ALCONPAT Journal
www.revistaalconpat.org
eISSN 2007-6835

Journal of the Latin-American Association of Quality Control, Pathology and Recovery of Construction

Analysis of non-conformity concrete: long time effects

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Article information
DOI:
http://dx.doi.org/10.21041/ra.v6i3.154
Article received on March 03, 2016, reviewed under publishing policies of ALCONPAT journal and accepted on July 19, 2016. Any discussion, including authors reply, will be published on the third number of 2017 if received before closing the second number of 2017.

Legal Information
ALCONPAT Journal, year 6, No. 3, September-December 2016, is a quarterly publication of the Latinamerican Association of quality control, pathology and recovery of construction- International, A.C.; Km. 6, Antigua carretera a Progreso, Mérida, Yucatán, C.P. 97310, Tel.5219997385893, alconpat.int@gmail.com, Website: www.alconpat.org.
Editor: Dr. Pedro Castro Borges. Reservation of rights to exclusive use No.04-2013-011717330300-203, eISSN 2007-6835, both awarded by the National Institute of Copyright. Responsible for the latest update on this number, ALCONPAT Informatics Unit, Eng. Elizabeth Maldonado Sabido, Km. 6, Antigua carretera a Progreso, Mérida Yucatán, C.P. 97310, last updated: September, 2016.

ABSTRACT
The aims of this paper is to contribute to the analysis of non-conformity concrete, focusing on long time effects. A review of compressive strength evolution, results variability and acceptance criteria was made. In addition, it is presented a case study of a nonconforming concrete used in composite structures (concrete-filled steel columns) that present 28 days strength below the specified. Considering long time effects, a nominal strength gain above the limits considered in technical standards was observed. This analysis, associated with a revision of the structural design and a carefully assessment, could help decision taking in case of non-conformity concretes.
Keywords: non-conforming; strength gain; structural safety.

RESUMO
O presente artigo tem como objetivo contribuir para a análise de concretos com não conformidades, com foco nos efeitos de longa duração. Foi realizado um levantamento dos intervenientes na análise de não conformidades: evolução da resistência à compressão, a variabilidade dos resultados e critérios de aceitação do concreto. De forma complementar, é apresentado o estudo de caso de concretos não conformes empregados em estrutura mista (pilares metálicos preenchidos) que apresentaram resistências abaixo do especificado aos 28 dias. Considerando os efeitos de longa duração, um ganho de resistência nominal acima dos limites normativos foi observado. Esta análise, aliada a uma revisão do projeto e a uma inspeção criteriosa, pode auxiliar na tomada de decisão em casos de concretos não conformes.
Palavras-chave: não conformidade; crescimento de resistência; segurança estrutural.

RESUMEN
Este artículo tiene como objetivo contribuir al análisis del concreto en casos de incumplimiento normativo, centrado en los efectos a largo plazo. Se llevó a cabo una encuesta entre los participantes en el análisis de no conformidades: evolución de la resistencia a la compresión, variabilidad de los resultados y criterios de aceptación. Complementariamente, se presenta un caso de estudio de un hormigón en incumplimiento utilizado en una estructura mixta (pilares metálicos rellenos) que mostró una a 28 días menor que la especificada. Teniendo en cuenta los efectos a largo plazo, se observó una ganancia de resistencia nominal por encima de los límites reglamentarios. Este análisis, junto con una revisión del proyecto y una inspección minuciosa puede ayudar en la toma de decisiones en casos de hormigón en incumplimiento.
Palabras clave: incumplimiento; ganancia de resistencia; seguridad estructural.

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1. INTRODUCTION

The high mechanical strength along with low production cost and easiness of casting various geometries, make concrete the most used material in constructions, standing out in technical and economic aspects. (Mehta; Monteiro, 2014). Consequently, as concrete consumption grows, is expected a growth of projected and designed builds that require evaluation of its performance regarding functions for which it was designed, combining efficiency technical aspects. A good choice of materials as well an investigation of effects of employed technologies, associated with a structural system improvement are important factors to ensure safety conditions.

