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CONCRETE ANTICIPATED MIXTURE DESIGN AND CONTROL - PRACTICAL METHODS BASED ON CEMENT HYDRATION

CONCRETE ANTICIPATED MIXTURE DESIGN AND CONTROL - PRACTICAL METHODS BASED ON CEMENT HYDRATION

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1 INTRODUCTION

The Technological Research Institute (IPT) of São Paulo State Government has continuously improved a concrete mixture design method since 1927 [1]. This dynamically changing procedure is intensively used and well known as the "IPT Concrete Mixture Design Method" in cement and concrete media of Brazil [2,3], as well worldwide disseminated by old IPT collaborators [4].
Additionally, models for strength-time function were derived and verified with data from the Institute [5], and a derivative concrete strength prediction method was published and called "AMEBA Method" [6].
This work briefly presents the model’s fundaments, a practical example of mixture design method application with its strength anticipating improvements, as well concrete anticipated quality control results, adapted to the international ACI concrete control procedure with an example using pozzolan addition to ordinary portland cement for precast elements.

2 Hydration and strength development models

2.1 Basic mathematical model: strength versus w-c ratio versus time

One of Powers' approaches for compressive strength as a function of gel/space ratio, which is a function of the non-evaporable water and hydration degree in a cement paste, is similar to Abrams' "law" [7] and is given by equation 1 [8]:

$$f_{c,j} = A_p / B_p^{\,x/w_n} \tag{1}$$

Where:
$f_{c,j}$ = compressive strength at age j;
A_P and B_P = Powers' constants for paste, depending on materials and test conditions;
x = water-cement ratio;
w_n = relative mass of non-evaporable water,
Equation 1 can be seen as a time generalization of Abram's "law", because it is valid for any age, and paste-aggregate transition zone effects, not considered for paste, can be regarded by adequately adjusted constants A_p and B_p also for concrete. From equation 1 it is possible to arrive to equation 2 [6]:

$$f_{c,j} = A / B^{\,x/h_j} \tag{2}$$

Where:
A and B = constants depending on materials (paste-aggregate transition zone included) and test conditions;
h_j = hydration degree at age j.

Inverse of hydration degree can be given by equation 3 [5]:

$$1/h_j = 1 + j^{-n} . (h'^{-1}_{max} + h''^{-1}_o . x^{-1}) \qquad (3)$$

Where:
j^{-n} = transformed time, age j elevated to -n, with n = 0.5 for no-slag or low-slag cements;
h'_{max} = maximum initial hydration "speed" considering the transformed time T;
h''_o = derivative of the initial hydration "speed" as a function of x, when x = 0.

Then, we can write equation 4 substituting equation 3 given value in equation 2:

$$f_{c,j} = A / B^{(x + x . j^{-n} / h'_{max} + j^{-n} / h''_o)} \qquad (4)$$

We can write equation 4 as equation 5:

$$f_{c,j} = A / (B^x . D^{x.j^{-n}} . E^{j^{-n}}) \qquad (5)$$

Where:
$E = B / h'_{max}$ = constant;
$D = B / h''_o$, = constant.
Equation 5 assumes the aspect shown in figure 1 when graphically expressed.

