The effect of metakaolin on the durability of concrete hollow blocks used in masonry: evaluation of degradation caused by driving rain

Efeito do metacaulim na durabilidade de blocos vazados de concreto para alvenaria: avaliação da degradação por chuva dirigida

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Abstract

Driving rain, considered one of the major factors in the degradation of external seals, may cause esthetic problems and material decomposition to facades and masonry. In the present research, the production of concrete hollow blocks for masonry underwent testing for which 20 years of exposure have been considered, taking into account the annual precipitation in the State of Paraíba. This was assessed by replacing 10, 15 and 20% of cement for metakaolin using as parameter the specimen's mass loss at end of the test. It has was found that the concrete with metakaolin revealed values of weight loss greater than those of the reference concrete, without metakaolin, and that these values increased as the level of substitution increased. However, for mixtures with lower cement content, the use of 10% by metakaolin promoted results that have been considered similar to the reference. The test results are, therefore, consistent with those reported in literature for assessment studies on actual exposure situations; however, further studies will be developed to correlate the laboratory results obtained and from the resulting exposure to natural weather conditions.

Keywords: degradation; cement / metakaolin; driving rain.

Resumo

A chuva dirigida, considerada um dos fatores de maior degradação em vedações externas, pode acarretar desde problemas estéticos até a decomposição dos materiais que compõem as fachadas e alvenarias. Nessa pesquisa, concretos destinados à produção de blocos para alvenarias foram submetidos a ensaios que simularam 20 anos de exposição, tomando, como referência, a precipitação pluvial do Estado da Paraíba. Avaliou-se a substituição de 10, 15 e 20% do cimento por metacaulim, utilizando-se, como parâmetro de avaliação, a perda de massa dos corpos de prova ao final do ensaio. Verificou-se que os concretos com metacaulim apresentaram valores de perda de massa maiores do que concretos de referência, sem metacaulim, e que esses valores aumentam com a elevação do teor de substituição. Entretanto, para os traços com menor teor de cimento, o uso de 10% de metacaulim promoveu resultados similares aos de referência. Os resultados do ensaio estão compatíveis com a literatura para estudos de avaliação em situações de exposição real, porém estudos complementares deverão ser *desenvolvidos para se correlacionarem os resultados laboratoriais obtidos com os resultantes de exposição a condições climáticas naturais.*

Palavras-chave: *degradação; cimento/metacaulim; chuva dirigida.*

1. Introduction

The use of hollow concrete blocks for masonry has been consolidated due to the advantages they provide where performance and costs are concerned, combining quality, productivity and mainly dimensional accuracy. Studies (MARCHAND *et al*., 1996, SIDDIQUE and KLAUS, 2009, CASSAGNABÈRE *et al*., 2010) have showed that the use of mineral admixtures and mortar in concrete afforded porous structure refinement, increasing resistance to compression and bending while for the action of sulfates, it reduced the effects of alkali-aggregate reaction and its potential for efflorescence, increasing, thereby, the durability. However, the durability is not the material's specific property but the result of an interaction between the material and the surrounding environment (JOHN and SATO, 2006). Brick walls are susceptible to problems caused by water such as those caused by infiltration, capillary soil water, rain washing and the preservation of external seals. According to Sabbatini *et al*. (1998), this latter aspect can represent a degradation of between 40 to 70% in facades. In porous solids, water permeability is usually the determining factor in the rate of deterioration; however, not only porosity but also the diameter and interconnecting pores directly do influence the penetrating capacity of water which causes all problems related to concrete durability (METHA and MONTEIRO, 2008). Hydrolysis occurs when the components are under the effect of flowing water; the solution is diluted and the $Ca(OH)_2$ is removed by leaching, exposing the components to cement chemical decomposition which reduces resistance and may lead to the total degradation of the concrete. The efflorescence effects from the reaction of $Ca(OH)_2$ leached with carbon dioxide (CO_2), present in the air, result in the precipitation of calcium carbonate ($CaCO_3$) as a white crust on the surface of the concrete (FERNANDES, 2008). According to Rozière *et al*. (2009), this plays an important role in leaching the external attack by sulfates, for portlandite ($Ca(OH)_2$) leaching facilitates the invasion and production of sulphate ion reagents for the formation of expansive products. On the other hand, environmental hazards associated with the use of construction materials are primarily related to the potential release of contaminants (leaching) (VAN DER SLOOTH and DIJKSTRA, 2004, SCHIOPU *et al*., 2007, SCHIOPU *et al*., 2009).