In general, safety in structural design is introduced by safety partial factors that takes account inevitable imprecisions in load estimations or variability of mechanical properties of materials. Besides that, safety incorporates imperfections due to simultaneous actions that structure must support, but it also be included in these uncertainties the errors resulting from simplified design conception or capacity of redistribute action produced by eventual damages. When this aspects and coefficients are not addressed, neglected or verified, there is an increase of non-conformity cases and, thus, should be investigated. This can point out problems that put in doubt the structural design, possible repairs or total and/or partial condemnation of some elements.

Within this context, many studies and research has been made to understand non-conformity of structural concrete, addressing aspects of safety, confiability and risk analysis (Kausay; Simon, 2007; Pereira, 2008; Caspeele; Taerwe, 2011; Helene, 2011; Santiago, 2011; Santiago; Beck, 2011; Caspeele; Taerwe, 2014; Larrossa et al, 2014; Magalhães, 2014; Rao et al, 2014; Couto et al, 2015; Magalhães et al, 2015). In Brazil, the subject led the creation of a group of studies of the Brazilian Association of Structural Engineering and Consulting (ABECE), which resulted in the recommendation ABECE 001: Case studies in non-conformity of concrete. It is noteworthy that safety assessment of non-conformity structural concrete includes many stages and methods, which include extraction of concrete cores and design review with the obtained concrete compressive strength (Silva Filho; Helene, 2011).

This paper aims to review some of the main factors involved in the analysis of non-conformities in concrete. Aspects of variability of axial compressions test results, concrete acceptance criteria and compressive strength evolution in terms of long time effects are addressed. This review is complemented with a case study of a composite structure, with concrete-filled steel columns, which showed a lower compressive strength than the specified by the designer. With this analysis of long time effects on concrete compressive strength, is intended to contribute in decision making in the analys of non-conformities in concrete structures.

2. ANALYSIS OF NON CONFORMITY CONCRETE

2.1 Considerations on compressive strength gain over time

One possible approach to the assessment of structural safety consists in the analysis of long time behavior of concrete during time considering effects of strength evolution and long lasting load. In determining admissible compressive stress, $\sigma_{cd,}$ coefficients γ_c and β are used – design values based on characteristic values defined from probabilistic considerations for each limit state. γ_c coefficient represents differences between concrete from standard specimen and concrete from structural element as well uncertainties related to actions (Couto *et al*, 2015), while β is derived from the product of partial coefficients, i.e., by the multiplication of benefic effects of compressive strength evolution over time (β_1) by harmful effects of long lasting load (β_2) (Silva Filho; Helene, 2011).

Compressive strength evolution over time can be calculated by using mathematic models related to the compressive strength at 28 days. (Klemczak *et al*, 2015). It is well knowed that this evolution varies depending on the cement type, ambient temperature and curing conditions (CEB, 1990). Maintaining the ideal curing conditions and temperature at 20ºC, it is possible to estimate strength gain over time, using equations (1) and (2), proposed by fib *Model Code 2010* (CEB, 2012). This formulation is accepted by Brazilian Standard ABNT NBR 6118:2014 to ages under 28 days.

$$f_{cm}(t) = \beta_1(t) \times f_{cm} \tag{1}$$

$$\beta_1(t) = \exp\left\{ s \left[1 - \sqrt{\left(\frac{28}{t}\right)} \right] \right\} \tag{2}$$

$f_{cm}(t)$: Compressive strength at t days;
f_{cm}: Compressive strength at 28 days;
$\beta_1(t)$: Coefficient that depend on time (t);
t: Age at which is desired to obtain compressive strength;
s: Coefficient that depend on cement type: *s*=0.20: for high strength and rapid hardening cement type (case of CPV-ARI in Brazil); *s*=0.25: for ordinary and rapid hardening cement type (case of CPI and CPII in Brazil); and *s*=0.38: for slow hardening cement type (case of CPIII and CPIV in Brazil).