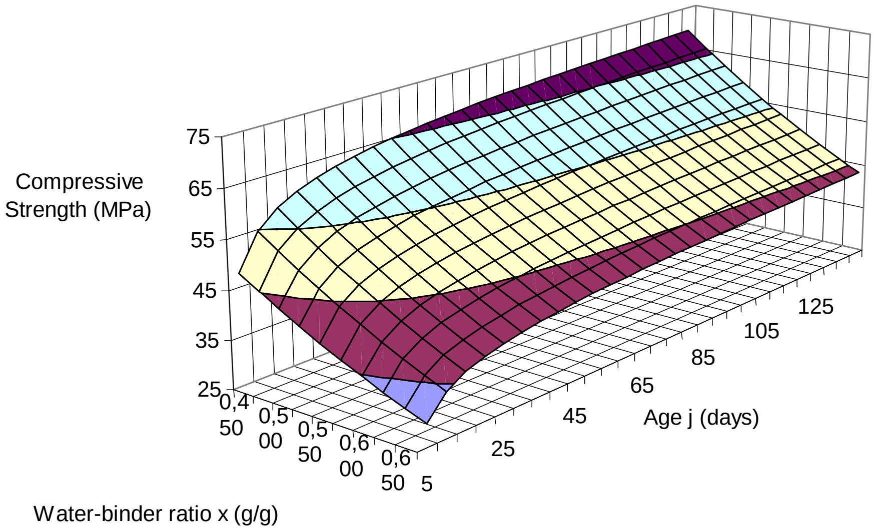

Figure 1. 3-D diagram representing equation 5, adjusted from concrete data using OPC, silica fume, and HRWR admixture.

2.2 Linearization for extrapolation and prediction of strength.

Equations 4 and 5 are linearizable, that means, it is possible to transform a surface shown in figure 1 to a ruled (composed by straight lines) surface, applying the logarithm function to compressive strength, and elevating age to exponent –n. Figure 2 shows a view of a linearized graphic with plotted real compressive strength data from three different concrete mixture proportions (with ingredients from the same samples) poured in 1935 by Ary Torres [9, 10]. Transformed time ($j^{-0.5}$) is represented on abscissa's axis, where real age grows from right to left and zero means infinite age.

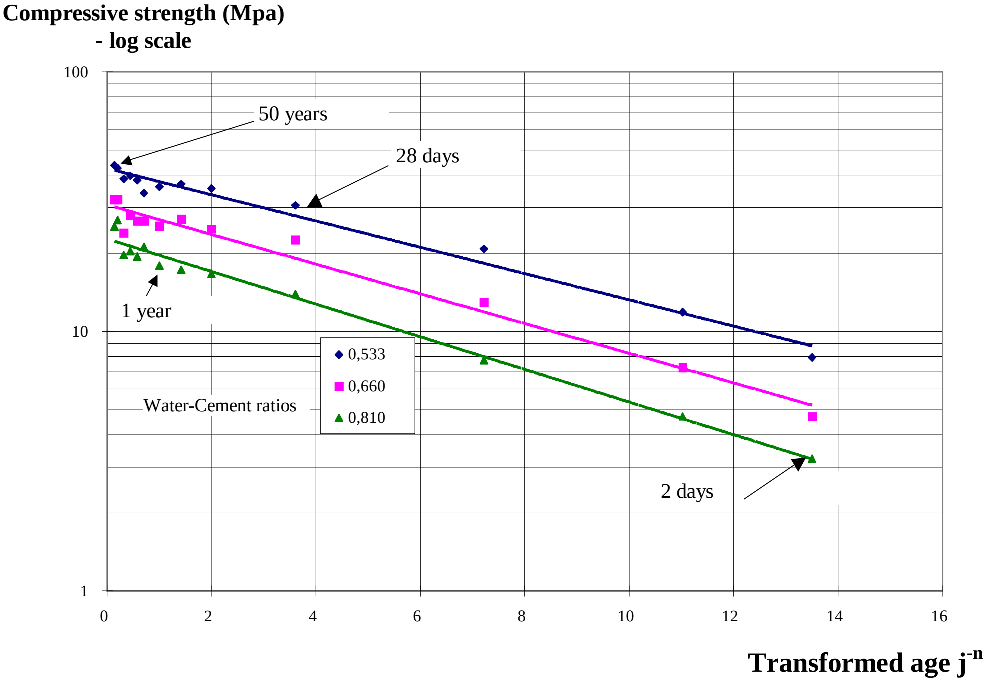

Figure 2. Transformed strength-transformed age diagram (n = 0.5)

3 – DESCRIPTION WITH AN EXAMPLE OF ANTICIPATED EXPERIMENTAL MIXTURE DESIGN METHOD

The following steps briefly describe and exemplify the IPT concrete mixture design method [3]:

3.1 First step, rough estimative of concrete mixture proportions

First step utilizes the equation 5, and also equation 6, this last one as follows:

$$m_{est} = x_{est} / [F + G . \log(d_{max}) + H . a_{tc}] - 1 \tag{6}$$

Where:

x_{est} = estimated water-binder ratio, in the example calculated as 0.362 kg/kg using equation 5 for compressive strength (f_{cj}) at age (j) of interest, (in the example, 49,1 MPa at 28 days, exponent n= 0.5) and constants with prior adjusted values for similar concretes, (in the example, for Brazilian type V-ARI cement with 10 % of silica fume, A = 106.7; B = 4.320; D = 19.81; and E = 1.260);
d_{max} = required maximum aggregate size, in the example, 19.0 mm;
a_{tc} = required slump, in the example 100 mm;
F, G, H, previously found empirical constants [2], in the example with the values 8.029×10^{-2}, -1.946×10^{-2}, and 7.447×10^{-5}, respectively, for ordinary portland cement with silica fume with HRWR admixture, crushed granite cubic aggregate;
m_{est} = roughly estimated aggregate-binder proportion, in the example calculated as 4.75 kg/kg.

3.2 Second step, experimental establishment of dry mortar-dry concrete proportion

Second step is an operation with fresh concretes [2], which procedure is to vary mortar content (dry mortar = cement + fine aggregate) into a mixer, (each tentative mixture varying 2%) with constant coarse aggregate amount and constant aggregate-binder proportion, making the mortar content choice for desired workability. In the example, experiments resulted into 50 % for mortar/concrete (dry basis, weight). A necessary amount of water for workability can be used without preoccupation at this step.

3.3 Third step, preparing of specimens with “rich”, “medium” and “poor” mixture proportions

Third step consists in making experimental concretes with aggregate-binder proportions m_{est} (“medium”), $m_{est} - 1$ (“rich” in cement), and $m_{est} + 1$ (“poor” in cement). Each of these mixtures is made with mortar-concrete proportion above determined (50 %) and its water-binder ratio is tentatively established to obtain desired slump; practical binder consumption is calculated from density measuring of the fresh mixtures. Specimens are poured and cured to desired ages for each of the three mixtures. Table 1 shows results obtained for the given example.

Table 1. Example of fresh concrete data at third step

HRWR/ binder (% Weight)	Silica fume/ binder (% Weight)	Slump range (mm)	Aggregate/ binder (kg/kg)	Water/ binder (kg/kg)	Binder content (kg/m^3)
1.0	10	100 ± 10	3.75	0.454	461
			4.75	0.515	382
			5.75	0.614	325

Note: Binder = cement + silica fume

3.4 Fourth step, hardened concrete tests

Specimens are tested at different ages, as indicated in table 2, that summarizes results.

Table 2. Example of hardened concrete data at fourth step

Water/binder (kg/kg)	Mean Compressive strength of 3 tests, (MPa) at age					
	3 days	7 days	14 days	28 days	63 days	91 days
0.454	41.3	51.3	58.0	63.3	66.1	65.2
0.515	36.3	44.1	49.0	55.2	59.0	59.2
0.614	29.3	36.5	43.1	46.0	50.2	53.3

3.5 Fifth step, adjusted equations and mixture design diagram

At the end of this step, the anticipated or definitive experimental concrete proportioning is obtained for specified job.

Equation 5 is the generalization of Abrams’ “law” for any age, and above results lead to the following exemplificative situations when it is adjusted using Minimum Square Method and exponent n is assumed 0.5:

$$f_{c,j} = 189.1 / (7.615^{x} . 2.562^{x.j^{-0.5}} .1.234^{j^{-0.5}}) \tag{5a}$$

When only results till 7 days where available (equation 5a is the anticipated equation), and

$$f_{c,j} = 141.6 \ / (4.179^{x} \ . 4.286 \, . \, E^{x.j^{-0.5}} \ .1.399^{j^{-0.5}}) \qquad (5b)$$

Using all results in the regression.

For the desired compressive strength 49.1 MPa at 28 days, the above equations lead to necessary water/binder of respectively 0.593 (anticipated 21 days) and 0.584 (definitive).

