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Effect of particle packing in the durability of high performance concretes

Efecto de empaquetamiento de las partículas en la durabilidad de los hormigones de alto desempeño

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Abstract

Due to the high aggressiveness in which the concrete structures are exposed, many researches have been developed in this area and search for materials with superior mechanical performance and durability has been the target of the researchers of concrete technology. Therefore, concrete obtained from the microstructure engineering are needed. Being composites made of fine grain particles and a low water/binder ratio, these materials have dense matrix by optimizing the packing of granular materials. Thus, this paper uses the concept of particles packing in the design of special concretes, analyzing the durability of these materials by determining the water absorption by immersion and by capillary, and chloride ion penetration. The properties of concrete designed based on this concept are compared to high performance concrete designed from conventional methodology, indicating superior properties in terms of durability.

Keywords: Special concretes, durability, water absorption, high-performance concrete

Resumen

Puesto que las estructuras de hormigón están expuestas a un alto grado de agresividad, se han realizado muchas investigaciones al respecto, en el área de la tecnología del hormigón. Los investigadores se han enfocado en la búsqueda de materiales que posean un mejor comportamiento mecánico así como una mayor durabilidad, para lo cual es necesario un hormigón obtenido mediante la ingeniería de la microestructura de los materiales. Como los materiales compuestos están formados por partículas de granulometría fina y una baja razón agua/aglomerante logran una matriz densa cuando se optimiza el empacamiento de sus partículas. Basándose en el concepto de empacamiento de las partículas en el diseño de los hormigones de alto desempeño, este trabajo analiza la durabilidad de esos materiales a través de la determinación de la penetración del ion cloruro y absorción de agua por inmersión y capilaridad. Se compararon las propiedades del hormigón diseñado bajo este concepto con las de los hormigones de alto desempeño diseñados de acuerdo a la metodología convencional, mostrando mejores propiedades en términos de durabilidad.

Palabras clave: Hormigones especiales, durabilidad, absorción de agua, hormigones de alto desempeño

1. Introduction

The durability and service life of concrete structures have been widely discussed in the international technical-scientific community, especially in recent decades, seeking better ways for the specification and design of new buildings, as well as performing repairs, reinforcements and reconstructions of a large number of constructions with early pathological problems.

One of the main pathological problems is steel corrosion that is considered by many researchers as the most serious and frequent problem in reinforced concrete structures. In addition to being a technical-economical problem, it also represents an immense waste of natural resources and constitutes a local and global problem.

Estimates of the annual cost of steel corrosion in the United States are about billions of dollars, being the corrosion in bridges the major problem. The collapse of the Silver Bridge deck in Ohio River has cost 40 lives and 500 million dollars (Fontana, 1986). According to Long (1993), in England, studies conducted in 1990 indicate an annual cost of around 36 billion dollars in maintenance and repairs of concrete structures. Recent data published by Ueda and Takewaka (2007) outline the costs for construction of new structures and spending on maintenance and repair of structures in different countries, as shown in Table 1.

In Brazil, the incidence of corrosion of embedded steel reinforcement in the context of structural problems is quite significant, reaching 64% of the main pathological problems found in buildings in some regions of the country (Andrade, 1997). The intervention costs in the structure to achieve certain level of durability and protection grows with the waiting time to make such intervention, being the evolution of this cost represented by a geometric progression of ratio 5, known as the law of 5 or Sitter rule (Helene, 1997), shown in Figure 1. In some cases, the repair and rehabilitation of deteriorated structures have a higher cost than that of a new structure.

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Table 1. *Maintenance and repair works in some countries (Ueda and Takewaka, 2007)*

Country	Spending in 2004		
	New structures	**Maintenance and repair works**	**Total spending**
Japan	52.5 trillion yen	10.7 trillion yen	63.2 trillion yen
Korea	116.8 trillion won	21.1 trillion won	137.9 trillion won
France	85.6 billion euro	79.6 billion euro	165.2 billion euro
Germany	99.7 billion euro	99.0 billion euro	198.7 billion euro
Italy	58.6 billion euro	76.8 billion euro	135.4 billion euro
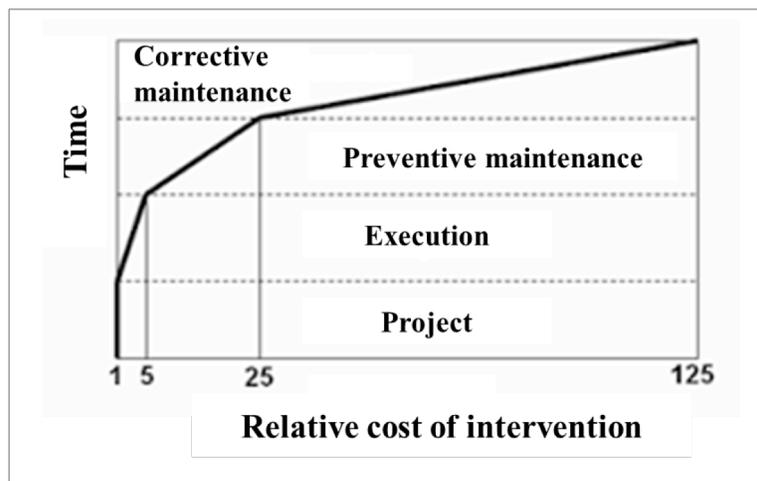
Figure 1. *Representation of the evolution of intervention costs according to the period in which it is carried along the structure life time (adapted from Helene, 1997)*

In studies related to the durability of reinforced concrete structures, it appears that steel corrosion caused by the action of chloride ions is one of the most serious structural problems that can occur. In reinforced concrete, reinforcing steel with adequate cover should not be susceptible to corrosion because the highly alkaline conditions present within the concrete (pH > 12) cause a passive iron-oxide film to form on the steel surface. However, carbonation and the presence of chloride ions can destroy this protective film. Chloride ions are considered more aggressive since they can destroy the steel protective film even under extremely high pH conditions, when present above the critical level.