The loss of load capacity by long lasting loads was studied by Rüsch (1960). This decrease is constant and independent of studied concrete f_{ck}, besides that, is maximum of 25% (Silva Filho; Helene, 2011). The *fib Model Code 2010* (CEB FIP, 2012) proposes an equation (3) to determine coefficient β_2, wherein the reduction coefficient varies according to the loading age.

$$\beta_2 = \frac{f_{c,sus,j}}{f_{c,t0}} = 0.96 - 0.12 \times \sqrt[4]{\ln(72 \times (j - t_0)} \tag{3}$$

$f_{c,sus,j}$: Compressive strength of concrete under sustained load, at j days, in MPa;
$f_{c,t0}$: Potential compressive strength at time (age) t_0 just before application of long lasting load, MPa;
β_2: Harmful effects of long lasting load (t);
t_0: Load application age, in days, considered significant;
j: Any age of concrete after t_0, expressed in days.

It is estimated that the Brazilian Standard NBR 6118:2014 sets value of 1.16 to β_1 and 0.73 to β_2, considering load values at 28 days until 50 years, resulting in a β of 0.85 (Silva Filho; Helene, 2011). It is observed that this values are conservative, since it admits a strength gain of only 16% in a period of 50 years and a greater decrease than the maximum established by Rüsch (1960) (Helene, 2011). Thus, it is appropriate check the values of β_1 e β_2 considering formulation proposed by *fib Model Code 2010* (CEB, 2012) and considerations made by Rüsch (1960).

2.2 Considerations on variability of compressive strength test results

Another factor to be verified is the variability of compressive strength test results. Magalhães (2014) points out that all steps of concrete production leads to a dispersion of test results, which can be grouped in 3 different aspects: influence of materials, production methods and test procedures. Table 1 shows main factors that can affect compressive strength test results, as well the maximum variability of each factor.

Table 1. Factors that can affect compressive strength test results

Variation origin		Maximum variability
Materials	Variability of cement strength	±12%
	Variability of total amount of water	±15%
	Variability of aggregates	± 8%
Man-power	Variability of time and mixing procedure	-30%
Equipment	Lack of scale calibration	-15%
	Initial mixture, over and under charging, belts, etc.	-10%
Test procedure	Inaccurate acquisition	-10%
	Inappropriate concrete compaction	-50%
	Cure (considered at 28 days or more)	±10%
	Inappropriate concrete capping	-30% to concavity;-50% to convexity
	Rupture (loading rate)	± 5%

Source: Adapted from Helene and Terzian (1992).

It can be seen that several procedures involved in preparation, acquisition and test can directly affect test results and may reduce by up to 50% of concrete compressive strength. Indeed, this variability is true, as we can see in data from research and laboratorial tests. Santiago (2011) compiled technological control data of more than six thousand test specimens, coming from nine Brazilian states. The author identified non-conformity percentages of up to 28% for C40 concrete class. This values reaches 84% for C50 concrete class.

2.3 Considerations on concrete acceptance

Another aspect to be considered is concrete receiving and acceptance. Observing the main Brazilian national and international concrete standards, it appears diverging aspects regarding method and acceptance criteria. (Pacheco; Helene, 2013; Magalhães, 2014). The Brazilian standard, NBR 12655 (ABNT, 2015), presents two kinds of concrete sampling: total and partial. In partial concrete sampling, only some of the total batches is sampled. In total concrete sampling, all batches are sampled and the acceptance criterion is that none of the individual sample presents compressive strength below than the characteristic strength. Despite the high cost, this sampling method is widely used in Brazil (Pacheco; Helene, 2013).

The American standard, *ACI 318-11: Building Code Requirements for Structural Concrete*, establish three different criteria: the average of 3 consecutive test results must be equal or exceeds characteristic strength defined in design; no individual strength test is below than f_{ck}-3,5MPa (to concrete with f_{ck} below 35 MPa) and no individual strength test is below than 0,9* f_{ck} (to concrete with f_{ck} below 35 MPa) (Magalhães, 2014). Additionally, the standard does not provide total concrete sampling, establishing minimum criterion of only one sample per day to each 115 m^3 of concrete or each 465 m^2 of builded area. (Pacheco; Helene, 2013).

