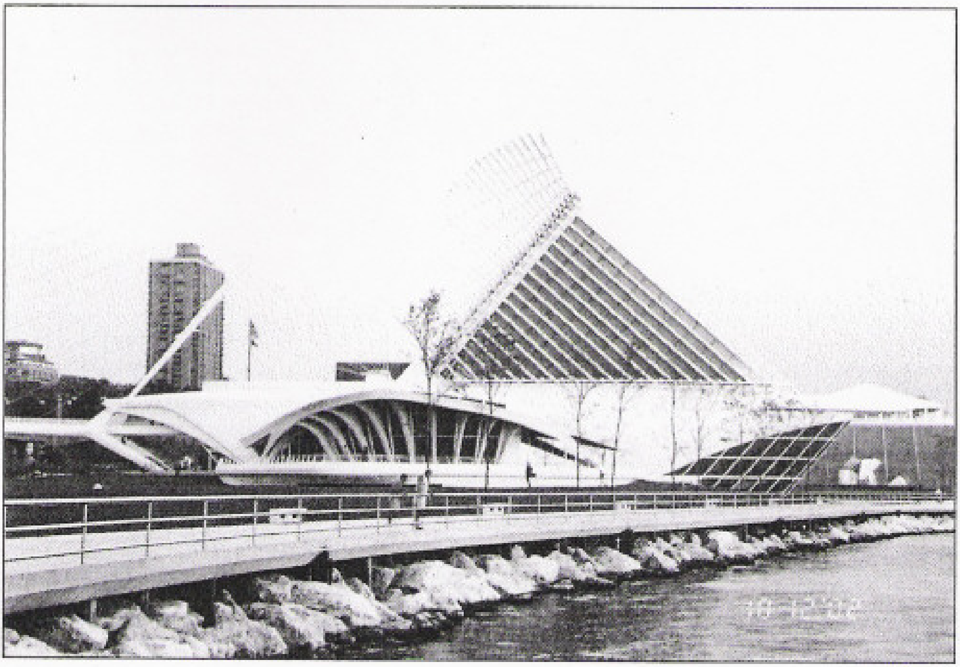
Supplementary Papers



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Pavan Gupta and Prabha Gupta

Mechanical Properties of High-Performance Concrete with Fly Ash

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

Synopsis: High-performance concrete is generally produced using carefully selected high quality materials. These materials increase significantly the initial cost, hence, limiting its use. In this research work, the performance of concrete was enhanced through incorporating low cost untreated material like fly ash and crushed aggregates. Thus, it can be produced enhanced or even high-performance low cost concrete and, also, decrease significantly the use of cement and non-renewable natural resources (river/sea sand), contributing to the necessary sustainability of construction.

From experimental program, the effect of replacing cement by fly ash (up to 60%) in the mechanical properties (compressive strength, splitting-tensile strength, flexural-tensile strength and shear strength) was evaluated.

The results obtained show that it is possible to produce high-performance concrete with the selected materials replacing up to 40% of cement by fly ash. In specimens of such mixtures, cured at least 56 days, mechanical properties evaluated were similar to those of the control mixtures.

Keywords: fly ash, high-performance concrete, mechanical properties

A. Camões is an Assistant Professor in the Department of Civil Engineering at the University of Minho, Guimarães, Portugal.

P. Rocha is a Research Assistant at the Superior School of Technology and Administration, Viana do Castelo, Portugal

B. de Aguiar is an Associate Professor in the Department of Civil Engineering at the University of Minho, Guimarães, Portugal.

S. Jalali is an Associate Professor in the Department of Civil Engineering at the University of Minho, Guimarães, Portugal.

R. Delgado is a Full Professor in the Department of Civil Engineering at the University of Porto, FEUP, Porto, Portugal.

INTRODUCTION

Nowadays, the world's eco-system is faced with the growing problem of global warming which is associated with the emission of CO_2. The construction industry is responsible for a significant part of these emissions. The cement industry is a high consumer of energy and contributes with about 7% in total of CO_2 expelled to the atmosphere. On the whole, each ton of Portland cement produced releases about one ton of CO_2. With the objective of reducing these levels of CO_2, it is urgent to reduce the cement consumption. But, this reduction must be done without compromising the requirements of the performance of concrete structures.