Of course, the later result prevails for establishment of designed definitive mixture proportions. For establishment of mixture proportions at 28 days, extrapolation from 3 and 7 days is acceptable and calculations agree reasonably [6].

Relating concrete proportions water/binder (x), aggregate/binder (m) and cement content (C) in the fresh state, equations 7 and 8 (called “Lyse’s” and “Molinari’s”) are inferred [3, 4]:

$$x = 0.08016 \, . \, m + 0.1466) \qquad (7)$$

(Adjusted Lyse’s equation [3] for the example)

$$1/C = 0.0004549 \, . \, m + 0.0004623) \qquad (8)$$

(Adjusted Molinari’s equation [3] for the example)

Anticipated curves from the anticipated situation are graphically expressed in the IPT Mixture Design Diagram shown in figure 3 (Diagram for a concrete family with OPC, silica fume, HWRA admixture, 19 mm crushed granite, river sand and 10 ± 1 cm slump. Curves without experimental points are extrapolations to the future).

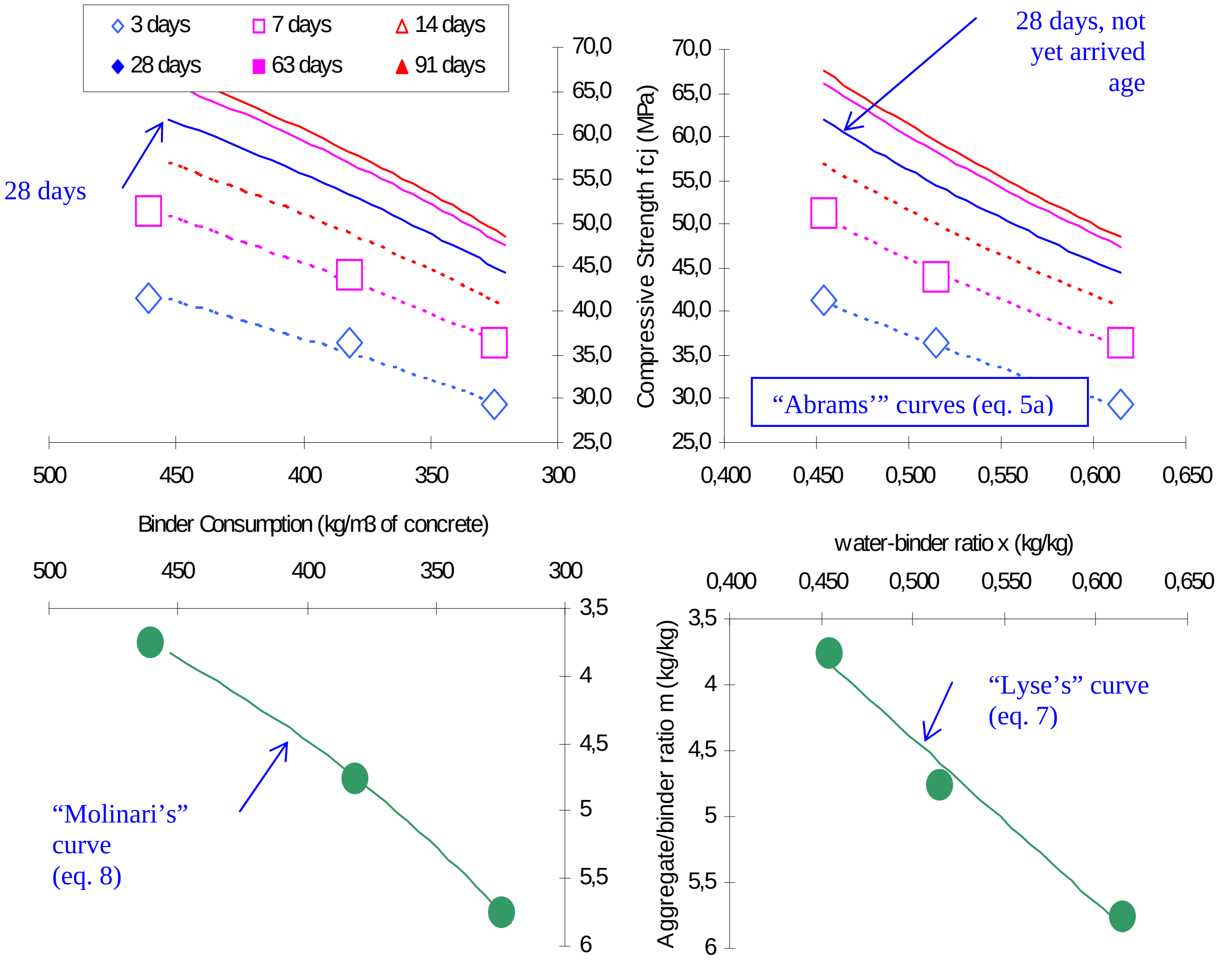

Figure 3. "IPT Mixture Design Diagram" [2, 3, 4] relating predicted (after 7 days) concrete compressive strength to mixture proportions.

In the example, it is possible to arrive to the mixture proportions given in table 3.

Table 3. Concrete mixture weight proportions for the example (binder is considered unity)

Status of mixture design	Used equations	Cement	Silica fume	HRWR admix.	Fine Aggr.	Coarse Aggr.	Water
Anticipated from 3 and 7 days ages only	5a and 7	0.900	0.100	0.010	2.283	3.283	0.593
Definitive after 91 days age	5b and 7	0.900	0.100	0.010	2.228	3.228	0.584

Note: proportions for obtention of 49.1 MPa at 28 days age, dry mortar/dry concrete = 50%.

3 ANTICIPATED CONTROL METHOD (E.G. FOR PRECAST POZZOLAN CONCRETE)

The "AMEBA" method name is due to the general principle of extrapolating compressive strength at a late or high ("Alta" in Portuguese) age with results obtained earlier at medium ("Média") and low ("Baixa") ages. It was demonstrated that method applies to cement products as concrete, grout or mortar, including cement plant control [6].

