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Critical Analysis of HPC Having Very High Contents of Mineral Additions (Part II) Mix Proportion and Durability

Análise Crítica de CAD com Teores Muito Altos de Adições Minerais (Parte II) Dosagem e Durabilidade

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Abstract

The increasing amount of research and number of constructions accomplished using HPC, containing high contents of cement mineral addition substitutions (over 50%, per mass), has been the subject of concern in some studies on topics related to durability of these kinds of concrete, especially shrinkage, due to parameters used in the mix proportions. Accordingly, the low cement content combined with the large amount of cementitious materials would call for an increase in the total water content that, despite the lower w/cm ratios, would cause higher shrinkage and durability loss. This paper presents critical analysis of these subjects and shows data on the research conducted by the authors, compared to other studies published in literature. It has been demonstrated that lower cement content and higher total water per m³ of concrete do not result in consequences related to durability and shrinkage, but lead to the attainment of durable concretes, in such mix proportion conditions. This paper is the second part of a larger project, the first of which deals with mix proportion and carbonation.

Keywords: mix proportion, durability, mineral additions, high contents, shrinkage.

Resumo

O aumento do número de pesquisas e construções realizadas em CAD contendo altos teores de substituição de cimento (acima de 50%, em massa) por adições minerais, tem revelado apreensões entre alguns pesquisadores sobre tópicos relacionados com a durabilidade destes concretos, especialmente retração e durabilidade devido aos parâmetros utilizados na dosagem. Assim, o baixo teor de cimento combinado com a grande quantidade de materiais cimentícios induziria ao aumento da quantidade total de água que, a despeito dos baixos teores das relações a/mc, acarretaria retração alta e perda de durabilidade. Este trabalho apresente análise crítica a respeito desses assuntos, apresentando dados de pesquisas realizadas pelos autores, comparados com outros publicados pela literatura. É demonstrado que baixo teor de cimento, alto conteúdo de água por m³ de concreto não acarretam conseqüências para a durabilidade e retração, induzindo à obtenção de concreto duráveis sob tais condições de dosagem. Este trabalho é a segunda parte de um projeto mais amplo, em que a primeira parte versou sobre dosagem e carbonatação.

Palavras-chave: dosagem, durabilidade, adições minerais, altos teores, retração.

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1 Introduction

Substituting cement for contents having very high mineral additions is used to increase durability of concrete structures, to decrease cement consumption, reduce economic costs and energy expenses. Despite the technical and economic advantages obtained from high pozzolan or slag content in structural concrete, literature shows that shrinkage and long-term durability could be among some of the possible side effects, due to the very high content of fines derived from the cementitious materials. In order to reach higher levels of compressive strength required by the HPC, low w/cm ratios must be used to compensate for the low rate of hydration or pozzolanic reaction and promote high physical effects. In these concrete types, the w/cm ratio decrease presents consequences in the mixture proportion, inherent to the mineral addition reactivity and its content in the mixture, substituting cement. Mineral additions with lower reactivity such as fly ash or granulated blast furnace slag have lower efficiency than that of cement, that is, to obtain the same performance level of the axial compressive strength a higher quantity of addition is necessary, greater than that of the substituted cement.

Therefore, reduction of the w/cm ratio and the increase of mineral addition in the mixtures can lead to increments in the paste volume that, generally, are partially compensated by lower volume of the added sand, for the purpose of maintaining the same mortar volume in the mixture proportion. As a consequence of the higher quantity of cementitious materials in the mixture and the adoption of low w/cm ratio, the total added water quantity increases, even though more efficient superplasticizer admixtures are used. In general, these mixture conditions may induce higher shrinkage or creep.

It is well known that for a given water/cement ratio the drying shrinkage and the creep increase according to the increased cement content [1, 2, 3]. Replacement of cement by mineral additions such as pozzolans and slags tends to increase the finer pore volume in the cement hydration products. Since the shrinkage is associated with the water content in the small pores (3-20 nm), the mineral additions that cause pore refinement normally increase the drying shrinkage [3].

For the same w/cm ratio, Brooks and Neville [4] found that in a higher proportion of fly ash or slag, shrinkage increased 20% for the former and up 60% to the latter. On the other hand, other research [5, 6, 7] that investigates concrete mixtures with high volumes of fly ash and cementitious materials ranging from 400 to 500 kg/m³ concludes that the total binder content has little effect on drying shrinkage. Concrete mixtures with cement replacement of 70% of slag or more, tend to present the same behavior, that is, similar or lower drying shrinkage than the reference mixtures [8, 9, 10, and 11].

In order to contribute toward the study of these issues, the present work is a critical analysis of the mix proportion of HPC in binary and ternary mixtures with cement replacement of 70% of slag and 20% fly ash plus 70% slag, with total cementitious materials ranging from 418 to 627 kg/m³. The main purpose of this paper is to study the role of these mix proportions on the shrinkage and durability performance compared to results of other researchers with similar mineral addition content. The considerations and discussions are based on test results obtained from Concrete Studies and Research Group (GEPECON) of UFSM, whose arguments are based on the paper by Isaia and Gastaldini [12] and others published by GEPECON in recent years, related to this subject. This text is the second part of a larger work, the first of which was published previously and dealt with mix proportion and carbonation of these concrete mixtures with very low cement content.

Table 1 – Water, cementitious materials and cement content for 55 MPa at 91 days (12)

Mix *	Mineral Additions %	Total water l/m³	Cementitious Materials kg/m³	OPC kg/m³
Ref.	-	188	397	397
FL	50	168	418	209
F	50	184	536	268
SL	70	178	503	151
S	70	186	627	188
FSL	20+70	174	570	57
FS	20+70	192	590	59

2 Materials and experimental program

This study is part of the research project 'Hydrated Lime addition effects on structural concrete with high mineral addition content' developed by GEPECON. High-early strength cement CPV-ARI; fly ash from a power plant; rice husk ash from a local rice mill; packed calcitical hydrated lime; ether-carboxylic based superplasticizer admixture; natural quartzeous sand and dibasic crushed coarse aggregate were employed.