The concept of durability encompasses both porosity and permeability properties of concrete. According to Hearn, Hooton and Nokken (2006) the pores can exert their influence on the properties of the concrete in several ways. With regard to the mechanical strength and elasticity of the concrete, it is primarily the total volume of pores the important factor, not their size or continuity. However, the durability is influenced by permeability that, in turn, depends on the volume, size, and continuity of the pores.

Thus, the durability of concrete largely depends on the ease with which fluids, both liquid and gas, can enter into the concrete and move within it. The size, pore volume and continuity, as well as understanding the transport mechanism of aggressive agents in concrete are important factors when estimating the useful life of concrete structures, as well as ensuring their quality.

In this paper, the aim is to improve specific characteristics of the concrete in terms of its durability (water absorption and ion chlorides penetration), in order to prolong the useful life of concrete structures based on the concept of particle packing described in the following.

Particle packing

In recent years the interest in particle packing increased in different engineering areas. This interest can be explained by the fact that a large part of natural or industrial materials daily used are - or contain - particles of different shapes and sizes. In this context, the particles are considered as the grains of aggregates, mineral, metal or chemical powders, soils, molecules, pores or rocks. Thus, the behavior of such materials depends partially on the properties of their

components and partially on the interactions between them (Stroeven et al., 1999a).

The initial flow of concentrated suspensions such as concrete also depends on physical considerations, i.e., on the particle size distribution, the shape index and the surface texture of the particles (Bonen et al., 1995). The particle size distribution design is of fundamental importance, as it promotes the packing and, with the fluid, defines the rheological properties of the material during the mixing process and when in the fresh state. Thanks to the simultaneous use of chemical admixtures and mineral additions it has been possible to produce high performance concretes, which concern not only because of the high mechanical strength, but also by other characteristics such as higher elastic modulus, lower bleeding, less creep and shrinkage, and higher durability (De Larrardet al., 1994; Hu et al., 1996). Thus, the concept of high packing density has recently been rediscovered as a key parameter for obtaining cementitious materials of superior mechanical performance and durability.

The particle packing study can be defined as the problem of selecting the proper size and proportion of the particulate materials, so that larger voids are filled by smaller particles, whose voids will be filled again with even smaller particles, and so on (Oliveira et al., 2000).

In 1892, Féret published the first treatise on particle packing in concrete, in which he presented the possibility of the selection of suitable types of aggregates and the relationship between porosity and the compressive strength of the hardened material when subjected to the normal curing process - wet curing (De Larrard et al., 1994; Aiqin et al., 1997; Aiqin, 1999). Since then, some particle packing models have been proposed as tools for calculating the particle packing density, and thereby to optimize concrete granular materials.

After extensive comparative analysis between two basic models proposed (Furnas and Andreasen), some considerations were made, being proven that both models mathematically converge on a same equation (Equation 1). Commonly known as the Alfred model, this is a refinement of previous models and shows that, in fact, the Furnas model (discrete) and the Andreasen model (continuous) can be considered as two distinct ways of expressing the same thing. In addition to introduce the concept of minimum particle size in the Andreasen equation, it also involves a mathematical review of the Furnas model (Oliveira et al., 2000; Funk et al., 1994).

$$CPFT(\%) = 100 \left(\frac{D^q - D_S^q}{D_L^q - D_S^q} \right) \qquad (1)$$

where: CPFT is the volumetric percentage of particles smaller than the diameter D, D_L is the diameter of the largest particle, D_S is the diameter of the smallest particle, and q is the distribution coefficient.

Using computer simulations it has been verified that q values less than or equal to 0.37 can favor the maximum packing limit for infinite distributions, while values above 0.37, there is always a residual porosity. For a mixture to exhibit good flowability, the value of the distribution coefficient should be less than 0.30; so the consideration of q values close to 0.30 favors the production of concrete compacted by vibration, while values less than 0.25 result in self-compacting mixtures (Vanderlei, 2004). The effect of reducing the distribution coefficient value occurs when the content of fine particles increases, which influences the interaction between the particles.

In general, the random packing of spherical monodispersions always results in the same packing factor (between 0.60 and 0.64), but the shape of the granular materials particles commonly found in concrete is far from a sphere and thus several factors can alter the packing of a particular set of these particles.

The first to be considered is the existence of particles with different particle size distributions by changing the initial dispersion condition. The other factor is the particle shape, so that the less spherical is the particle, the lower the packing density of a distribution that contains it, as occurs friction between the particles from their irregular surfaces contact (Oliveira et al., 2000).

The particle internal porosity also changes the density of a material. To obtain a packing of maximum density, considering a particular particle size distribution, it is necessary to use non-porous particles. For effect of particle size distribution, the particles having closed porosity are similar to the dense ones, but result in mixtures with higher density, while particles having open porosity disturb the packing due to their irregular shape and also result in mixtures with lower packing densities (Oliveira et al., 2000).

Analyzing the influence of the particle size distribution on the packing density and the hydration degree of a cement-based material, it is verified that a continuous particle distribution is sought for packing state, while a heterogeneous distribution is more suitable for hydration rate. Thus, the two effects are exactly the opposite; but for the material properties, they must be considered simultaneously: on the one hand, a higher packing density is required, while on the other hand, a higher hydration degree is desirable. Briefly, the material must be as porous as possible (Aiqin et al., 1997).

The particle dispersion state should also be considered when seeking a maximum packing. An inadequate particles dispersion (agglomerates formation) may change the particle size distribution curve originally provided, increasing the effective minimum diameter of the composition and thus reducing packing density. Moreover, the agglomerates formed are equivalent to empty particles that originates pores in the microstructure, impairing the mechanical performance of the material.

Thus, for developing concretes with superior mechanical performance and durability, the particle packing characteristics are of fundamental importance. These concretes are considered, in fact, as materials with high packing density and the idea behind this concept is the attempt to reconstruct a solid rock from elements that have complementary particle sizes (Stroeven, 1999b).

In recent years, many researches have been developed and the search for materials with superior mechanical performance and durability has been the target of the concrete technology researchers. To this end, concretes obtained from the microstructure engineering are needed. Being composites constituted of particles with fine particle size distribution (particles with smaller size) and low water/binder ratio, these materials have dense matrix by packing optimization of the granular materials, while adequate workability is obtained by the particle dispersion promoted by the incorporation of chemical admixtures.