Another environmental problem associated with the construction industry is the high consumption of non-renewable natural resources. The increase in construction, especially in the last decades, has provoked a significant reduction of these resources. So, it is mandatory to contribute to its maintenance.

High-performance concrete (*HPC*) has demonstrated to be a reliable alternative to conventional concrete, namely in special structures. In the meantime, *HPC* is, in general, produced using high quality selected materials, which results in a considerable increase of its initial costs and hinders its general use.

Hence, this research work was carried out with the objective of evaluating the possibility of producing low cost *HPC* using high quantities of fly ash (*FA*) for substitution of cement and using crushed aggregates, thus, reducing the consequences associated with high consumption of cement (*C*) and extraction of aggregates, particularly sand, from river beds, estuaries and sea coasts.

To accomplish the objectives described, an experimental program was carried out in order to evaluate the workability, mechanical properties and durability of concrete compositions, which were produced with 400 *kg/m*^{3}, 500 *kg/m*^{3} and 600 *kg/m*^{3} of binder content ($C + FA$) and cement substitution by *FA* of 0%, 20%, 40% and 60% (percentage of the binder weight).

The influence of the amount of binder, the percentage of cement replaced by fly ash, as well as the concrete age on the mechanical behaviour (compressive strength, splitting-tensile strength, flexural-tensile strength and shear strength) was assessed carrying out experimental tests. The results obtained are presented and analysed.

The durability of the mixtures produced was also evaluated, through chloride ion migration test, electrical resistivity and water absorption. The durability results obtained are presented elsewhere[1, 2].

MATERIALS, MIXTURE PROPORTIONS, MANUFACTURE AND CURING

All the aggregates used in this research work were obtained from crushed granite of the same quarry. Two sands of maximum aggregate sizes (D_{max}) of 2.38 *mm* (fine sand) and 4.76 *mm* (coarse sand), and a coarse aggregate of D_{max} of 9.53 *mm* were used as received, without any treatment.

Ordinary Portland cement (*C*) type CEM I 42,5R was used.

The *FA* was supplied by the Portuguese Thermoelectric Power Plant of Pego. The quantities of loss on ignition (*LOI*) varied between 6% and 9%, resulting in an average value over 7%. The *LOI* value is higher than the maximum allowed by the European Standard EN450[3] and the American Standard ASTM C618[4], which limit *LOI* to 5% and 6% respectively. This would mean that the *FA* used can be considered a poor quality *FA*, with high carbon content. However, previous studies[4] have shown that concrete using this *FA* achieved levels of performance similar to those using the same fly ash when the excess unburned carbon was removed by sieving. Table 1 indicates the principal chemical and physical properties of *C* and *FA*.

The superplasticizer (*SP*) used had a chemical composition based on naphthalene sulphonate formaldehyde condensates. In previous works[5], the optimum *SP* solid content was estimated to be between 0.5% and 1.0% of the mass of binder. Due to economic reasons, the value of 0.5% was adopted.

More details of the main characteristics of the materials are elsewhere[1, 2, 5].

Twelve different mixtures corresponding to three binder contents (*B*) and four levels of cement replacement were studied. Binder contents of 400 *kg/m*^{3}, 300 kg/m^3 and 500 kg/m^3 were adopted and the corresponding water/binder ratio (*W/B*) was maintained constant for each binder content and was determined experimentally to achieve 200 *mm* slump when 40% *FA* was used. The mixture proportions were estimated using the Faury method and are presented in Table 2, where the workability obtained using the Slump and the Flow Table test is also indicated.

Cubic specimens of 100 *mm* edge, cylindrical specimens of 150 *mm* diameter and 300 *mm* height and 850x100x100 mm^3 beam specimens were moulded.

The specimens were placed into a curing room, at a temperature of 21°C and at a constant relative humidity of 80%. The specimens were demoulded 24 hours after have been cast, and were stored immersed in water at 21° until their preparation for testing.

EXPERIMENTAL RESULTS AND ANALYSIS

The influences of the age and percentage of cement replaced by *FA* on the studied mechanical properties were evaluated. Each value presented is the average of the results recorded in three specimens. The results obtained are presented and analysed. The possible correlations are discussed.

Compressive Strength

Cubic specimens with 100 *mm* edge and cylindrical specimens of 150 *mm* diameter and 300 *mm* height were tested for evaluating the compressive strength.