Basic principles reside on the linear aspect shown in figure 2 for the strength-time transformed curve of a given set of constituents and mixture proportions, mainly water-binder ratio.

Prediction is made with a simple rule of three with transformed time and transformed strength differences; after re-transforming, calculation results in equation 9:

$$f_{ca} = f_{cm}^{\mathrm{AMEBA}} / f_{cb}^{\mathrm{AMEBA-1}} \tag{9}$$

Where:
f_{ca} = compressive strength at a late age "a" or control age, example, 28 days;
f_{cm} = compressive strength at a medium age "m", example, 7 days;
f_{cb} = compressive strength at a low age "b", example, 3 days.
AMEBA = function of the three ages in study, given by equation 10:

$$\mathrm{AMEBA} = (a^{-n} - b^{-n}) / (m^{-n} - b^{-n}) \tag{10}$$

Equation 9 was used to simulate an anticipated control using the American Concrete Institute control principles [11], with the concrete production data of precast elements in Ilha Solteira Hydroproject, Brazil, with the following characteristics:

3.1 Concrete design requirements for strength simulated control in the example

Practical control age: 3 days;
Required minimum (5 % percentile) compressive strength at practical control age: 14,7 MPa;
Design control age: 28 days (simulation);

Required ACI [11] minimum compressive strength f'_c at 28 days(simulation)= 36.6 MPa;
Initially estimated production standard deviation of compressive strength s_d = 7.0 MPa (simulation);
Mean mixture design target strength f'_{cr} = 46 MPa.

Concrete composition (weights for 1 m3 of concrete): Cement, 271 kg; Pozzolan, 53 kg; Water, 132 kg; Natural Sand, 571 kg; Gravel 19 mm, 690 kg; Gravel 38 mm, 690 kg; Plastifying Admixture, 0,810 kg.
Slump range: 40 $\pm$ 5 mm.