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Thus, this paper aims to apply the concept of particle packing in the design of concretes containing Portland cement and industrial by-products, with the intent of obtaining denser matrices and, therefore, more durable in aggressive environments. The properties of designed concretes based on this concept are presented and compared to those of high performance concretes considered in civil construction researches. The tests include water absorption by immersion and by capillary, and chloride ion penetration through wetting and drying cycles of concrete in NaCl solution.

2. Experimental Program

2.1 Materials

The cement used in the mixtures of the reference concrete and in the particle packed concrete was the high-early-strength Portland cement (CPV ARI), which chemical and physical properties are presented in Table 2. The particle size distribution of this cement is given in Figure 2.

To produce the reference concrete, crushed stone and natural sand were used as the aggregates components of the mixture. The crushed stone was of basaltic origin, classified as size number 0, and the natural sand was natural quartzous sand classified as a fine sand, being both classifications made according to NBR 7211 (2009). The fineness modulus and the maximum size of these aggregates were determined from the particle size distribution test (NBR NM 248, 2003) and the values obtained were, respectively, 5.29 and 9.5 mm for the crushed stone, and 2.34 and 4.8 mm for the sand.

The aggregates AG 10-20, AG 05-08, AG 40-50 and AG 80-100 were used in the composition of new concrete (designed based on the concept of particle packing). They are all natural quartzous sands constituted of rounded grains. The particle size distribution of these aggregates is controlled by statistical techniques of effective size and uniformity coefficient, while their physical and chemical characteristics are maintained stable and in accordance with the market specifications (commercially available sands, applied in the production of filters, glasses and ceramics).

The particle size distribution of the aggregates used in the production of both concretes is presented in Figure 2, while the unit weight and the density of these aggregates are summarized in Table 3.

Table 2. Chemical composition and physical properties of CPV ARI

Chemical composition: determinations	Results (%)	Physical properties	Results
SiO_2	21.16	Normal consistency paste	0.30
Al_2O_3	4.71	Density (g/cm³)	3.16
Fe_2O_3	1.89	Blaine (m²/kg)	700
TiO_2	0.15	Initial setting time (min)	143
CaO	68.08	Final setting time (min)	338
MgO	0.48	Compressive strength (MPa)	
Na_2O	0.29	1 day	25.2
K_2O	0.56	3 days	36.2
P_2O_5	0.28	7 days	39.8
Loss on ignition	2.39	28 days	47.4

Table 3. Chemical composition and physical properties of CPV ARI

Aggregate	Unit weight (g/cm³)	Density (g/cm³)
Crushed stone	1.49	2.87
Fine sand	1.67	2.61
AG 10-20	1.48	2.62
AG 05-08	1.46	2.63
AG 40-50	1.45	2.63
AG 80-100	1.43	2.64

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The SM 200, SM 400 and SM 500 quartz powders were used only in the composition of the new concrete. These powders are ground silica and obtained from raw materials of superior quality, using advanced equipment, in order to meet the strictest technical specifications of the market (materials available in different size distributions, applied in the production of paints, plastics, rubber, polishes, abrasives, etc.). The MS 920U silica fume, used in the composition of both concretes (reference and new), is a non-densified silica obtained from the manufacture of silicon metal or ferrosilicon alloys. It is an extremely fine material, constituted of small spherical particles with mean diameter around 50 to 100 times smaller than the mean diameter of cement particles, resulting in a high specific surface area. Silica fume has a consistent chemical composition, being regarded as nearly pure since its particles have high contents of amorphous silica when compared to the presence of small amounts of other elements. The particle size distribution of the fine materials used is shown in Figure 2. The physical properties of these materials – specific surface area and density – are presented in Table 4.
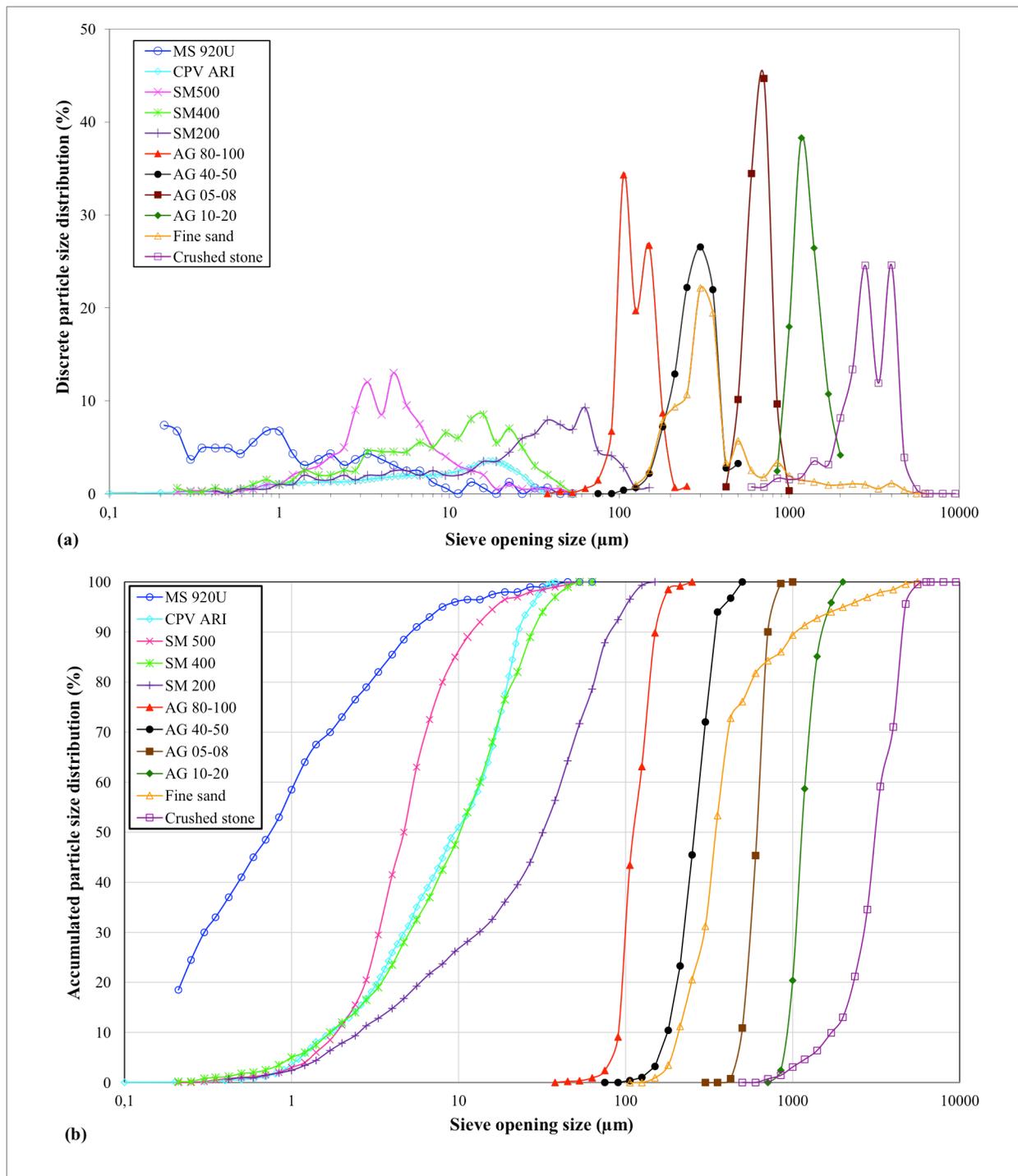
Figure 2. Particle size distribution – (a) discrete and (b) accumulated – of the materials used in the production of both concretes