Table 2 – Durability test results for 55 MPa at 91 days(12)

Mix	Mineral Additions %	Oxygen Permeability $10^{-17}m^2$	Capillary Absorption g/m²	Chloride Penetration coulomb	Cl^-/OH^- Ionic relationship
Ref.	-	10.6	469	2775	1.06
FL	50	2.4	1289	1050	0.21
F	50	9.2	2327	765	0.74
SL	70	0.5	210	971	0.26
S	70	9.9	210	779	0.30
FSL	20+70	20.3	149	445	0.35
FS	20+70	315	1269	425	0.97

Eleven mixtures with 0.35, 0.45 and 0.55 w/cm ratios, one as reference and ten with cement substitution in contents from 50% to 90% of fly ash, rice husk ash and/or slag were cast. Hydrated lime was used as an addition to the cementitious materials, in 15% and 18% contents, near the CH replacement ones produced by the cement, to restore the alkaline reserve. The mixture proportions were made for 60±15mm slump, in equal parts of mortar volume.
The following durability tests were conducted: a) compressive strength in 10x20 cm specimens according to Brazilian Standard NBR 5738 (ASTM C 39) [13]; b) oxygen permeability by the RILEM-CEMBUREAU method [14]; c) water capillary absorption in 5x15 cm specimens according to RILEM TC 116-PCD recommendation [14]; d) chloride permeability test according to the ASTM C-1202 method [15]; e) ionic Cl^-/OH^- relationship according to [16]. The strength equality procedure among the durability variables was adopted for results analysis. The 55 MPa strength level was chosen to represent high-performance concrete. Table 1 shows the water, cementitious materials and cement consumption per cubic meter of concrete for some selected mixtures and Table 2 the durability test results. More details about materials and results are obtained in the Isaia and Gastaldini [12] paper.
Table 1 shows that for slag binary and ternary mixtures, with or without lime, the total cementitious materials per m³ of concrete ranged from 418 and 627 kg/m³ for 55 MPa compressive strength level at 91 days. According to established knowledge, these high fines content may produce higher shrinkage and cracks in the concrete paste. Despite this, Table 2 demonstrates that, for these mixtures, in general, the durability performance was better than the reference concrete, with 397 kg/m³ of OPC, values from 27% and 58% inferior to the former ones in the mentioned mineral additions mixtures. Some critical considerations about these subjects will be made as follows.

3 Discussion

3.1 Mix proportion and shrinkage

It is well known that shrinkage depends on many factors such as w/cm ratio, unit cement and water content, paste/aggregate ratio, etc. The higher these factors, the greater the shrinkage will be. However, for HPC with very high mineral additions content, the denser microstructure and interstitial transition zone (ITZ) due to the refinement of the pores structures, added to the lower cement content (less autogenous shrinkage) and diminished w/cm, may counterbalance any eventual increase of the paste or water content. To exemplify this argument and compare it with the obtained results in this paper, Table 3 presents some selected results from literature about the total shrinkage, ordered according to the increase of the total cementitious material content.
In order to compare the data presented in Table 3 with specified values of codes, some statements have been made. Mehta and Monteiro [3] declare that drying shrinkage in concrete present micro strain from 400 to 1000x10^{-6} (0.04 to 0.10 %); and Mehta and Aitcin [17] state that, frequently, the shrinkage strains in concrete are as high as 0.08%. According to Brown [18], there is a rapid test available in BS 812: Part 120 to classify aggregates into low and high shrinkage, as advice to indicate the basis on which such aggregates can be used. So, this Code states that, for all concreting purposes subject to deflection design checks for highly eccentrically prestressed concrete, the drying shrinkage must be below 0.075%. According to CEB Model Code [59] for concrete structures with compressive strength between 60-70 MPa in 50% RH environment and slender structural pieces, the drying shrinkage ranges between 0.06-0.07%. Luther and Hansen [19] calculated the mixture proportion referred to in Table 3, item 14, according to the ACI 209, found for the ultimate shrinkage 0.062%. All these figures state that to achieve good quality HPC, shrinkage must be below a percentage of around 0.065%.
It is evident that care must be taken when comparing data of tests made with different materials, ages and curing conditions. Taking into account this precaution, Table 3 reveals data of different papers, in which it is possible to establish a trend of the shrinkage behavior with the ascending amount of the cementitious materials in the mixtures. It is possible to separate the results into two groups as shown in Table 4, together with the 3 mixtures F, S, and FSL of the present experimental study, according to Table 1. Comparing the results of the two groups, it can be seen that group 1 shows lower unit water content, higher w/cm ratio, lower CM and compressive strength and higher shrinkage compared to the group 2. These results suggest that shrinkage depends, in a higher degree, on the w/cm than the unit water content, because in group 1 the mean water content is 162 l/m³ and the w/cm = 0.42, for a mean shrinkage of 0.061%, while for group 2 the mean water content increased to 182 l/m³ (+12.3%) and the w/cm decreased to 0.31 (-26,2%), and the mean shrinkage decreased to 0.055% (-9,8%). Therefore, for higher CM content and lower w/cm, even with higher unit water content, a denser microstructure and ITZ is obtained due to the pore refinement resulting in lower shrinkage degree, confirming Coppola's [20] and Nagataki's [21] opinions.
Table 4 shows that group 2 compares better with the mixtures of this paper because they relate to HPC with w/cm, unit water and CM with figures closer than those of group 1. Returning to Table 3 can be observed that there is a close relation to the cementitious materials (CM). Making a statistical correlation through a simple linear regression among data of columns (6) and (8) of group 2 (items 7 to 17), the following equation was found:

$$Shr_{\%} = 1.014 \cdot 10^{-4} CM_{kg/m^3} - 1.82 \cdot 10^{-3} \quad (r = 0.75 \text{ or } r^2 = 0.56) \qquad (1)$$

The determination coefficient shows that 56% of the CM total variance is explained by the shrinkage variance, which is a median correlation, with an estimative standard error of s_e = ± 0.003.

According to Table 4, group 2, the figures for a specific range of w/cm (≤ 0.40), of compressive strength (≥ 54 MPa) and mixtures of concrete with mineral additions content between 466 and 667 kg/m³, include the figures of this paper. This correlation indicates that there is an increasing tendency toward shrinkage with the increase of the CM unit content. Those data demonstrate that even for the highest shrinkage displayed in Table 3 (item 17, CM = 667 kg/m³, Shr = 0.065%), they comply with the limits specified by codes, as mentioned above, that is, 0.065% as a maximum value for good quality concrete.

Data on shrinkage is not presented in the experimental study of this paper because this test is part of the second phase of another ongoing research program. However, to give an idea of the shrinkage range with the data of the present paper, Table 5 presents data of a research program that was accomplished with the same materials (sand, coarse aggregate, FA) of the present program, according to Isaia [33].

Table 3 – Shrinkage data of concretes with high content of cementitious materials

Item	w/cm	Fc MPa (days)	PC kg/m³	CM kg/m³	Total CM kg/m³	Water l/m³	Shrinkage %	Age * days	Curing days **	Reference
1	0.43	35 (91)	230	77 (FA)	307	132	0.068	448	7	Gleber, Klieger (22)
2	0.55	58 (91)	238	102 (SF)	340	191	0.065	91	1	Yamato et al. (23)
3	0.31	35 (28)	157	215 (FA)	372	115	0.061	224	1	Sivasundaram et al. (24)
4	0.40	72 (91)	289	124 (FA)	413	165	0.062	182	n.a.	Fukudome, et al. (25)
5	0.43	64 (84)	131	306 (slag)	437	188	0.053	70	14	Brooks et al. (4)
6	0.40	54 (180)	200	250 (FA)	450	180	0.058	504	7	Swamy, Hung (6)
7	0.32	60 (28)	233	233 (FA)	466	147	0.048	730	1	Swamy, Mahmud (26)
8	0.34	70	150	350 (slag)	500	170	0.052	182	7	Maeda et al. (27)
9	0.33	77 (28)		514 (slag)	514	168	0.041	28	7	Yasumoto et al. (28)
10	0.35	70 (28)	405	135 (FA)	535	190	0.052	365	3	MacGregor (5)
11	0.30	57 (28)	557		557	169	0.053	38		Ohno, Umoto (29)
12	0.30	54 (28)	340	225 (FA)	565	170	0.060	56		Sirivivatnanon et al. (30)
13	0.29	79 (91)	479	90 (FA)	569	167	0.052	400	7	Luther, Hansen (19)
14	0.28		143	429 (slag)	572	160	0.064	110	1	Matsushita et al. (31)
15	0.30	73 (28)	417	179 (LF)	596	181	0.053	56	seal	Montgomery et al. (32)
16	0.30	58 (28)	307	307 (FA)	614	183	0.064	182	7	Isaia (33)
17	0.30	78	467	200 (SF)	667	200	0.065	400		Tazawa, Yonekura (34)