Available control results: 186 series with compressive strength average results at 3, 7, and 28 days corresponding to a period

3.2 Characterization of concrete constituents in the control example – need for pozzolan

Cement in the example was an ordinary portland type with Brazilian standard strengths 19.5, 27.8, 39.1, and 45.3 MPa at 3, 7, 28, and 90 days, respectively, and Blaine fineness 354 m^2/kg (averages of all the production).
Blaine fineness of the pozzolan was 790 m^2/kg; pozzolanic activity indexes were 84.7 % with cement and 7.3 MPa with lime, with a water requirement of 105 %. Reduction in expansion was 97.2 %. Results of all job averages for cement and pozzolan chemical analysis are in table 4.

Table 4. Chemical analysis of cement and pozzolan (average values for all the job)

Average for	Ignition loss	I.R.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Eq. Alkalis
Cement (%)	1.14	0.13	21.36	-	3.53	63.77	2.47	1.65	0.15	0.66	0.58
Pozzolan (%)	1.39	-	66.65	24.45	5.36	-	1.10	Nihil	-	-	-

The concrete aggregates used were a blend of natural aggregates (river gravel and sand). In the studies carried out it was observed that the alluvial aggregates were made up of medium and coarse sand and gravel with a certain mineralogical uniformity and predominant presence of quartz, quartzite, agate, chalcedony, silicificated sandstone, silicificated limestone, chert and ferruginous concretions. The petrographic evaluation (ASTM-C-295), chemical analysis (ASTM- C-289) and mortar bar tests (ASTM-C-227) showed the presence of deleterious minerals and expansion due to the alkali- aggregate reaction. Because of the potential reactivity of the aggregates, a pozzolanic material, from calcined kaolinitic clay, was used as a partial cement replacement, including the use for precast elements with higher earlier strengths.

3.3 Concrete control simulation with example's real data

For 28, 7 and 3 days ages, n = -0.50, AMEBA can be calculated as 1.9478, and equation 9 is expressed as equation 9a:

$$f_{c28} = f_{c7}^{\ 1.9478} / f_{c3}^{\ 0.9478} \tag{9a}$$

The above equation was used with the first series (n exponent is 0.5, indicated when materials have not a previous background). At series number 72, n (see equation 9) was changed because in a real situation it would be reasonable to have sufficient available data for a better evaluation of the exponent. For subsequent series, equation 9b, which n value is 0.67, was used:

$$f_{c28} = f_{c7}^{\ 1.7917} / f_{c3}^{\ 0.7917} \tag{9b}$$

Effectively, exponent 0.67 was considered good for this condition as shows the linearity obtained in figure 4.