The compressive strength of the produced concretes was evaluated from uniaxial compression tests carried out in a closed-loop servo controlled compression-testing machine. A linear voltage displacement transducer (*LVDT*) of 5 *mm* linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.12 *mm/min* (cylindrical specimens) or 0.36 *mm/min* (cubic specimens).

Figs. 1, 2 and 3 show the average values obtained in cubic specimens ($f_{cm,cube}$), as well as the best fit of results using the hyperbolic equation (Eq. 1), proposed by Carino[6] and Knudsen[7].

$$f_c = f_{max} \frac{k(t-t_0)}{1+k(t-t_0)} \qquad \text{(Eq. 1)}$$

where f_c is the compressive strength predicted at a given time t; t_0 is the time needed before the strength gain begins ($t_0 = 0$ was considered); f_{max} is the final strength when t tends to infinity; and k, expressed in $days^{-1}$, is a constant.

Results obtained (see Figs. 1, 2 and 3) indicate that:

a) Low cost *HPC* can be produced using materials currently used for conventional concrete, achieving compressive strength in cubic specimens ($f_{cm,cube}$) around 60 *MPa* at 28 days and 65 *MPa* at 56 days for a total binder content (B) of 500 kg/m^3. Increasing B to 600 kg/m^3, $f_{cm,cube}$ rises to about 70 *MPa* at 28 days and 75 *MPa* at 56 days;

b) The use of $B = 400$ kg/m^3 gives lower values of $f_{cm,cube}$. The maximum $f_{cm,cube}$ was reached when *FA* was not used, achieving about 45 *MPa* at 28 days and approximately 50 *MPa* at 56 days;

c) In spite of the low strengths measured in the early ages, the compositions with 60% of *FA* obtained relatively high compressive strength at longer curing times. The compressive strength of such compositions was about 50 *MPa* at 90 days for $B = 500$ kg/m^3 and around 65 *MPa* at 90 days for $B = 600$ kg/m^3. This is especially significant bearing in mind the low cement content of these mixtures, i.e. $C = 200$ kg/m^3 and $C = 240$ kg/m^3;

d) As expected, the rate of strength gain with the time is smaller with higher percentages of cement replacement. This is due to the lower rate of *FA* pozzolanic reaction;

e) The composition with $B = 500$ kg/m^3 and 40% *FA* replacement indicates strength gain far beyond the expected. However, this behaviour may be due to experimental problems. Compressive strength tests using cylindrical specimens showed that the strength gain with time for this mixture was similar to the mixture with $B = 600$ kg/m^3 and $FA = 40\%$.

Splitting-Tensile Strength

The splitting-tensile strength of the studied concretes was determined from diametric compression tests carried out in a closed-loop servo controlled compression-testing machine. A *LVDT* of 5 *mm* linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.12 *mm/min*.

The specimens used results from the cutting of the 300 *mm* height cylindrical specimens moulded. They were obtained by cutting one specimen in three similar portions of 150 *mm* diameter and about 95.5 *mm* height.

The compositions with $B = 400$ kg/m^3 were tested at 7, 28, 56, and 330 days while the others were tested at 7, 28, 56 and 420 days.

Fig. 4 shows the variation of splitting-tensile strength ($f_{ctm,sp}$) with the specimen's age and *FA* content. The results obtained indicate that:

a) The $f_{ctm,sp}$ is clearly affected by the presence of *FA* in the concrete composition. The higher the amount of *FA* the lower the $f_{ctm,sp}$. However, this effect is detected at early ages and is attenuated with curing time;

- There is a small effect of binder content on splitting-tensile strength at long curing times, i.e. longer than 28 days. For example, the difference between compositions with 20% of *FA* and $B = 500\ kg/m^3$ or $B = 600\ kg/m^3$ is about 10%.

The $f_{ctm,sp}$ can be predicted using the compressive strength of cylindrical specimens ($f_{cm,cil}$), using expressions suggested in the available references such as:

ACI *Committee* 363[8] – $21\ MPa < f_{cm,cil} < 83\ MPa$:

$$f_{ctm,sp} = 0.59\sqrt{f_{cm,cil}}\ (MPa) \qquad \text{(Eq. 2)}$$

Carrasquillo, Nilson and Slate[9] – $21\ MPa < f_{cm,cil} < 83\ MPa$:

$$f_{ctm,sp} = 0.54\sqrt{f_{cm,cil}}\ (MPa) \qquad \text{(Eq. 3)}$$

Ahmad and Shah[10] – $f_{cm,cil} < 84\ MPa$:

$$f_{ctm,sp} = 0.462\, f_{cm,cil}^{\ 0.55}\ (MPa) \qquad \text{(Eq. 4)}$$

Burg and Ost[11] – $85\ MPa < f_{cm,cil} < 130\ MPa$:

$$f_{ctm,sp} = 0.61\sqrt{f_{cm,cil}}\ (MPa) \qquad \text{(Eq. 5)}$$

Iravani[12] – $50\ MPa < f_{cm,cil} < 100\ MPa$:

$$f_{ctm,sp} = 0.57\sqrt{f_{cm,cil}}\ (MPa) \qquad \text{(Eq. 6)}$$

Fig. 5 presents the experimental results and the predicted values using the above mentioned equations. It can be seen that, for lower strength classes, the predicted values are mostly higher than the experimental values, while this tendency is inverted for higher strength concretes. This tendency is more pronounced for the lower values of $f_{ctm,sp}$ which correspond to the lower compressive strengths detected for curing times up to 7 days and for the compositions with higher quantities of *FA*.

Using the overall results of the tested compositions, equations (Eq. 7) and (Eq. 8) are suggested that give a better fit for the data obtained with a correlation coefficient equal to 86% and 87%.

$$f_{ctm,sp} = 0.8062\sqrt{f_{cm,cil}} - 1.7375 \qquad \text{(Eq. 7)}$$

$$f_{ctm,sp} = 35.2584\, f_{cm,cil} - 40.7074 \qquad \text{(Eq. 8)}$$

Fig. 6 indicates that both equations have similar results for $f_{cm,cil}$ between 30 MPa and 70 MPa.

Flexural Tensile Strength

The flexural behaviour of the produced concretes was evaluated carrying out ree-point bending tests according to RILEM recommendations[13] using 850x100x100 mm^3 beam specimens.

In the pre-test preparation phase of beam specimens, a notch of 5 *mm* width and 25 *mm* depth was sawn in a beam face parallel to the casting direction.

Loading, support conditions and the arrangement of the LVDTs are show in Figs. 7 and 8. The tests were controlled by *LVDT1* of 5 *mm* of linear measuring length and 0.05% of accuracy. A Japanese-Yoke-system was used to avoid that *LVDT1* has registered extraneous displacements[14]) (see Fig. 7). *LVDT2* and *LVDT3* were placed according to Fig. 7 for the estimation of the deformations at the fracture zone. *LVDT2* had 5 *mm* of linear measuring length and 0.09% of precision, while *LVDT3* had 6.3 *mm* of linear measuring length and 0.05% of precision. A load cell of 10000 *N* of bearing capacity and 0.05% of accuracy was used to measure the force. All the tests were performed with a mid-span deflection increase at a constant rate of 0.36 *mm/min*. The tests were carried out using closed-loop equipment developed in the University of Minho.

The compositions with $B = 400$ kg/m^3 were tested at 155 days, while the other compositions were tested at 7, 28, 56 and 165 days.

Fig. 9 shows the variation of flexural-tensile strength ($f_{ctm,fl}$) with the specimen's age and *FA* content for compositions with $B = 500$ kg/m^3 and $B = 600$ kg/m^3. Results obtained indicate that:

a) For the designed compositions $f_{ctm,fl}$ remained practically constant for ages greater than 56 days. For compositions without *FA*, $f_{ctm,fl}$ remained constant after 28 days of curing. For compositions with $B = 500$ kg/m^3, apart 500*FA*60 mixture, marginal increments on the $f_{ctm,fl}$ were observed after 28 days. Similar trend was verified for $B = 600$ kg/m^3, but only after 56 days of curing;

b) In the compositions with 60% of *FA*, values of $f_{ctm,fl}$ significantly smaller than the values recorded in the other mixtures were obtained. However, increasing the binder content from 500 kg/m^3 to 600 kg/m^3, $f_{ctm,fl}$ became closer to that of the remaining compositions;

c) Increasing the binder content from 500 kg/m^3 to 600 kg/m^3 had a marginal effect on $f_{ctm,fl}$. Only in compositions with 60% of *FA*, the use of higher binder contents seems to be advantageous.