* Total time of shrinkage test ** days under moisture before air-curing

Table 4 – Groups of the selected concrete mixtures (from Table 3)

Items	Table 3 Group 1	Table 3 Group 2	Mixtures * FSL, SL, S
Items	1 to 6 (n = 6)	7 to 16 (n = 10)	(n = 3)
Water – l/m³ (range)	115 – 191	147 – 200	174 –186
Water – l/m³ (mean)	162	182	179
w/cm (range)	0.31 – 0.55	0.28 – 0.35	0.29 – 0.37
w/cm (mean)	0.42	0.31	0.33
CM – kg/m³ (range)	307 – 450	466 – 667	503 – 627
CM – kg/m³ (mean)	387	559	567
Shrinkage % (range)	0.053 – 0.068	0.041 – 0.065	n.a.
Shrinkage % (mean)	0.061	0.055	
fc – MPa (range)	35 – 67	54 –78	
fc – MPa (mean)	54	68	55

* Mixtures of the experimental study of this paper

To compare the most similar mixtures between Isaia's [33] data and this paper, Table 6 shows that, except for the paste content, all other parameters are very close and there are only little differences between them. The shrinkage value obtained from the test, for the FA/RHA mixture, was the same as the S mixture calculated by equation (1). These results demonstrate that the estimation made through the statistical model with data of Table 3, in line with the test data obtained from the same materials of this paper.

The data for shrinkage showed in Table 6, compared to that obtained by the authors listed in Table 3 (column 8) evidence that they are close, considering items from 7 to 17. All of them are below the limits indicated by codes, as stated above. This data show that the use of very high mineral additions content in HPC with low w/cm ratios does not impair shrinkage performance.

3.2 Mix proportion and durability

Also included in the scope of this paper is a discussion of the durability of HPC with cement replacement by very high mineral additions' content, equal to 55 MPa compressive strength. According to hypothesis, considering that the mixtures of this experimental study would have to fulfill simultaneously the following imposed durability conditions:

a) oxygen permeability coefficient: $k_{O2} \leq 30 \cdot 10^{-17}$ m² (moderate coefficient), according to Lee et al. [35];

b) water capillary absorption: $Q_w \leq$ 1,000 g/m² (low absorption): arbitrated value based on data presented by Baroghel and Larrard [36];

c) chloride-ion penetration: C ≤ 1,000 coulomb (very low penetration), according to ASTM C1202 [15];

d) ionic Cl^-/OH^- ratio ≤ 0.6, according to Haussmann [16];

e) cement consumption: OPC ≤ 200 kg/m³, arbitrated value based on sustainability performance.

Comparing these figures with the Table 1 and 2, the mixtures that fulfilled these conditions are shown in Table 7.

The best result was obtained for the FSL mixture with 90% of mineral addition, with w/cm = 0.32, containing only 57 kg/m³ of OPC and 570 kg/m³ of CM and 174 l/m³ of

Table 5 – Shrinkage data according Isaia (33)

Mix	w/cm	Paste volume %	OPC kg/m³	CM kg/m³	Total CM kg/m³	Shr. Test %
REF	0.30	38	614		614	0.063
FA	0.30	41	307	307	614	0.064
FA/SF	0.30	42	307	307	614	0.064
FA/RHA	0.30	42	307	307	614	0.061

Table 6 – Comparison between FA/RHA (33) and S mixtures (present paper)

Mix	w/cm	Paste %	OPC kg/m³	CM kg/m³	Total CM kg/m³	Shr % Test
FA/RHA	0.30	42	307	307	614	0.061
70 S	0.29	38	188	439	627	0.061*
Difference %	7	10			2	0

* Datum calculated according equation (1) – mean value

Table 7 – Mixtures the complied with the case study conditions

Items	Mixture	CM content %	w/cm	OPC kg/m³	CM kg/m³	Total Water l/m³
1	FSL	20FA+70S	0.32	57	570	174
2	SL	70S	0.37	151	503	178
3	S	70S	0.29	188	627	186

water. This 55 MPa mixture performed as shown below compared to the specified limits mentioned above:
i) Oxygen permeability coefficient = $20.3.10^{-17}$ m² - 1.5 times lower than a);
ii) Water capillary absorption = 149 g/m² - 6.7 times lower than b);
iii) Chloride-ion penetration = 445 coulomb – 2.2 times lower than c);
iv) Cl^-/OH^- ratio = 0.35 - 1.7 times lower than d);
v) Cement consumption = 57 kg/m³ - 3.5 times lower than e):

Despite the very low cement consumption and relative high total water content, the figures above regarding short-term durability performance, will probably also represent, good long-term performance for such mixture.

There is a belief that the use of very a high amount of mineral additions and, as a consequence, very low cement content, combined with the use of more than 150 l/m³ of water, will not confer long-term durable concrete. This suspicion is groundless because many papers have been published about this subject contradicting the former statement, according to the following references. The main question is: what is a long-term durable concrete? A great part of the researchers that deal with concrete technology know that durability is a vague concept. Aitcin [37] states that it is difficult to make statements about the durability of a 'new material', because durability relates to the long-term performance of a particular material, in a particular environment, under particular service conditions and, since durability cannot be assessed if this knowledge of its long-term behavior is unreliable, it is very difficult in a more and more litigious human environment to specify a 'new material'.

Durability it is not a property that depends on concrete itself only, but on the environmental microclimate that surrounds the structural concrete. Concrete is able to be durable under specific conditions and not others. So, a determination as to whether concrete is durable or non-durable with a given mixture proportion with mineral additions is a relative concept. There is not a deterministic or prescriptive approach that determines whether a concrete will or will not be durable. Only extensive delimitations can be settled in order to set some reasonable general concepts to define durability of a specific concrete mixture. The statement that one or the other concrete will or will not be durable will depend on many interconnected parameters and conditions, most of them depending on the materials and environmental conditions. In fact, Shilstone and Shilstone [38] affirm that there are no quantitative means known that can help one proportioning mixtures to select proportions that will meet high-performance needs for durability because there are too many variables affected by shape, texture, availability and cost. They also state that there are no engineering formulas that can be used to design a concrete mixture that will be durable because technology is knowledge based.