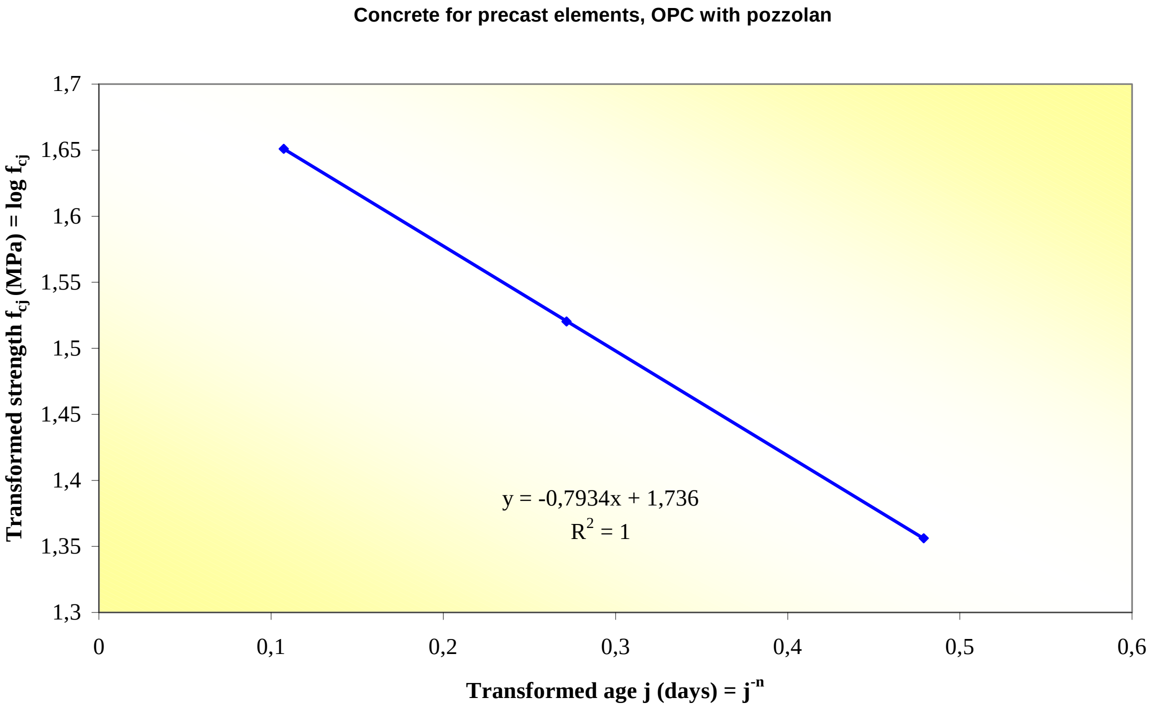

Figure 4. Transformed strength-time diagram for three points, each one being respectively the representation of all job average strength at 3, 7 and 28 days, using n = 0.67 in time transforming.

Figures 5 and 6 show control charts for the job with simulated-predicted and effective results of tests at 28 days.

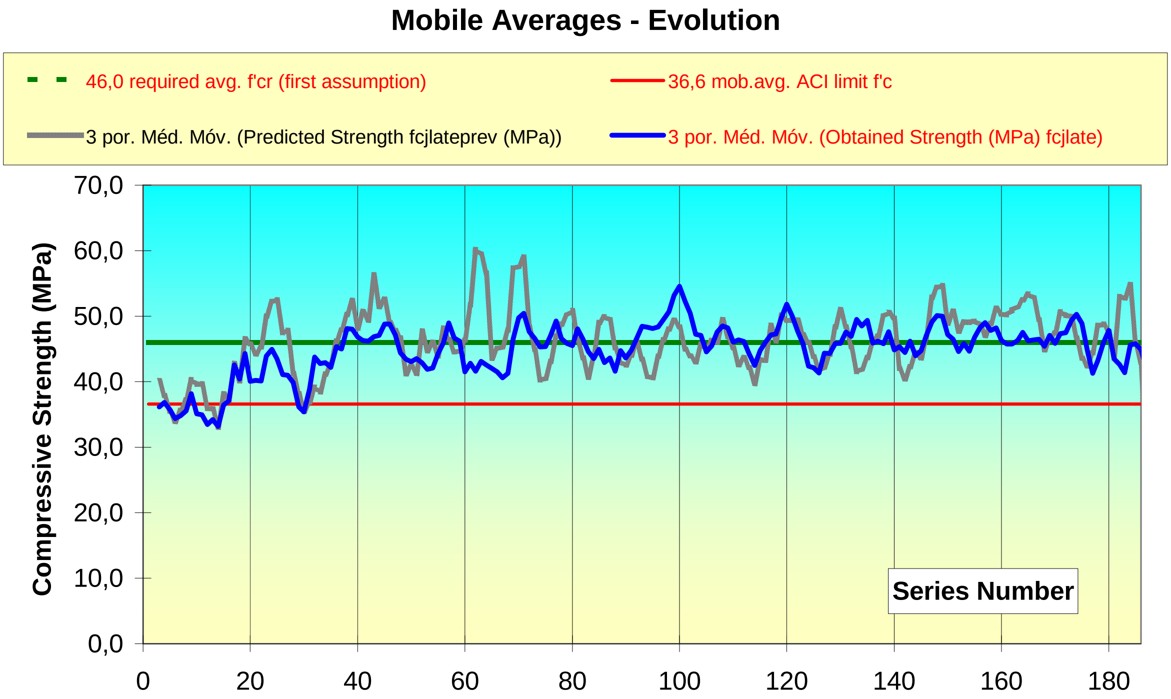

Figure 5. Predicted and effective mobile averages of 3 series along concrete production.