Another widely used standard, the British standard *BS EN 206:2013 - Concrete. Specification, performance, production and conformity*, presents different criterion according to the period of production: initial production or continuous production, when more than 15 results are avaible (Magalhães, 2014). The first criterion is related to the average of test results, that must be above or equal to f_{ck}+4,0MPa, to initial production, and above or equal to f_{ck}+1.48*s (standard deviation of results), to continuous production. The second criterion is related to individual test results, that, for both types of production, must be above than f_{ck}-4,0MPa (Pacheco; Helene, 2013; Magalhães, 2014).
Larrossa *et al* (2014) conducted a comparison of the above mentioned sampling criteria to 32 concrete batches. The authors pointed out that NBR 12655 (ABNT, 2015) presents most rigid criteria, followed by EN 206 and ACI 318-11. Indeed, comparing acceptance criteria adopted by international standards with the established by Brazilian standard, it can be seen that the acceptance criteria is more restrictive (Pacheco; Helene, 2013; Magalhães, 2014).

3. CASE STUDY

3.1 Methodological procedures

In conformity control realized in a building construction, by following procedures of NBR 12655 (ABNT, 2015), concrete compressive strength (f_c) of three batches of 8m^3 presented test results below than the f_{ck} of 40 MPa, specified by designer. As the building presents obstacles to extraction of concrete cores, since the structure is made of concrete-filled steel columns, a study of concrete compressive strength evolution was made, in order to helps in the safety assessment of structure. It is noteworthy that this analysis is complementary and must be performed together with other verifications, as the design review with the obtained concrete compressive strength and realization of non-destructive tests. Concrete mix proportions are presented in table Table 2.

Table 2. Concrete mix proportions

Material	Quantity	Unit
Cement CPV-ARI RS	341	kg
Pozzolan	114	kg
Fine sand	284	kg
Medium sand	426	kg
Coarse aggregate	1025	kg
Water	191	l
Polyfunctional admixture	3.41	kg
Superplasticizer	1.14	kg

Source: Concrete supplier

On specified dates, compressive tests were made at certified laboratory, following standards procedures. All specimens were grinded and tests were performed in a universal machine *EMIC – PC 200 CS.* Results are presented in Table 3.

Table 3. Compressive strength test results of non-conforming samples

Sample	Consistency (mm)	Test date	Age (days)	ø (mm)	fc (MPa)	Potential fc (MPa)
1	180	18/02/2015	7	100	23.9	23.9
		18/02/2015	7	100	23.3	
		11/03/2015	28	100	35.2	37.1
		11/03/2015	28	100	37.1	
2	230	18/02/2015	7	100	23	24.6
		18/02/2015	7	100	24.6	
		11/03/2015	28	100	37.4	37.4
		11/03/2015	28	100	34.6	
3	200	31/03/2015	7	100	23.3	23.9
		31/03/2015	7	100	23.9	
		21/04/2015	28	100	38.2	38.6
		21/04/2015	28	100	38.6	

Source: Adapted from tests reports

Regarding to conformity control used in building construction, it is important to mention that total concrete sampling was used (100%), where all of the batches are sampled. In this case, NBR 12655 (2015) states that the acceptance criterion is when all of the individual samples meet the f_{ck} specified by designer. As can be seen in Table 3, the potential strength, at 28 days, does not show strength above or equal than the 40 MPa specified.
Another pointed aspect is strength evolution after 28 days. In a study conducted by concrete supplier, in a year, the concrete presented a strength gain of 32.6% (cement CPV-ARI sulphate resistant with 22% of pozzolan addition), higher than the 16% considered by the ABNT NBR 6118:2014.

3.2 Results and analysis

From test results, it was performed an analysis of concrete compressive strength gain. Initially, β_1 values were calculated using s value of 0.20, since cement type is CPV-ARI. However, an addition of 33% of pozzolan was made (value relative to cement content), so it is appropriate calculate a β_1 value to a CPIV cement type, which contains 15% to 50% of pozzolan. Finally, a third β_1 value was calculated, for an intermediate s value. β_1 values for a 50 years, used in β calculation, are presented in Table 4.

Table 4. β_1 coefficient for different cement types

β1 values for 50 years	
CPV-ARI	1.21
CP “Intermediate”	1.33
CPIV	1.44
ABNT NBR 6118:2014	1.16

Compressive strength evolution over time for the three assumptions (CPV-ARI, CPIV e CP “intermediate”), considering lowest value of $f_{ck,est}$ (37,1 MPa) and a period of 365 days, can be verified in Figure 1.