However, some general rules are outlined by International Institutions such as Fib (ex-CEB), RILEM, ACI, ENV, etc., that prescribe generic conditions for long-term durability of concrete structures. The most important one is the use of low w/c or w/cm that must be below, in general, to 0.45 or, for some severe conditions, 0.40, especially for HPC. All 55 MPa mixtures mentioned in Table 4 of this paper fulfill the latter limit (FSL, SL and S). The other ones presented w/cm ≤ 0.46.

The classic paper by Mehta and Aitcin [17] establishes that a durable HPC should meet lower impermeability (chloride-ion penetration ≤ 500 C) and high dimensional stability (high elastic modulus, in general ≥ 30 to 35 GPa, low creep and drying shrinkage) and present, also, w/cm ≤ 0.4. For HPC,

Table 8 – Mixture proportions of selected buildings

Building	CM kg/m³	Water l/m³	w/cm	fc MPa	Reference
Commerce Tower – Houston	490	161	0.33	65	Mehta, Aitcin (17)
River Plaza Chicago	565	195	0.35	78	Aitcin (39)
Demix Béton Montreal	577	172	0.30	66	Aitcin (39)
Water Tower Place – Chicago	565	195	0.35	79	Aitcin, Neville (40)
Chibune Riverside Vila Tower	500 *	187	0.37	54	Takahata et al. (41)
FSL 55	570	183	0.32	55	This paper
SL55	503	184	0.37	55	This paper

* Only ordinary Portland cement

Table 9 – Mixture proportions of selected SCC

Item	w/cm	PC kg/m³	CM kg/m³	Total CM kg/m³	Water l/m³	fc MPa (days)	Reference
1	0.30	430	170	600	180	82 (28 d.)	Coppola et al. (20)
2	0.44	425	60	485	190	65 (91 d.)	Collepardi et al. (42)
3	0.29	407	244	651	186	70 (28 d.)	Gettu et al. (43)
4	0.45	440	120	560	203	40 (28 d.)	Corinaldesi et al. (44)

35% cement paste, in volume, represents an optimum solution in balancing the conflicting requirements of strength, workability and dimensional stability. In other words, by using suitable coarse aggregate, adequate dimensional stability of HPC concrete (elastic behavior, drying shrinkage and creep) can be obtained at a fixed cement/paste ratio of 35 to 65% in volume. These authors state also that for HPC compressive strength for 65 MPa grade, the maximum water content must be 160 l/m³, decreasing 10 l/m³ for each 10 MPa increase. As this paper discusses concrete mixtures with 55 MPa compressive strength, performing an extrapolation for this value, the HPC mixtures with this strength grade would present maximum water content of 170 l/m³.

Table 8 show examples of mixture proportions from selected buildings that have been built more than 15 year ago. The cementitious materials, total water, w/cm and compressive strength present figures similar or close to this paper. This demonstrates that mixtures with CM ≥ 500 kg/m³ and water ≥ 150 l/m³ and low w/cm are able to be characterized as durable structures, since some of these constructions are near of 30 years old. Comparing the mixture proportion of the Chibune Riverside Vila Tower with the SL55 mixture of this paper it shows almost the same figures, except for the cementitious material that, for the first one, was composed only by ordinary Portland cement (100%) and the second presented OPC = 151 kg/m³ (30%) and 352 kg/m³ of slag (70%), what induces a better long-term durability performance than the former one.

On the other hand, today, the experimental research tendency is using self-compacting concrete (SCC) in a several kinds of structural applications. The mixture proportion of these concretes requires high paste dosage (≥ 40%), high fines content, generally as cementitious materials (≥ 500 kg/m³) and water content (≥ 180 l/m³). Some recent investigations are presented in Table 9. Except reference of item 2 (Collepardi et al., [42]) the other figures are similar or higher than the present investigation ones.

In the investigation of Coppola et al. [20] in which 600 kg/m³ of CM and 180 l/m³ of water with w/cm = 0.30 were used, the authors conclude that as consequence of the experimental results and on the basis of data available in technical literature, self-compacting concrete (SCC) should provide higher intrinsic durability and a lower tendency to crack. In other words, structures with SCC could be significantly more durable than those manufactured with conventional concrete.

Despite the low cement content of the FSL mixture (OPC = 57 kg/m³) of this paper, which acts as activator for 513 kg/m³ of CM, plus 108 kg/m³ of lime, there is a sufficient amount of cementitious compounds to form a compact microstructure, such as in SCC of Coppola et al. [20] paper. The advantage of the FSL mixture is the great pore refinement due to the pozzolanic and hydration reactions, and the physical effects caused by the surface actions between the finer grains.

Corroborating the remarks on this subject, Nagataki [21] says that the use of a large amount of mineral admixture with the expectation of benefiting from its effect as a fine powder rather than as a cementing material and the addition of a large amount of fly ash or ground-granulated blast-furnace slag, for the purpose of increasing the fines, also results in improved long-term strength and lower heat of hydration.

The discussion above demonstrates that, despite the very low content of OPC (10%) and very high total cementitious materials (90%), the data showed in the paper related to the durability properties attest to good performance for the concrete mixtures that are similar to those employed in tall buildings 30 years ago or, nowadays, in self compacting concrete.

3.3 Durability with very low cement content

Today, the term "cement", as the classic definition states, has become more common because of the great number of cementitious materials that are ground with the clinker or substitute part of the OPC at the ready mixer's plant or at the job site. According to ASTM C 1157 [45], what matters is that the CM contributes to the strength-building properties of the cement. Regardless of the cementitious materials blend used together with OPC, the most important effect of these additions is that the cementitious compounds formed by hydraulic, pozzolanic or physical-chemical action, show over time, strength and durability gains, according the specificities of each blend. Today, the tendency is to use large amounts of these mineral additions in order to benefit from technical, economical and social gains. As Mehta [46] states superplasticized concrete mixtures containing 60 to 70% fly ash or slag by mass of the total cementitious materials show high strength and durability at relatively early ages and it is obvious that large-scale cement replacement in concrete with these in-

Table 10 – Mixture proportions for 65-MPa compressive strength (47)

Mixtures %	w/cm	OPC – kg/m³	CM – kg/m³	Water – l/m³	MPa/kg of CM
100-PC	0.38	456	456	170	0.143
50-FA	0.32	265	530	151	0.122
50-RHA	0.38	222	444	159	0.146

dustrial by-products will be highly advantageous from the standpoint of durability.

The 55 MPa 70%-slag (SL) and 20%-fly ash plus 70-slag (FSL) mixtures, both with lime, presented in this paper, due to the figures that demonstrate the good durability performance, are a practical example of the viability of using large amounts of CM and low cement content. Regardless of the relative amount of OPC compared to other CM in the mixture, what matters is the final result of the resistant compounds formed by different reactions or mechanisms. Isaia et al. [47] state that when using cement with mineral additions, it is necessary to have a compatible combination of minimum amounts of solid material per volume units of Portland cement paste and a hybrid, combined and synergistic action among three effects is necessary: hydration, pozzolanic and physical effects. It is necessary to provide the paste with a given minimum unitary strength to reach the desired real strength level.