ACI lower limit f'$_c$ not being respected is an alert for changing in the production process. As seen in figure 5, concrete became better in the beginning of production and remained stable after series about number 40.

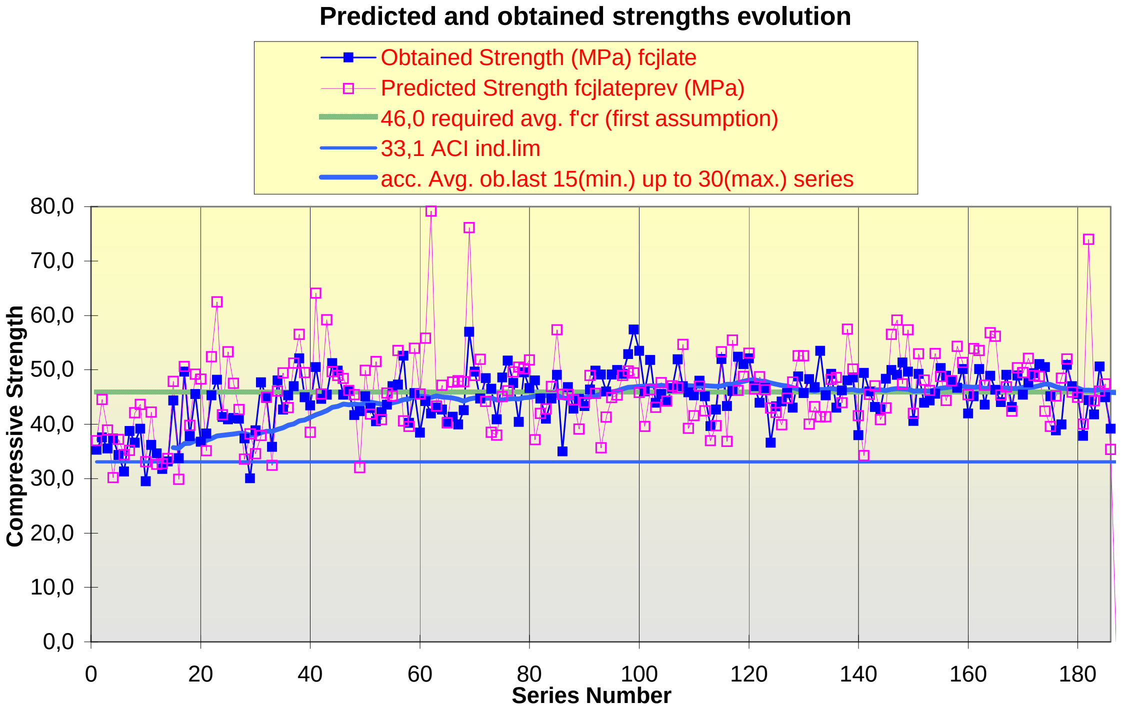

Figure 6. Predicted and effective individual values along concrete production.

In figure 6, ACI individual limit is stated as f'$_c$ – 3.0 MPa. One single value below this limit implies in revision of control, additional verification tests if judged necessary, and revision of corresponding concrete utilization or demolition in worst situations. Note that dispersion of prediction values is higher than of effective, but dispersion has a preference for higher values of strength.

4 CONCLUSION

This work summarizes and exemplifies methods for utilization in concrete technology of a linear model given by equation 5 and illustrated by figure 1, derived from hydration evolution theories. Examples and refereed works permitted to conclude that it is possible to use those methods efficiently for anticipated experimental concrete mixture design or for anticipated concrete control (in this work, specifically, with ordinary portland cement and pozzolan addition, and adapted to ACI control procedures).

Obviously a prediction method is not deterministic, and uncertainties are associated, as can be seen by observed differences and dispersion more accentuated for predictions than for effective values. As a result, the methods can be advantageously used with precautions, based in a reasonable knowledge of their principles and characteristics.

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