Fig. [illegible] shows the compressive strength, $f_{cm,cu}$ versus $f_{ctm,fl}$. The results obtained confirm splitting-tensile strength results (see Fig. 6). Large variations are noted in the results from the flexural test.

Fig. 11 shows the splitting-tensile strength results ($f_{ctm,sp}$) versus those obtained in flexural tests ($f_{ctm,fl}$). The best fit of data is also presented in Fig. 11. It can be noted that values of $f_{ctm,fl}$ are larger than those of $f_{ctm,sp}$.

The discrepancy between the values of $f_{ctm,sp}$ and $f_{ctm,fl}$ has already been identified by other authors[15, 16]. It is noted that the fracture mechanism apparently is not the same for the two tests. Visual observation of the fractured surface of the specimens subjected to flexural tests indicates that fracture surface has occurred along the aggregate-paste interface, whereas in splitting tests, the fracture surface passes through the large aggregates. Thus, the results from the two tests may be not directly related.

The axial tensile strength (f_{ctm}) can be estimated using the results of the splitting test as suggested by CEB-FIP[17], which considers that f_{ctm} is 90% of $f_{ctm,sp}$. Using $f_{ctm,fl}$ it is also possible to estimate f_{ctm}, according to CEB-FIP[18]:

$$f_{ctm,fl} = f_{ctm}\frac{1+\alpha_{fl}\left(\dfrac{d}{d_0}\right)^{0.7}}{\alpha_{fl}\left(\dfrac{d}{d_0}\right)^{0.7}} \quad \text{(Eq. 9)}$$

where d is the height of the specimen and $d_0 = 100$ *mm*. The parameter, α_{fl}, depends on the ductility of the concrete and decreases as the concrete becomes less ductile. If α_{fl} is considered a constant and equal to 1.5, as indicated by CEB-FIP[18], the estimated values of f_{ctm} are slightly higher than the results from the splitting tests, as can be noted in Fig. 12. However, using the best fit of data for estimating the value of α_{fl} ($\alpha_{fl} = 1.7777$) it is possible to minimise the deviations (see Fig. 12).

Shear strength

The shear strength was estimated by loading 100 *mm* side cubic specimen conveniently cut, so that shear stress would occur on a section of 30x100 mm^2 (see Fig. 13). Compositions with $B = 400$ kg/m^3 were tested at an age of 330 days while the other mixtures were tested at 7, 28, 56 and 420 days.

The shear strength tests were performed in the closed-loop equipment used for flexural tests. A *LVDT* of 5 *mm* linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.09 *mm/min*.

The shear strengths (τ_m) obtained are presented in Fig. 14. It is noted that shear strength gain with curing time and *FA* content is similar to the compressive strength gain and other properties already mentioned. However, it's still possible to state that:

a) τ_m remained approximately constant for curing times between 56 and 420 days, irrespective of the binder and *FA* content;
b) For early ages, increasing quantities of *FA* decreases τ_m of the concretes studied. This effect is particularly noticeable at 7 days curing time, becoming less significant at long curing times. Mixtures with up to 40% of *FA* show similar values of τ_m at 56 days curing time;
c) Compositions made with 60% of *FA* show values of τ_m significantly lower than the other mixtures. Mixtures with 20% of *FA* resulted in τ_m slightly higher than mixtures without *FA*. Mixtures with $B = 600\ kg/m^3$ showed practically the same shear strength for 40% of *FA* and 0% of *FA*;
d) The increase of $B = 500\ kg/m^3$ to $B = 600\ kg/m^3$ was beneficial only at short curing times and in compositions with 60% of *FA* content, becoming practically irrelevant at 28 days and *FA* up to 20%.

The best fit of data for shear strength versus compressive strength is shown in Fig. 15. The results obtained indicate that the gain in shear strength is smaller than the compressive strength gain.

CONCLUSIONS

The results showed that *FA* addition decrease the concrete mechanical properties, mainly when evaluated at young ages. This undesirable effect of *FA* decreases with the age of the concrete.

In general terms, at the age of about 56 days, the compressive strength, the splitting-tensile strength, the flexural-tensile strength and the shear strength of the compositions with *FA* content up to 40% (percentage of the binder weight) are not significantly different. This indicates that, *HPC* can be designed with the use of relatively high percentage of *FA* (up to 40% of the binder content) since live loads in a concrete structure are, in general, applied when the concrete is several months old.