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Table 4. *Specific surface area and density of the fine materials used*

Fine material	Specific surface area (m²/kg)	Density (g/cm³)
SM 200	758	2.72
SM 400	1.346	2.72
SM 500	2.498	2.70
MS 920U	14.270	2.42

To achieve the desirable workability of concrete mixes a chemical admixture was used, that is, a polycarboxylate-based superplasticizer admixture, known as a third generation admixture.

2.2 Mixture Proportions

The composition of the concrete mix design used in the study was based on earlier studies, when concretes were produced with different particle packing coefficient (Castro et al., 2009) and different cement types (Castro et al., 2011). Due to the small difference between the results obtained for these concretes, one was selected for the evaluation of the properties related to durability, and a high performance concrete widely used in practice to compare the results.

2.2.1 Reference concrete (REF):

The reference concrete (Castro, 2007) corresponds to a high performance concrete mix design, widely considered in investigations aimed the development and application of special concretes in construction works. It is composed of cement, sand, crushed stone, silica fume, superplasticizer admixture and water, and it was developed from the initial study of the phases that constitute concrete: cement paste and aggregates.

The study of the cement paste matrix was undertaken to assess the compatibility between the binder materials and the superplasticizer admixture, as well as to determine the saturation point of the admixture, since cement pastes that have good flow behavior result in concrete with satisfactory fluidity and consistency.

The aggregate phase was studied in order to obtain the best particle packing by determining the optimal composition between them. This optimal composition was determined according to the recommendations of Helene et al. (1992): two aggregates with distinct particle size distributions are combined in various fractions, being determined the unit weight in compressed state of each combination. The composition is considered optimal when the value obtained for the unit weight is maximum. For the reference concrete, the optimal composition was determined between fine natural sand and crushed stone.

Having defined the two phases composing the concrete, the final mix design composition was undertaken. The proportions between the constituent materials of the mixture were directly determined after defining the characteristics of their constituent phases. A slump value of (160 ± 20) mm was established and if it was not achieved, adjustments would be made by varying the admixture content, since the amount of mixing water was kept constant.

The final mix design of the reference concrete was 1 : 1.75 : 1.75, with a water/binder ratio of 0.40, silica fume content of 10% replacing cement in volume, and superplasticizer content of 0.61% on the mass of cement.

In the laboratory, the reference concrete was produced using a rheometer. The addition sequence of the constituent materials and the mixing procedure considered in the production of the reference concrete were based on the mixing process widely used in practice, namely:

- initially crushed stone and 90% of the total mixing water were mixed for 1 minute at low speed (20 RPM);
- the mixer was stopped for 1 minute, and after being added the cement and silica fume, the mixer was turned on and the mixture was held for 1 minute at low speed;
- the mixer was stopped again, and allowed to rest for 1 minute while the sides of the bowl were scraped with a spatula to remove the retained material. Then the fine natural sand was added and the material was once again mixed for 1 minute at low speed;
- once again mixing was stopped for 1 minute so that the sides of the bowl to be cleaned and, in this interval, the remainder of the mixing water and superplasticizer was added;
- finally the material was mixed for 3 minutes at high speed (60 RPM), being the total mixing time of 9 minutes.

2.2.2 Concrete designed from the particle packing concept (0.26):

The new concrete composition was designed based on the computational concept of particle packing, from the Alfred model, where the value assumed for the distribution coefficient (q) was 0.26 (Castro et al., 2009). The amount of each raw material, defined by the particle packing study, is shown in Table 5 and Figure 3.

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Table 5. *Proportion of raw materials for the concrete mixtures*