To illustrate this statement, according to Isaia et al. [47], Table 10 shows that in order to obtain the 65 MPa compressive strength grade, for fly ash, pozzolan with less reactivity, it was necessary to add a greater amount than RHA because of its higher reactivity. The greater the cement substitution, the higher mineral additions' content with low reactivity that must be present in the mixture, in order to counterbalance the resistant compounds with lower CaO/SiO_2 ratio, mainly C-S-H of lower density. For FA mixture it was necessary CM = 530 kg/m³ while for RHA only 444 kg/m³, 86 kg/m³ less. The problem with the latter pozzolan was the CH depletion that, in this case, reached almost zero. The decrease of the alkaline reserve is the main reason for adding lime in order to replace the one that was not formed by the cement substitution.

Table 11 shows the same figures for the 3 mixtures of this paper. For the FSL mixture with only 57 kg/m³ of OPC and 570 kg/m³ of CM, the unit strength was 0.096 MPa/kg of CM to reach the 55 MPa compressive strength level. On the other hand, for the SL mixture with 188 kg/m³ of OPC (3.3 times higher than the latter) and 627 kg/m³ of CM (1.1 times higher) the unit strength was 0.088 MPa/kg of CM (9% lower than the preceding one). The SL mixture with lime showed an unit strength of 0.109 MPa/kg of CM, 1.24 times higher than the S one without lime, revealing the advantage of the lime addition in order to enhance the microstructure compounds with less cement (151 against 188 kg/m³ - 20% lower). The FSL mixture with only 57 kg/m³ of OPC and w/cm = 0.32 showed better durability performance than the S one with 188 kg/m³ of PC, with lower w/cm = 0.29. These figures illustrate the arguments abovementioned.

Therefore, whatever the composition of the cementitious paste microstructure, ordinary Portland cement, pozzolans, slag, etc., the important factor is the amount of resistant compounds (in primary or secondary bonds) per volume or mass unit, in order to confer strength and durability, through the choice of an adequate w/cm relationship that propitiate pore structure compatible with the specified properties required by the concrete structure during its useful life. In fact, Mehta [48] states that it is strongly recommended that pozzolanic and cementitious by-products are addressed by the term complementary cementing materials. These materials need Portland cement for their activation; and Portland cement-based products need them to improve their durability and ecological profile.

Ordinary Portland cement may act as a main binder for a mixture with complementary cementing materials or as an activator when present in low content in the mixture. Thus, the amount of OPC in a cementitious mixture will depend on the type and quantity of the mineral addition in the mixture proportion. With binary mixtures containing silica fume the Portland cement substitution can reach 10-15%, with RHA 30-40%, with fly ash 50-60% and with ground-granulated blast-furnace slag 60-90% or even 100% in the alkali-activated slag cements. All these mixtures proportions may show long-term durability in structural concrete, when adequate materials' choice and proper mixture proportion are applied. As the better dura-

Table 11 – Mixture proportions for 55MPa compressive strength (this paper)

Mixtures	w/cm	OPC – kg/m³	CM – kg/m³	Water – l/m³	MPa/kg of CM
90%-FSL	0.32	57	570	174	0.096
70%-SL	0.37	151	503	178	0.109
70%-S	0.29	188	627	186	0.088

bility performance was for the SFL mixture in this paper, the 10%-OPC content acted as activator of the slag and fly ash. In fact, Swamy [49] says that because of their nature, FA and slag react more slowly with lime and water than OPC, but they can be activated chemically and, from a practical point of view as well as for long-term material stability, ordinary Portland cement is the best activator for the production of concrete.

Currently, many papers discuss the good performance of mixtures with lean OPC content and very high quantity of slag or fly ash, mainly related to properties connected to durability such as elastic properties, shrinkage, creep, freezing-thawing resistance and others. Haynes and Connell [50] presenting the prior art of the GGBS use in concrete, state that the significant benefit from using slag in a concrete mix is the decreased heat of hydration which reduces

Table 12 – List of some researches about lean OPC content

Item	Author(s)	w/cm	Cementitious Materials (OPC) kg/m³	Mineral addition %	Main conclusions on durability properties (compared with the OPC mixtures)
1	Langley et al. (8)	0.33	240 (48)	80% fly ash	Good performance to elastic properties, drying shrinkage, creep and freezing-thawing
2	Roy (51)	-		50-85% slag	Lowest Cl^- penetration to 85% slag mortars. Diminished pore size, increased durability to Cl^-
3	Cook et al. (52)	-	280-550 (55-168)	40-90% slag	Cl^- penetration decreased with the cement increase. Slag as a good cement replacement in marine environments.
4	Brooks et al. (53)	0.43		30-70% slag	Great long-term strength, similar shrinkage, lower basic creep, similar or lower total creep.
5	Tomisawa et al. (10)	-		15-90% slag	The higher slag content the lower bleeding ratio, less adiabatic temperature rise, higher compressive strength, similar shrinkage and higher carbonation.
6	Nagataka (21)	-		≥65% slag	Better chemical resistance due to improved water tightness, suppression the infiltration of Cl^- and the alkali-aggregate reaction.
7	Boukendakdjii et al. (11)	0.43	437 (87-219)	50-70% slag	Similar shrinkage, lower total creep
8	Lang and Geiseler (54)	0.29	455 (100)	78% slag	Low capillary porosity, higher impermeability to organic liquids, higher freeze-thaw and deicing agent resistance.
9	Nakamoto et al. (55)	0.38	280 (42)	85% slag	Lower coefficient of water permeability
10	Nakamoto et al. (56)	0.33	306 (15)	95% slag	Better performance to freezing-thawing test and higher durability factor after 300 cycles.
11	Aldred and Rangan (57)	0.40		65-85% slag	Lower Cl^- penetration depth.

the risk of cracking during the early stages of hardening the concrete structure and consequently will enhance the durability of the concrete structure. These authors conclude that incorporating GGBS in concrete mixes provides enhanced resistance to sulphate attack, alkali silica reaction, acid attack and seawater attack and the increased durability of such concretes will result in the increased service life of a given structure. Table 12 summarizes some of these papers published along the last years.

Comparing the SFL mixture proportion for strength level of 55 MPa, with 57 kg/m³ of OPC of this paper to the data displayed by Table 12, a close similarity is evidenced, because all of them showed OPC substitution by slag in the higher range from 65% to 95% and, obviously, from 5% to 35% of OPC (15-87 kg/m³), that is, very low cement content. The data and conclusions of these papers show the good durability performance and practically all properties of these concrete were benefited with the increase of the slag amount and do not entailed harmful consequences to the concrete structures, except to the low early-age strength progress and carbonation depth.