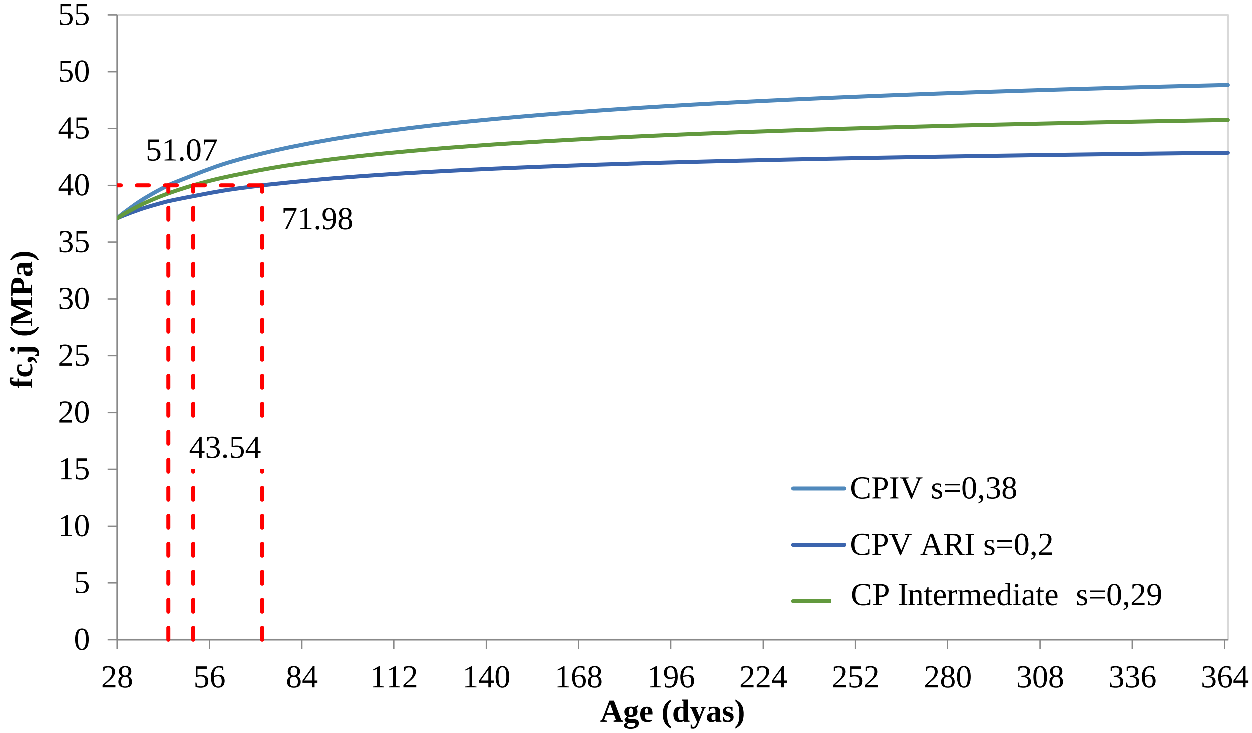

Figure 1. Strength evolution according to fib *Model Code 2010*

As can be seen in Figure 1, to achieve specified 40 MPa, it will take 45 days for β_1 to CPIV concrete, 51 days for β_1 to CP "intermediate" and 72 days for β_1 to CPV ARI. After defining β_1, it was calculated β coefficient, considering two different β_2 – 0.73, as defined by ABNT NBR 6118:2014, and 0.75, maximum value as defined by Rüsch (1960). Values are presented in Table 5.