Raw material	q = 0.26 (new concrete) %-w	REF (reference concrete) %-w
Crushed stone	-----	39
Fine sand	-----	38
AG 10-20	24	-----
AG 05-08	7	-----
AG 40-50	29	-----
AG 80-100	7.5	-----
SM 200	7	-----
SM 400	3	-----
SM 500	2.5	-----
MS 920U	10	6.6
CPV ARI	10	16.4
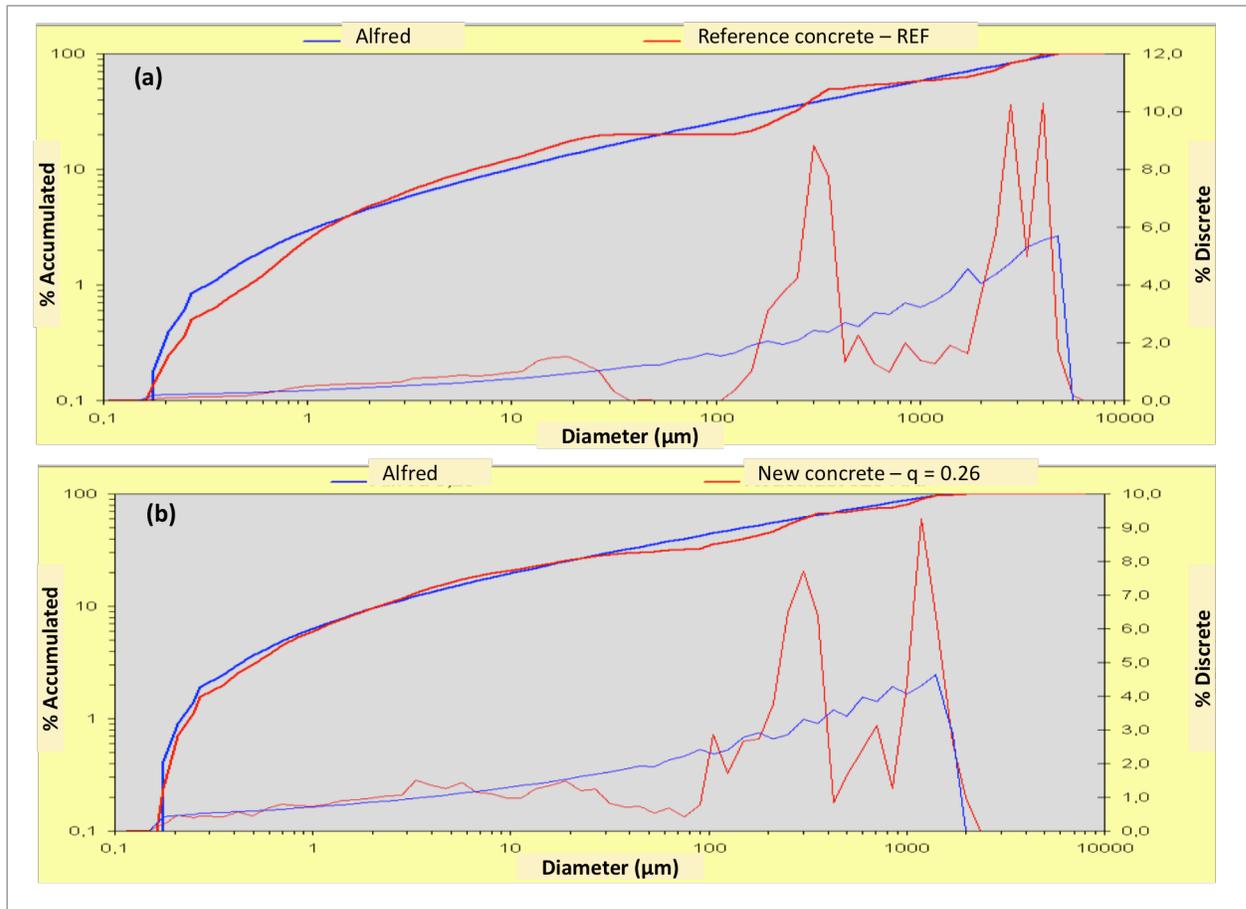
Figure 3. *Particle size distribution curves of (a) the reference concrete (REF) and (b) the concrete designed from the particle packing concept (new concrete – q = 0.26)*

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Having defined the granular system that constitutes the mixture (q = 0.26), the study to determine the saturation point of the superplasticizer admixture (optimal content) was performed. Successive admixture additions were made until the free flow index measured was equal or greater than 80%. The water/total granular materials ratio was set at 7% and the optimum additive content was of 0.65%. It should be remembered that the contents of water and superplasticizer were determined for the total amount of granular materials and not only for the amount of cement and/or binder - cement and silica fume (Castro et al., 2009).

The mixing procedure used in the production of the new concrete was distinct from that used in the production of reference concrete. For the new composition, the dry granular materials were previously manually homogenized in plastic bags. Then, all mixing water was added and the material was mixed for 1 minute at low speed (20 RPM). The mixer was stopped for 1 minute while the sides of the bowl were scraped with a spatula to remove the retained material and in this interval, the superplasticizer was added. Subsequently, the material was mixed for 5 minutes at high speed (60 RPM), being total mixing time of 7 minutes.

3. Methods

3.1 Capillary water absorption

Capillary water absorption test was used to determine the water absorption in concretes with 7 and 28 days of moist curing and was conducted in accordance with standard ABNT 9779 (2012). Cylindrical specimens of 50 mm diameter and 100 mm in length were used. The lateral side of the specimens was sealed with silicon up to 3 cm in height so that only one circular face of the specimen was exposed to water. The water level during the test was kept constant at 5 mm above the specimen surface in contact with water. The weight of the specimens was monitored throughout the period (0–72 hours) the cement was in contact with the water.

Sorptivity, given by the volume of water penetrating per unit of area and time, was calculated to facilitate the interpretation of the results. In the present paper, the time considered to calculate sorptivity was 72 hours. Thus, sorptivity is obtained empirically from the slope of the cumulative volume of water absorbed per unit of surface area versus the square root of time, as represented in Equation 2.

$$S = \frac{V_w}{A_c \times t^{1/2}} \qquad (2)$$

where: S is the sorptivity (g/cm²); V_w is the volume of water absorbed by the specimen (mm³); A_c is the cross-sectional area of each specimen (mm²); and t is the time of exposure (h).

After final weighing, the specimens were broken by diametrical compression to allow verifying the water distribution inside them and, thus to determine the water capillary rise in the concrete specimen. The maximum internal height of water capillary rise was expressed in centimeters, and the internal distribution of absorbed water was recorded by taking a picture of the tested specimen.

3.2 Water absorption by immersion

The test of water absorption by immersion is used to estimate the maximum amount of water that can be absorbed by a dry sample and, thus, to provide a measure of the total permeable pores that exist within the concrete.

The water absorption and percent voids of the concrete were determined according to standard NBR 9778 (2005). Cylindrical specimens of 50 mm diameter and 100 mm in length were used, being the determinations made after 7 and 28 days of moist curing.