In order to compare the data mentioned above in Table 12 to the FSL concrete mixture of this paper with 70% of slag, 20% of FA and 10% of OPC, Table 13 summarizes the mixture proportion data with the test results. The reference column shows specified limits given in the literature. Table 13 shows that all durability variables comply with the minimum (or maximum) specified values. Therefore, this concrete (as the 55 MPa SL one) could be classified as durable, under long-term conditions, despite the great amount of CM and moderate unit water content. It is obvious that the tests presented in this paper (Table 13) alone are not enough to ensure long-term durability. An extensive long-term experimental research program with prototypes would provide further answers. The authors are convinced that with the data presented in this paper, the forecast for a long-term durable concrete with low OPC content are promising. Nevertheless, more tests are required in order to strengthen this position through specific tests, such as elasticity modulus, tensile strength, shrinkage and creep, freeze-thaw, resistance to acids and to deicing salts scaling and others. Therefore, taking into account the data, arguments and references presented above, it was demonstrated that the 55 MPa SFL, SL and S mixtures present requirements to be considered as durable concrete over the long-term.

4 Conclusions

According to the test results, as well as the discussion made in this paper, along with the references of the revised bibliography and the references of the selected literature, the main conclusion may be summarized as follows:

a) The figures for shrinkage obtained in the investigation compared to data obtained by the selected authors (Table 3, column 8) evidence that they are close and are below the limits indicated by codes. These data show that the use of very high mineral additions' content in HPC with low w/cm ratios does not impair shrinkage performance.

b) Despite the very low content of OPC (10%) and very high total cementitious materials (90%), the figures showed in the paper related to the durability properties attest good performance for the concrete mixtures, that are similar of those employed in tall buildings as much as 30 years old and nowadays in self compacting concrete or mixtures with lean OPC content and high volumes (65-95%) of slag.

c) By comparing data of some selected durability properties of the FSL concrete mixture with the specified limits given by the literature (Table 13), it has been shown that the w/cm, the O_2 oxygen coefficient, the water absorption, the pH, the Cl^-/OH^- ratio and the Cl^- penetration comply

Table 13 – Mixture proportions and test result of the SFL 55 MPa mixture (reference limits of the literature for durable HPC)

Materials/tests	Data (results)	Limits (reference)
Portland cement	57 kg/m³ (10%)	
Slag + fly ash	513 kg/m³ (90%)	
Total CM	570 kg/m³	
w/cm	0.32	≤ 0.40 (Mehta, Aitcin (17))
Total water	174 l/m³	170 l/m³ (Mehta, Aitcin (17))
Oxygen diffusion coeff.	$20.3 \cdot 10^{-17}$ m²	$10 \leq KO2 \leq 30.10^{-17}$ m² = moderate coefficient (Lee et al. (35))
Water absorption	149 g/m²	≤ 1000 g/m² (very low absorption) (Baroghel, Larrard (36)) *see item 3.2
pH	12.9	≥ 12.5 (FIP (58))
Cl^-/OH^-	0.35	≤ 0.6 (Haussmann (16))
Chloride penetration	445 coulombs	≤ 500 coulombs = very low penetration (Mehta, Aitcin (17))

with the minimum (or maximum) specified values. So, this concrete could be classified as a durable one, under long-term conditions, despite the great amount of CM and moderate unit water content.

d) The data and demonstrations presented in this paper show the good durability performance and practically all studied properties benefited from the increase of the slag or fly ash amount in the mixture, and do not entail harmful consequences to the concrete structures, except for the low early-age strength progress and carbonation depth.

e) The results presented in the paper evidence that the forecast for a long-term durable concrete is evident. Nevertheless, more tests are required in order to strengthen this position.

Nomenclature/definition/abbreviation list

ACI – American Concrete Institute
ASTM – American Society for Testing Materials
Binary Mixture - OPC plus one mineral addition (fly ash or slag)
CEB – Comité Européen du Béton (European Concrete Committee)
CEMBUREAU – The European Cement Association
Cl^-/OH^- – ionic relationship between the total retained chloride and the hydroxyls (in mmol/g or %
CM – cementitious materials
CPV- ARI – high-early strength cement type CP V (Brazilian Standard)
ENV – European Pre Standard
F – binary mixture with 50% of fly ash
FA - fly ash
fc – compressive axial strength, in MPa
FIB – Fédération Internationale du Béton (International Federation for Structural Concrete)
FIP – Féderation Internationale de la Précontraintre (International Federation of Prestressed Concrete)
FL – binary mixture with 50% of fly ash plus lime (calcium hydroxide)
FS – ternary mixture with 20% of fly ash plus 70% of slag
FSL – ternary mixture with 20% of fly ash, 70% of slag plus lime (calcium hydroxide)
GEPECON – Concrete Studies and Research Group
GGBS – ground granulated blast-furnace slag (= slag)
HPC – high-performance concrete
ITZ – interstitial transition zone
NBR – Norma Brasileira (Brazilian Standard)
OPC – ordinary Portland cement
REF – reference concrete with OPC only
RH – relative humidity
RHA – rice husk ash
RILEM - International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM, from the name in French)
S - binary mixture with 70% of slag
SCC – self-compacting concrete
SF – silica fume
Shr – shrinkage
SL – binary mixture with 70% of slag plus lime (calcium hydroxide)
Ternary Mixture – OPC plus two mineral additions (fly ash and slag)
UFSM – Federal University of Santa Maria

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6 References

[01] MINDESS, S., YOUNG, J. F. *Concrete*. Prentice-Hall, Englewood Cliffs, 1981.
[02] NEVILLE, A. M. Properties of concrete. Pearson Educational, Edinburgh Gate, 3rd ed., 1995.
[03] MEHTA, P. K., MONTEIRO, P. *Concrete – Structure, properties and materials*. Englewood Cliffs: Prentice-Hall, 1993, 2nd ed.
[04] BROOKS, J. J., NEVILLE, A. M. Creep and shrinkage of concrete as affected by admixtures and cement replacement materials. In: DAYE, M. A., FU, C. C. (eds). ACI Committee 209 Creep and Shrinkage Concrete *Proceedings*. Detroit, American Concrete Institute, 1992, p. 19-36 (SP-135).
[05] MACGREGOR, I. D. A comparison of mechanical properties of Hong Kong medium and high-strength NPC and fly ash concretes. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, 2 v., v.1, p. 129-158 (SP-178).
[06] SWAMY, R. N., HUNG, H. H. Engineering properties of high volume fly ash concrete. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, 2 v., v.1, p. 331-359 (SP-178).
[07] BOUZOUBAÂ, N., ZHANG, M. H., MALHOTRA, V. M., GOLDEN, D. M. Mechanical properties on durability of laboratory produced high-volume fly ash blended cements. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, 7th., Madras, 2001. *Proceedings*. Farmington Hills, American Concrete Institute, 2 v., v. 1, p. 55-82, 2001.
[08] LANGLEY, W. S., CARETTE, G. G., MALHOTRA, V. M. Structural Concrete incorporating high volumes of ASTM Class F fly ash. In: Meeting of Transportation Board, 67th, Washington D. C., 1988.

[09] BROOKS, J. J., Wainwright, P. J., Boukendakji, M. Influence of slag type and replacement level on strength, elasticity, shrinkage and creep of concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 4th, Istanbul, 1992. *Proceedings.* Detroit: American Concrete Institute, 1992, 2 v., v.2, p. 1325-1341 (SP-132).