In concrete compositions with 60% of binder replaced by *FA*, the mechanical properties evaluated were considerably lower than those of the corresponding reference series (0% of *FA*). However, it is interesting to note the relatively high values of the mechanical properties at long curing times, achieved with such a high *FA* content.

In most cases, a good linear correlation was obtained between the evaluated mechanical properties (splitting-tensile strength, flexural-tensile strength and shear strength) and the square root of compressive strength. This indicates that an increase of the compressive strength corresponds a less pronounced increase of the tensile and shear strength.

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Table 1 – Chemical composition and physical properties of the cement and fly ash

	Cement	Fly Ash
SiO_2 (%)	19.71	42.16 – 58.46
Al_2O_3 (%)	5.41	21.04 – 32.65
Fe_2O_3 (%)	3.34	3.51 – 9.13
CaO total (%)	61.49	1.67 – 9.18
MgO (%)	2.58	0.65 – 2.59
SO_3 (%)	3.22	0.22 – 1.04
Cl^- (%)	0.01	0.00 – 0.06
Free CaO (%)	0.81	0.00 – 0.12
Loss on ignition (%)	2.52	5.60 – 9.28
Insoluble residue (%)	1.94	—
Specific weight (kg/m^3)	3150	2360
Blaine specific surface (m^2/kg)	358.4	387.9
Fineness (%)	1.7 (> 90 μm)	14.1 – 31.6 (> 45 μm)
Water demand (%)	28.0	29.7

Table 2 – Concrete mixture proportions and workability

Concrete	*W/B*	Cement (kg/m^3)	Fly Ash (kg/m^3)	Fine Sand (kg/m^3)	Course Sand (kg/m^3)	Course Aggregate (kg/m^3)	Slump (*mm*)	Flow (*mm*)
400*FA*0	0.40	400	0	614	234	857	105	450
400*FA*20		320	80	592	262	879	210	485
400*FA*40		240	160	553	285	876	180	550
400*FA*60		160	240	503	301	855	205	535
500*FA*0	0.30	500	0	503	308	866	25	315
500*FA*20		400	100	462	334	870	105	395
500*FA*40		300	200	407	349	847	205	474
500*FA*60		200	300	364	374	849	230	550
600*FA*0	0.25	600	0	377	368	851	35	350
600*FA*20		480	120	327	400	856	125	365
600*FA*40		360	240	271	408	833	200	510
600*FA*60		240	360	223	421	824	230	530

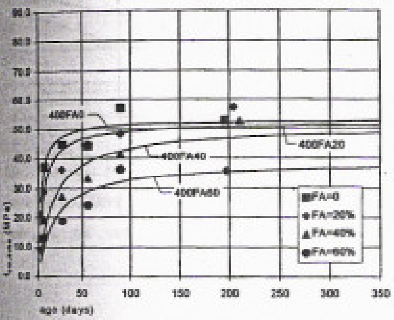

Fig. 1 – Compressive strength
($B = 400\ kg/m^3$)

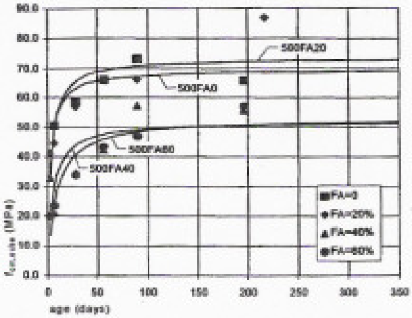

Fig. 2 – Compressive strength
($B = 500\ kg/m^3$)

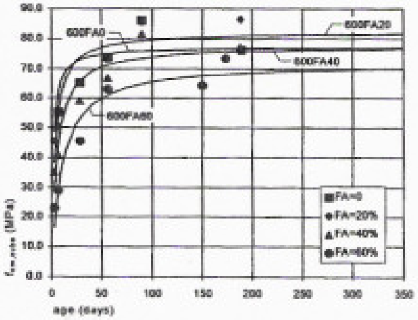

Fig. 3 – Compressive strength ($B = 600\ kg/m^3$)