Initially the specimens were dried in an oven for a period of 72 h, determining their mass at the end of the drying period. After air-cooling to room temperature, the specimens were immersed in water at 23°C and kept in this condition for 72h, recording the mass after this period. Completed the saturation stage, the specimens were placed in a container filled with water, gradually brought to boiling. The specimens were kept boiling for 5h, then were naturally cooled in water to room temperature, determining their immersed apparent mass with a hydrostatic balance. Following, the specimens were removed from water and lean with a damp cloth, recording their mass in saturated surface dry condition. The percent water absorption by immersion and voids volume were calculated according to Equations 3 and 4.

$$A = \frac{m_{sat} - m_s}{m_s} \times 100 \qquad (3)$$

$$I_V = \frac{m_{sat} - m_s}{m_{sat} - m_i} \times 100 \qquad (4)$$

where: A is the percent water absorption by immersion (%); I_V is the voids volume (%); m_s is the mass of oven-dried sample in air (g); m_{sat} is the mass of surface-dry sample in air after immersion and boiling (g); m_i is the apparent mass of sample in water after immersion and boiling (g).

3.3 Chloride ions penetration

Chloride ions penetration was determined by the colorimetric method of spraying silver nitrate. The test seeks to determine the penetration depth of chloride ions in the concrete after four weeks of wetting and drying cycles using a solution containing 10% NaCl. Cylindrical specimens of 50 mm diameter and 100 mm in length were used, starting the test after 28 days of moist curing.

Immediately after curing, the specimens were removed from the wet chamber and left in a laboratory environment for 14 days. After this period, they were placed in a container with 10% NaCl solution in which they remained partially immersed for 3 days. After the immersion period (wetting), a 4-day drying period for the specimens started (drying), and so on repeatedly until completing all cycles. The solution was replaced every week to maintain its concentration.

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When the set number of wetting and drying cycles were completed, the specimens were broken by diametrical compression and a 0.1 M concentration silver nitrate solution was sprayed on the exposed fractured surface. The specimens were taken to an illuminated environment for the solution to react with the chloride ions and, after a few hours, the penetration depth of chloride ions was measured with a ruler.

The spraying of the silver nitrate solution causes the silver chloride in the presence of free chloride, and silver oxide in the absence of chlorides, which colorations are contrasting. In the first case, the surface remains colorless, while in the second case the surface darkens.

4. Results and Discussions

4.1 Capillary water absorption

The values of capillary water absorption measured after 3, 6, 24, 48 and 72 hours are shown in Table 6, with the values representing the average of three readings. The capillary water absorption against the square root of time is shown in Figure 4.

Table 6. Capillary water absorption, in g/cm², of concretes.

Time (hours)	7 days		28 days	
	REF	0.26	REF	0.26
3	0.155	0.059	0.152	0.044
6	0.208	0.069	0.204	0.052
24	0.363	0.095	0.358	0.082
48	0.455	0.111	0.440	0.100
72	0.491	0.110	0.491	0.120
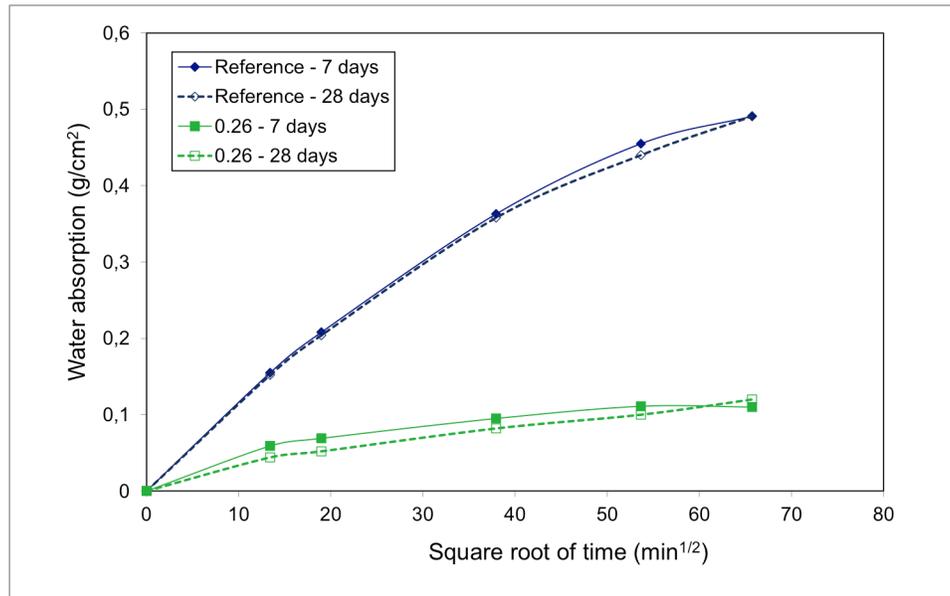
Figure 4. Results of the capillary absorption against the square root of time of concretes

The results presented in Table 6 and represented graphically in Figure 4 show that the concrete designed from the particle packing concept (0.26) presented much lower values of capillary absorption than the reference concrete (REF) – 0.120 g/cm² and 0.491 g/cm², respectively, ate the age of 28 days – due to the better particle packing and the denser microstructure of the material. It is worth noting that no significant differences were found between the values of capillary absorption for both concrete after 7 and 28 days.

From Figure 5 it can be seen that the water capillary rise in the concrete specimens designed from the particle packing concept (q = 0.26) was higher compared to the reference concrete (REF), but the absorption coefficients were lower (Figure 4). Moreover, the water rise shape was different in both compositions: in the reference concrete (REF), the rise occurred homogenously at the base of the specimen, with almost the same height of water being observed at the edges as at the center of the specimen; on the other hand, the water rise in the new concrete (q = 0.26) occurred only at the center of the specimen.

It is known that the smaller the capillary pore diameter, the higher the capillary pressure and, consequently, the greater the water penetration front within the concrete. Thus, the higher the capillary pore diameter, the lower the height of capillary water rise, although the total amount of water absorbed will be greater (Helene, 1993), as observed in this study. Therefore, it is observed that a refinement of the pores of the concrete occurs when using a computer-determined particle packing method. Therefore, it is observed that there is a refinement of the pores of the concrete (higher height of water capillary rise) when using the compute-mix design method based on the particle packing concept, but the water absorption coefficient of concrete is lesser.