[10] TOMISAWA, T., CHIKADA, T., NAGAO, Y. Properties of super low heat cement incorporating large amounts of ground granulated blast-furnace slag of high fineness. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, Istanbul, 1992. *Proceedings*. Detroit: American Concrete Institute, 1993, 2 v., v. 2, p. 1385-1399 (SP-132).

[11] BOUKENDAKJI, M., BROOKS, J. J., WAINWRIGHT, P. J. Influences of steam curing on strength, shrinkage and creep of OPC and slag concretes. In: DHIR, R. K., HEWLETT, P. (eds.) International conference on Concrete in the Service of Mankind – Radical Concrete Technology, Dundee, 1996. *Proceedings*. London: E & FN SPON, 1996, p. 367-374.

[12] ISAIA, G. C., GASTALDINI, A. L. G. Effects of durability of HPC with very high levels of mineral addition and hydrated lime. In: MALHOTRA, V. M. (ed.) International ACI/CANMET Conference of Concrete Structures and Recent Advances in Concrete Materials and Testing, 4th. Olinda, 2005. *Proceedings*. Farmington Hills: American Concrete Institute, 2005. p. 741-760 (Supplementary Papers).

[13] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *Procedimento para moldagem e cura de corpos de prova de concreto.* NBR 5738, Rio de Janeiro, 2003.

[14] RILEM. Permeability of concrete as a criterion of its durability – Recommendation TC 116 PCD. *Materials and Structures*. v. 32, n. 217, p. 174-179, 1999.

[15] AMERICAN SOCIETY FOR TESTING MATERIALS. *Test method for electrical indication of concrete's ability to resist chloride ion penetration*. West Conshohocken, 2006.

[16] HAUSSMANN, D. A. Steel corrosion in concrete: how does it occur? *Materials Protection*, v. 11, n. 6, p. 19-23, 1967.

[17] MEHTA, P. K., AÏTCIN, P.C. Principles underlying production of high-performance concrete. *Cement, Concrete and Aggregates*. American Society for Testing Materials, v. 12, n. 2, 1990.

[18] BROWN, B. V. Aggregate: the greater part of concrete. In: Dhir, R., Jones, M. R. (eds.) International Conference on Concrete 2000 – Economic and durable construction through excellence. Dundee, 2000. London: E & FN SPON, v. 1, p. 279-293.

[19] LUTHER, M. D., HANSEN, W. Comparison of creep and shrinkage of high-strength silica fume concretes with fly ash concretes of similar strengths. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 3rd, Trondheim, 1989. *Proceedings*. Detroit: American Concrete Institute, 1989, 2 v., v.1, p. 573-591 (SP-114).

[20] COPPOLA, L., CERULLI, T., SALVIONI, D. Sustainable development and durability of self-compacting concretes. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 8th, Las Vegas, 2004. *Proceedings*. Farmington Hills: American Concrete Institute, 2004, p. 29-50 (SP-221).

[21] NAGATAKI, S. Mineral admixtures in concrete: state of the art and trends. In: Mehta, P. K. (ed.) V. M. MALHOTRA Symposium on Concrete Technology Past, Present and Future. *Proceedings*. Detroit: American Concrete Institute, 1994, p. 447-482 (SP-144).

[22] GEBLER, S. .H., KLIEGER, P. Effect of fly ash on physical properties of concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 2nd, Madrid, 1986. *Proceedings*. Detroit: American Concrete Institute, 1986, 2 v., v.1, p. 1-50 (SP-91).

[23] YAMATO, T., EMOTO, Y., SOEDA, M. Strength and freezing-thawing resistance of concrete incorporating condensed silica fume. In: Malhotra, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 2nd, Madrid, 1986. *Proceedings*. Detroit: American Concrete Institute, 1986, 2 v., v.2, p. 1095-1117 (SP-91).

[24] SIVASUNDARAM, V., CARETTE, G. G., MALHOTRA, V. M. Properties of concrete incorporating low quantity of cement and high volumes of low-calcium fly ash. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 3rd, Trondheim, 1989. *Proceedings*. Detroit: American Concrete Institute, 1989, 2 v., v.1, p. 45-71 (SP-114).

[25] FUKUDOME, K., SHINTANI, N., SAITOH, T., KITA, T., SSASAKI, H. Utilization of coal ash produced from pressurized fluidized bed combustion power plant as a concrete mineral admixture. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute,

1998, 2 v., v.1, p. 527-544 (SP-178).
[26] SWAMY, R. N., MAHAMUD, H. B. Shrinkage and creep behavior of high fly ash content concrete. Shrinkage and creep behavior of high fly ash content concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 3rd, Trondheim, 1989. *Proceedings*. Detroit: American Concrete Institute, 1989, 2 v., v.1, p. 453-475 (SP-114).
[27] MAEDA, Y., CHIKADA, T., NAGAO, Y., DAN Y, MATSUSHITA, H. Studies on the properties of super workable concrete using ground granulated blast-furnace slag. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, 2 v., v.2, p. 837-855 (SP-178).
[28] YASUMOTO, A., EDAMATSU, Y., MIZUKOSHI, M., NAGAOKA, S. In: MALHOTRA, V. M. (ed) CANMET/ACI/JCI International Conference on Recent Advances in Concrete Technology, 4th, Tokushima, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, p. 651-669 (SP-179).
[29] OHONO, T., UOMOTO, T. Critical limit of concrete cracks due to drying shrinkage. In: GJORV, O E., SAKAI, K., BANTHIA, N. (eds). International Conference on Concrete under Severe Conditions 2, 2nd, Tromso, 1998. *Proceedings*. London: E & FN Spon, 1998, 3 v., v. 3, p. 1586-1595.
[30] SIRIVIVATNANON, V., CAO, H. T., NELSON, P. Mechanical and durability properties of high volume fly ash concrete. In: MALHOTRA, V. M. (ed) International Conference on Durability of Concrete, 3rd, Nice, 1994. *Proceedings*. Detroit: American Concrete Institute, 1994, p. 967-984 (SP-144).
[31] MATSUSHITA, H., TSURUTA, H., NAKAE, K. The influence of physical properties of aggregate on shrinkage in high-strength slag cement concrete. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, 2 v., v.2, p. 685-699 (SP-178).
[32] MONTGOMERY, D. G. VAN, B. K. HINCZAK I., TURNER, K. Limestone modified cement for high-performance concretes. . In MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, 2 v., v.2, p. 1075-1102 (SP-178).
[33] ISAIA, G. C. Effects of binary and ternary pozzolans' mixture in HPC: a durability study in view of corrosion rebar. *Doctorate Thesis*. Universidade de São Paulo. São Paulo, 1995
[34] TAZAWA, E., YONEKURA, A. Drying shrinkage and creep of concrete with condensed silica fume. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 2nd, Madrid, 1986. *Proceedings*. Detroit: American Concrete Institute, 1986, 2 v., v.2, p. 903-921 (SP-91).
[35] LEE, C. Y., MacCarthy, M. J., Dhir, R. K. Intrinsic permeability of fly ash concrete. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on Durability of Concrete, 4th, Sydney, 1997. *Proceedings*. Farmington Hills: American Concrete Institute, 1997, 2 v., v.1, p. 247-266 (SP-170).
[36] BAROGHEL-BOUNY, V., LARRARD, F. In place durability assessment of the next millennium – long-term study. In: MALHOTRA, V. M. (ed) International Conference on Durability of Concrete, 5th, Barcelona, 2000. *Proceedings*. Farmington Hills: American Concrete Institute, 2000, 2 v., v. 1, p. 319-338 (SP-192).
[37] AÏTCIN P. C. *High-Performance Concrete*. London: E & FN SPON, 1998.
[38] SHILSTONE, J. M., SHILSTONE, J. M. J. High-performance concrete mixtures for durability. In: ZIA, P. (ed.) High-Performance Concrete in Severe Environments. *Proceedings*. Detroit: American Concrete Institute, 1993, p. 281-305 (SP-140).
[39] AÏTCIN, P. C. Les bétons à três haute résistance. *Bulletin Laison des Laboratoires des Ponts et Chaussée*, n. 162, 1989, p. 55-60.
[40] AÏTCIN, P. C., NEVILLE, A. High-Performance concrete demystified. *Concrete International*, v. 14, n. 1, 1993.
[41] TAKAHATA, A., IWASHIMIZU, T., ISHIBASHI, U. Construction of high-rise reinforced concrete residence using high-strength concrete. In: HESTER, T. (ed.) International Symposium on High-Strength Concrete, 2nd, Berkeley, 1990. *Proceedings*. Detroit: American Concrete Institute, 1990, p. 741-786 (SP-121).
[42] COLLEPARDI, M., COLLEPARDI, S., OLAGOT, J. J., SIMONELLI, F. The influence of slag and fly ash on the carbonation of concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 8th, Las Vegas, 2004. *Proceedings*. Farmington Hills: American Concrete Institute, 2004, p. 483-494 (SP-221).
[43] GETTU, R., GOMES, P. C. C., AGUILLÓ, L., JOSA, A. High-strength self-compacting concrete with fly ash: development and