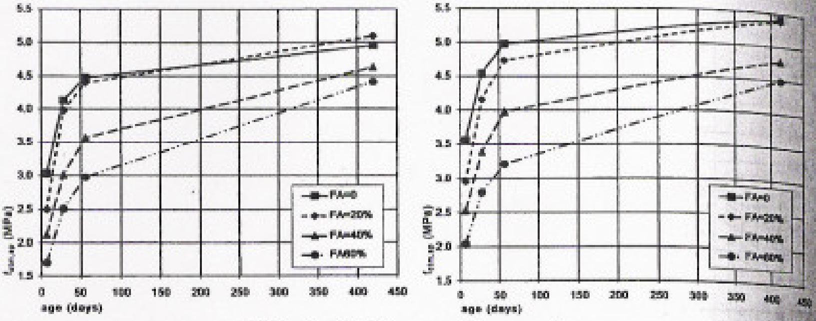

Fig. 4 – Splitting-tensile strength

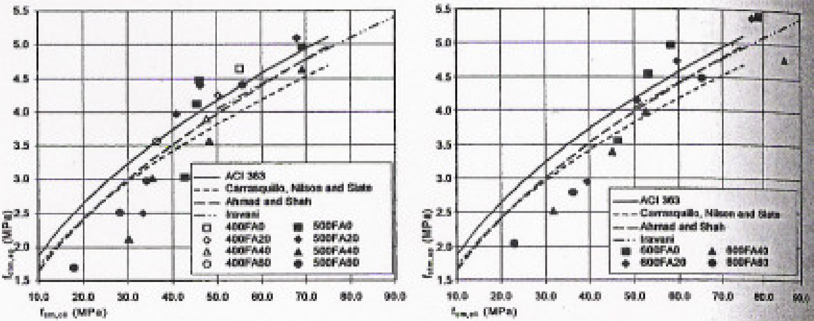

Fig. 5 – Compressive strength *vs.* splitting-tensile strength

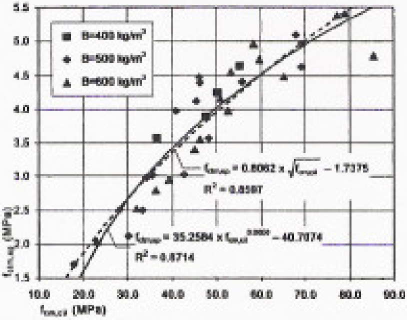

Fig. 6 – Best fit of compressive strength *vs.* splitting-tensile strength

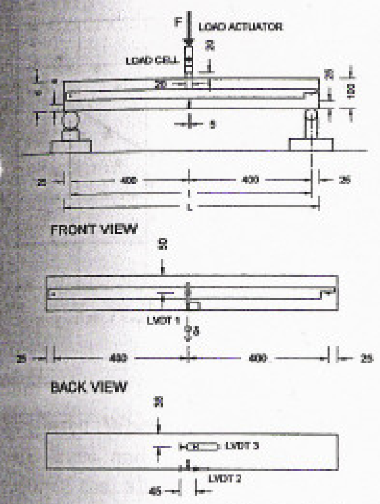

Fig. 7 – Three-point bending test set-up

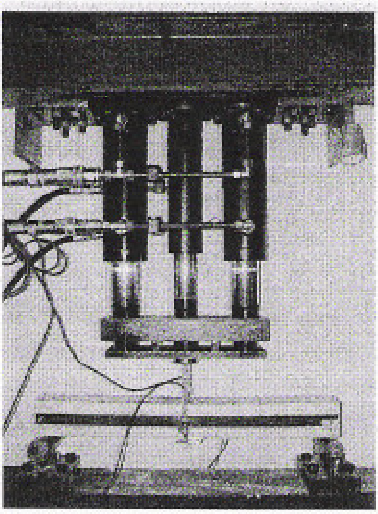

Fig. 8 – Three-point bending test photo

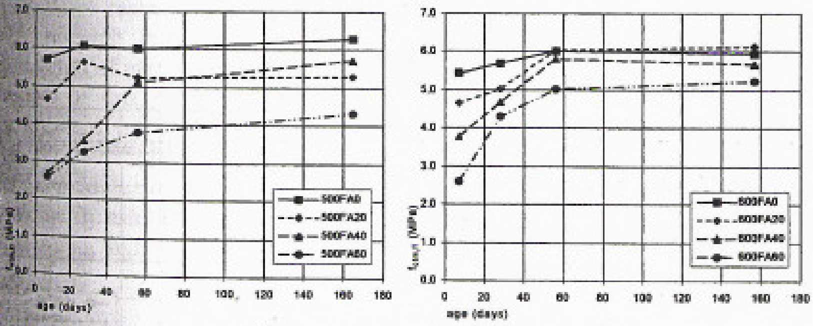

Fig. 9 – Flexural-tensile strength