4.2 Water absorption by immersion

The values of water absorption by immersion and volume of permeable pore space (voids volume) obtained for the concretes are shown in Table 7, with the values representing the average of three readings. Figures 6 and 7, respectively, represent water absorption and voids volume of the concretes after 7 and 28 days.
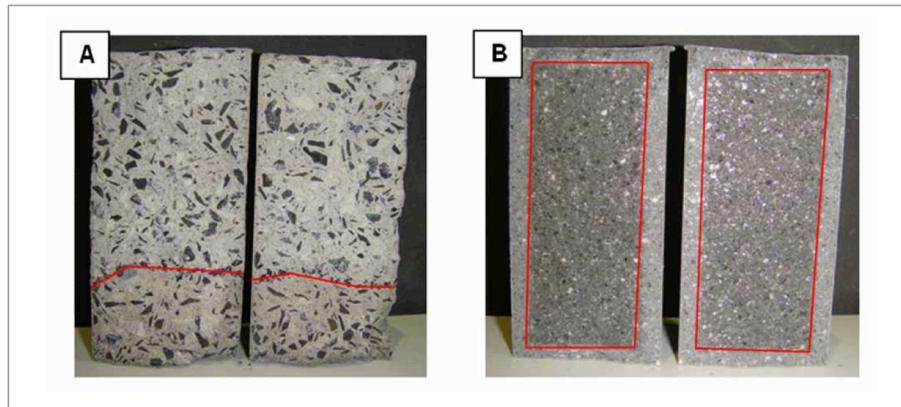
Figure 5. Fractured specimens after capillary water absorption test:
(A) reference concrete (REF); (B) new concrete (0.26)

Table 7. Capillary water absorption, in g/cm², of concretes.

Property	7 days		28 days	
	Reference	0.26	Reference	0.26
Water absorption	6.2	1.9	6.0	1.7
Voids volume	13.7	4.4	13.5	3.9

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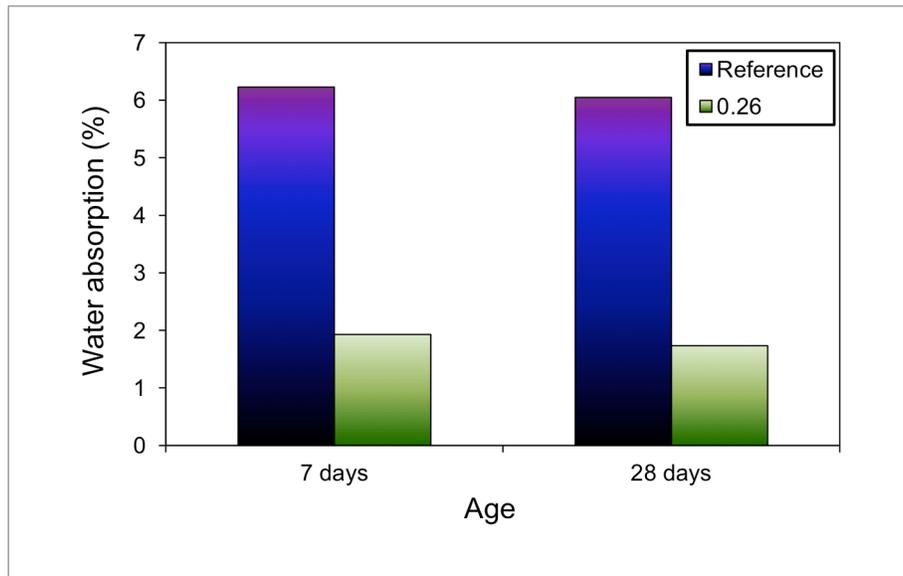
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Figure 6. Water absorption by immersion of the concretes
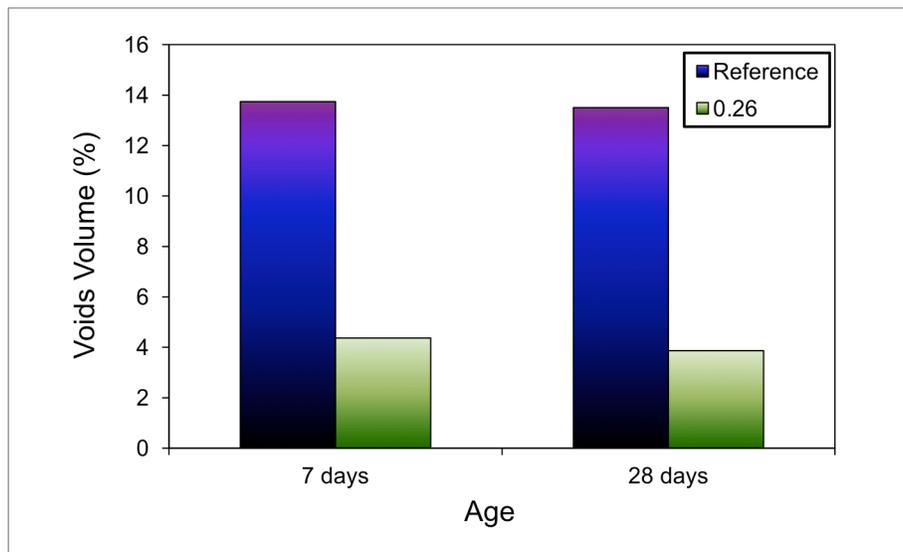
Figure 7. Voids volume of the concrete

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From the results shown in Table 7 and plotted in Figures 6 and 7, it is noted that both water absorption and voids volume in the reference concrete (REF) were much higher than for concrete designed from particle packing concept (0.26), remaining the same difference for all ages. The superior performance of the new concrete (0.26) is associated with the best particle packing, and consequently to the development of a denser matrix in this material.

CEB-192 (1998) relates concrete's water absorption to its quality: for a water absorption of less than 3%, the concrete is considered to have low absorption and good quality; with 3% to 5%, the quality and absorption are of medium quality; and if greater than 5%, the absorption is considered to be high and the quality of the concrete poor. In terms of the concretes studied, it was found that the new concrete (0.26) presented low absorption and high quality, while the reference concrete was considered to be a material with high absorption and thus of poor quality.