utilization. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 8th, Las Vegas, 2004. *Proceedings*. Farmington Hills: American Concrete Institute, 2004, p. 507-522 (SP-221).

[44] CORINALDESI, V., MORICONI, G. The role of recycled aggregates in self-compacting concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 8th, Las Vegas, 2004. *Proceedings*. Farmington Hills: American Concrete Institute, 2004, p. 941-955 (SP-221).

[45] AMERICAN SOCIETY FOR TESTING MATERIALS. *Performance specification for blended hydraulic cement*. West Conshohocken, 2003.

[46] MEHTA, P. K. Bringing the concrete industry into a new era of sustainable development. In: Mario Collepardi Symposium on Advances in Concrete Science and Technology. *Proceedings*. Rome, 1997, p. 49-68.

[47] ISAIA, G., GASTALDINI, A., MORAES, R. Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete. *Cement Concrete and Composites*, v. 25, n. 1, p. 69-76, 2003.

[48] MEHTA, P. K. Role of pozzolanic and cementitious material in sustainable development of concrete industry. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Farmington Hills: American Concrete Institute, 1998, p. 1-20 (SP-178).

[49] SWAMY, R. N. Design for durability and strength through the use of fly ash and slag in concrete. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on Advances in Concrete Technology, Auckland, 1997. *Proceedings*. Farmington Hills: American Concrete Institute, 1997, p. 1-72 (SP-171).

[50] HAYNES, D. J., CONNELL, M. D. GGBS environmental cement. In: DHIR, R. K., DYER, T. (eds.) International conference on Concrete in the Service of Mankind – Concrete for Environment Enhancement and Protection, Dundee, 1996. *Proceedings*. London: E & FN SPON, 1996, p. 331-342.

[51] ROY, D. M. Hydration, microstructure and chloride diffusion of slag-cement pastes and mortars. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, Trondheim, 1989. *Proceedings*. Detroit: American Concrete Institute, 1997, 2 v., v. 2, p. 1265-1281 (SP-114).

[52] COOK, D. J., HINCZAK, I., JEDY, M., CAO, H. T. The behavior of slag cement concretes in marine environment – chloride-ion penetration. In: MALHOTRA, V. M. (ed.) CANMET/ACI International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, Trondheim, 1989. *Proceedings*. Detroit: American Concrete Institute, 1997, 2 v., v. 2, p. 1467-1483 (SP-114).

[53] BROOKS, J. J., WAINWRIGHT, P. J., BOUKENDAKJI, M. Influence of slag type and replacement level on strength, elasticity, shrinkage and creep of concrete. In: MALHOTRA, V. M. (ed.) International Conference on fly ash, silica fume, slag, and natural pozzolans in concrete, 4th, Istanbul, 1992. *Proceedings*. Detroit: American Concrete Institute, 1992, 2 v., v.2, p. 1325-1341 (SP-132).

[54] LANG, E., GEISELER, J. F. Use of blast-furnace slag cement with high slag content for high-performance concrete. In: DHIR, R. K., HEWLETT, P. (eds.) International conference on Concrete in the Service of Mankind – Radical Concrete Technology, Dundee, 1996. *Proceedings*. London: E & FN SPON, 1996, p. 67-76.

[55] NAKAMOTO, J., TOGAWA, K., MIYAGAVA, T., FUJII M., NAGAOKA, S. Freezing and thawing resistance of high slag content concrete. In: MALHOTRA, V. M. (ed.) CANMET/ACI/JCI International Conference on Recent Advances in Concrete Technology, 4th, Tokushima, 1998. *Proceedings*. Detroit: American Concrete Institute, 1998a, p. 1059-1072 (SP-179).

[56] NAKAMOTO, J., TOGAWA, K., MIYAGAVA, T., FUJII M., NAGAOKA, S. Water permeability of high slag content concrete. In: Malhotra, V. M. (ed.) CANMET/ACI/JCI International Conference on fly ash, silica fume, slag and natural pozzolans in concrete, 6th, Bangkok, 1998. *Proceedings*. Detroit: American Concrete Institute, 1998b, p. 779-795 (SP-178).

[57] ALDRED, J. M., RRANGAN, B. V. The influence of Wick Action on chloride transport in concrete. In: MALHOTRA, V. M. (ed.) International Conference on Durability of Concrete, 6th, Thessalonic, 2003. *Proceedings.* Farmington Hills: American Concrete Institute, 2003, p. 807-821 (SP-212).

[58] FÉDÉRATION INTERNATIONALE DE LA PRÉCONTRAINTE/COMITÉ EURO-INTERNATIONALE DU BÉTON. *High strength concrete. State-of- the-art Report*. London. FIP, 1990.

[59] COMITÉ EURO-INTERNATIONAL DU BÉTON. *CEB-FIP Model Code 1990*. CEB, Lausanne, 1991 (Bulletin d´Information nº 203).