Table 5. β coefficients for different types of cement and load

Condition	β1	β2	β
ABNT NBR 6118:2014	**1.16**	**0.73**	**0.847**
β_1 from CPV-ARI / β_2 from NBR 6118	1.21	0.73	0.885
β_1 from CP "Intermediate" / β_2 from NBR 6118	1.33	0.73	0.968
β_1 from CPIV / β_2 from NBR 6118	1.44	0.73	1.052
β_1 from CPV-ARI / β_2 maximum - Rüsch (1960)	1.21	0.75	0.909
β_1 from CP Inter. / β_2 maximum - Rüsch (1960)	1.33	0.75	0.995
β_1 from CPIV / β_2 maximum - Rüsch (1960)	1.44	0.75	1.081

For verification of safety in this study case, it was calculated the design compressive strength of concrete f_{cd}, according to Equation 4, using coefficients defined in Table 5. Results are presented in Table 6.

$$fcd = \beta * \frac{fck}{\gamma c} \quad (4)$$

Table 6. Concrete compressive stress

Condition	f_c (MPa)	γ_c	β	f_{cd} (MPa)
ABNT NBR 6118:2014 (reference value)	**40**	**1.4**	**0.847**	**24.2**
β_1 from CPV-ARI / β_2 from NBR 6118	37.1	1.4	0.885	*23.4*
β_1 from CP "Intermediate" / β_2 from NBR 6118			0.968	25.7
β_1 from CPIV / β_2 from NBR 6118			1.052	27.9
β_1 from CPV-ARI / β_2 maximum - Rüsch (1960)			0.909	*24.1*
β_1 from CP Inter. / β_2 maximum - Rüsch (1960)			0.995	26.4
β_1 from CPIV / β_2 maximum - Rüsch (1960)			1.081	28.6
β_1 from CPV-ARI / β_2 from NBR 6118	37.4	1.4	0.885	*23.6*
β_1 from CP "Intermediate" / β_2 from NBR 6118			0.968	25.9
β_1 from CPIV / β_2 from NBR 6118			1.052	28.1
β_1 from CPV-ARI / β_2 maximum - Rüsch (1960)			0.909	24.3
β_1 from CP Inter. / β_2 maximum - Rüsch (1960)			0.995	26.6
β_1 from CPIV / β_2 maximum - Rüsch (1960)			1.081	28.9
β_1 from CPV-ARI / β_2 from NBR 6118	38.6	1.4	0.885	24.4
β_1 from CP "Intermediate" / β_2 from NBR 6118			0.968	26.7
β_1 from CPIV / β_2 from NBR 6118			1.052	29.0
β_1 from CPV-ARI / β_2 maximum - Rüsch (1960)			0.909	25.1
β_1 from CP Inter. / β_2 maximum - Rüsch (1960)			0.995	27.4
β_1 from CPIV / β_2 maximum - Rüsch (1960)			1.081	29.8

The values obtained showed that only when considering exclusively cement CPV ARI the final stress obtained is below than the expected. For concrete with cement with pozzolan addition, as is the case of this study, design compressive concrete strength is above that required. It can be seen a conservative nature of ABNT NBR 6118:2014 – expected characteristic of a technical standard. However, there is a possibility of using consolidated knowledge and move forward in the study of compressive concrete strength gain after 28 days.

It is noteworthy that, according to ABNT NBR 6118:2014, if the compressive strength kept lower than design f_{ck}, a new structural design with the obtained value should be realized. Still remaining the unsafety, the use of structure should be limited, a reinforcement should be designed or even the total or partial demolition of non-conformity elements should be done.

4. CONSIDERATIONS

By analyzing long time effects on concrete compressive strength, as well the recommendations from international standards and others factors involved in technological control of concrete, it can be seen that the requirements established in ABNT NBR 6118:2014 are conservative, leading to a higher safety degree, as expected in technical standards.

However, some criteria established by this standard does not take into account important factors, particularly regarding to concrete strength gain over time, as noted in case study presented. The standard does not take into account actual behavior of the material, since it ignores pozzolan addition effects in this strength gain, besides considering a decrease in strength (*Rüsch effect*) higher than the maximum defined by Rüsch (1960) (Helene, 2011; Silva Filho, Helene, 2011). This factors can affect, directly, β coefficient, that influences structural design.

It is noteworthy that before using new coefficients, another stages of safety assessment must be executed, such as the design review and a rigorous inspection, checking accuracy of execution, geometry and material quality. This stages, in addition to the estimation of performance of concrete over time, can help in safety assessment and in decision-making in cases of non-conformity in structural concrete.

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