Furthermore, on the basis of water absorption, concrete may be classified as durable (absorption lower than 4.2%), normal (between 4.2% and 6.3%) and deficient (higher than 6.3%) (Helene, 1893). According to this, the new concrete (0.26) is considered a durable material, while the reference concrete (REF) presents a regular performance in terms of durability.

4.3 Chloride ions penetration

The depth of chloride ions penetration was determined by spraying the silver nitrate solution on fractured concrete specimens. The results, which correspond to the mean of three determinations of the penetration depth, obtained for the reference concrete (REF) and the concrete designed from the particle packing concept (0.26) are shown in Figures 8 and 9 shows the pictures of the specimens after spraying with silver nitrate solution.
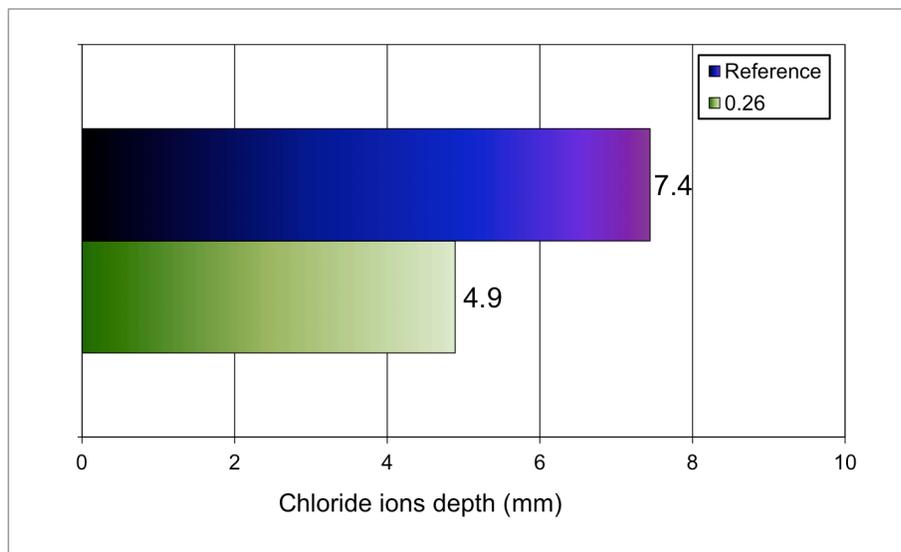
Figure 8. Depth of chloride ions penetration in the concretes specimens
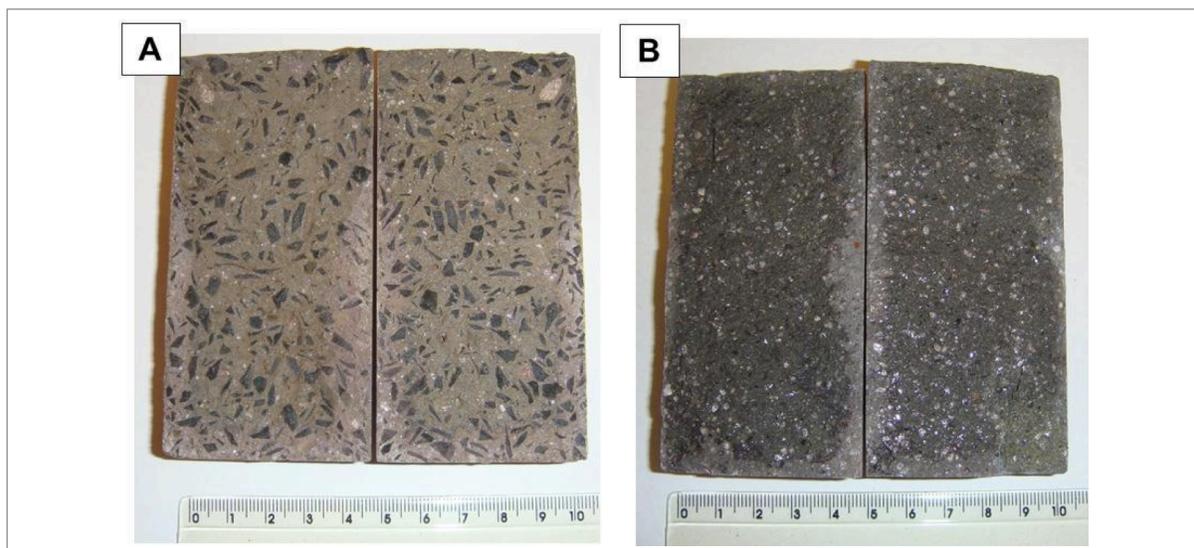
Figure 9. Fractured specimens after spraying with silver nitrate solution:
(A) reference concrete (REF); (B) new concrete (0.26)

From the results obtained (Figures 8 and 9), it may be observed that the concrete mix design from particle packing concept (0.26) and, consequently, the development of a denser microstructure resulted in a depth of chloride ion penetration considerably lower than in the reference concrete (REF).

It should be considered that the greater the amount of C-S-H in hardened concrete, whether due to the hydration reaction of the cement or the pozzolanic reaction of silica fume, the lower the rate of penetration of these ions in the concrete. Chloride ions may combine with the C-S-H: chemically adsorbed on the surface of the C-S-H; on the surface of the C-S-H layers and composing the structure of the C-S-H, influencing the kinetics of the reactions (Silva, 2006).

The water absorption coefficients of the new concrete (0.26), either by capillarity or by immersion, were much lower than the reference concrete (REF), indicating extremely low permeability for the material. The depth of chloride ions penetration also decreased after wetting and drying cycles in NaCl solution, constituting the new concrete (0.26) into a more efficient physical barrier for chloride ions penetration when compared with the high performance concrete studied (reference concrete – REF).

Thus, the application of particle packing concept, in order to increase the density of the granular system in cementitious materials, shows as a key parameter for obtaining concrete with high mechanical and durability performance for the application in civil construction.

5. Conclusion

Applying the particle packing concept in concrete mix design allowed the development of concretes with superior properties even when compared to other high performance concretes widely considered in researches focused on the design and implementation of special concretes in civil construction works.

6. Acknowledgments

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