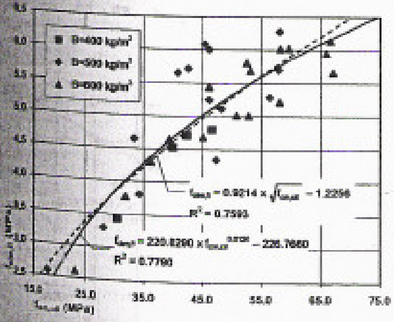

Fig. 10 – Compressive strength *vs.* flexural-tensile strength

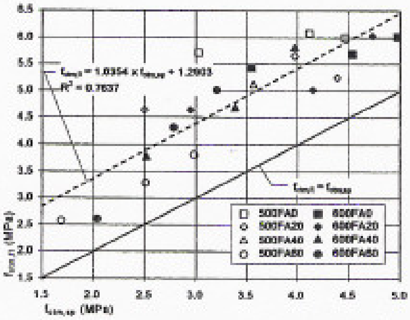

Fig. 11 – Splitting-tensile strength *vs.* flexural-tensile strength

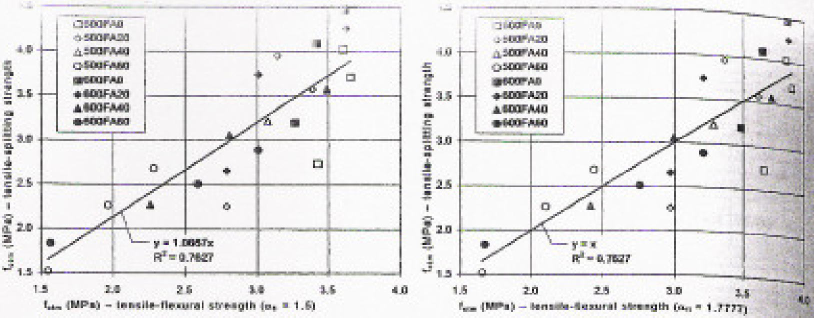

Fig. 12 – Estimated uniaxial tensile strength

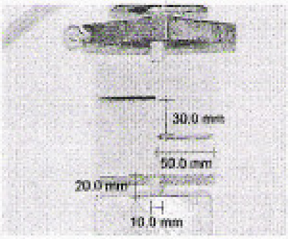

Fig. 13 – Shear strength test

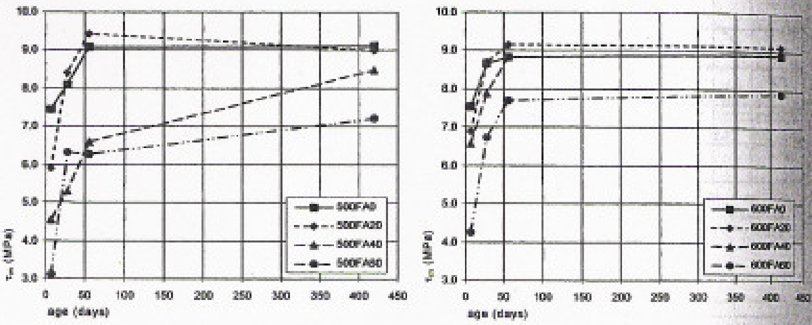

Fig. 14 – Shear strength

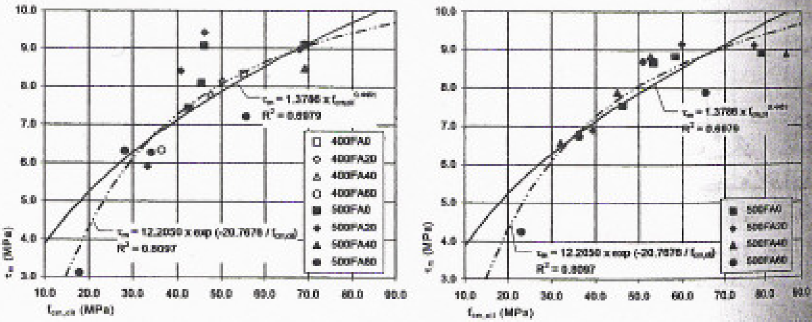

Fig. 15 – Compressive strength *vs.* shear strength