Studies on the higrotermia and durability of facades require quantification of loads and driving rain masonry response to these charges, being developed by experimental, semi-empirical or numerical methods. Semi-empirical methods are based on two reports presented by Hoppestad in 1955: the ratio of driving rain (Driving Rain Relationship - DRR) and the index of driving rain (Driving Rain Index - DRI), which is also used to classify the degree of exposure to which the construction is subjected (BLOCKEN and, CARMELIET, 2004).

During the 60s, DRI was established by CIB (Conseil International du Batiment) as the product of annual rainfall by annual average wind speed that can be obtained by Equation 1 (GIONGO *et al*., 2011):

$$DRI = V.P.10^{-3} \quad \text{Eq. 1}$$

where: DRI = driving rain index = ($m^2.s^{-1}$)
V = Average annual wind speed ($m.s^{-1}$) measured at 10m (height) and
P = annual precipitation (mm).

The classification of walls according to the degree of exposure depending on the DRI (CHAND and BHARGAVA, 2002, MELO JÚNIOR and CARASEK, 2011) is shown in Table 1.

Levels of exposure	Safe	Moderate	High	Severe
DRI Zone ($m^2.s^{-1}$)	DRI ≤ 3	3 < DRI ≤ 7	7 < DRI ≤ 11	11 < DRI

Table 1
Classification of the degree of exposure according to the DRI.

According to Heathcote (2002), the correlation between the DRI unit and precipitation was studied by Lacy, who, after studying 75 rainfall events during 16 years (1948-1963) in Garston, England concluded that such correlation corresponds to the first DRI 206mm of rain directed against a vertical wall. Subsequently, Henriques (1993) conducted experiments using gauges fixed on the walls and positioned randomly; concluding that the relationship between the index of driving rain and the amount of water collected in the rain gauge was 1 to 145 DRI L/m²/h.

In tests by simulation, models are used to represent the actual conditions of use. The chamber created by Ogunye and Boussabaine (2002) allows the application of the discharge of water over an area of about 1m² by using a spray nozzle positioned at a height of two meters from the specimens, which are supported on a tilted platform 30° to the horizontal. The rotor oscillates on the test area, and the number of oscillations per unit of time allows regulation of the water flow according to the desired rainfall intensity. The simulation involved an annual 3500mm precipitation over a 25 year period consisting of three 12h cycles of wetting and 42h of oven drying at 60°C and the difference between the final and the initial dry weight parameter was used to evaluate the degradation.

In the present research, the concrete used for the production of hollow blocks for masonry underwent testing that simulated 20 years of rain exposure, considering the annual precipitation in the State of Paraíba. Metakaolin was used to replace 10, 15 and 20% of the cement mass, the result of which were compared to that found in the reference concrete without metakaolin. The mass loss observed was used as an assessment parameter at the end of the test. An analysis of the water chemical composition was also carried out in order to verify the changes observed in its original composition.

2. Experiments

2.1 Materials

2.1.1 Cement

Portland cement was used, presenting high initial resistance, CPV ARI (ABNT, 1991).

This was due to the fact that, besides being recommended for use in precast concrete, pozzolanic additions were not found in its composition preventing the results from being influenced by the presence of other pozzolan material .

The characterization data of the cement are shown in Table 2.

Characteristics	Determinations		Cement CPV-ARI
Chemical	Loss on ignition[a]		4.31
Physical	Insoluble residue[a]		0.94
	Addition (CaO)[a]		2.16
	Specific area ($m^2.g^{-1}$) Blaine		0.42
	Specific gravity ($kg.cm^{-3}$)		3.13
Mechanical	Compressive strength (Mpa)	1 day	2.67
		3 days	36.15
		7 days	40.47

[a] % weight.

Table 2
Chemical, physical and mechanical properties of cement CPV-ARI (supplier's data)

2.1.2 Metakaolin

We used high reactivity metakaolin, the characterization data of which are described in Table 3.

Characteristics	Determinations	Metakaolin
Chemical	Loss on ignition[a]	2.62
	Sílica (SiO_2)[a]	51.57
	Aluminum oxide (Al_2O_3)[a]	40.50
	$SiO_2 + Al_2O_3 + Fe_2O_3$	94.87
	Sodium oxide (Na_2O)[a]	0.08
	Specific area ($cm^2.g^{-1}$BET)	327.00
Physical	Average diameter particle (μm)	12.40
	Specific gravity ($kg.cm^{-3}$)	2.65
	PAI[b] – Chapelle modified (l $CaO.g^{-1}$)	771.2

[a] % weight; [b]Pozzolanic activity index.

Table 3
Chemical and physical properties of metakaolin (supplier's data)

2.1.3 Aggregates

Used as aggregates were, gravel source granite, quartz sand and stone dust, whose physical characterization data (Table 4) were obtained from tests conducted in accordance with the rules of the ABNT (Associação Brasileira de NormasTécnicas).

Aggregate	Fine gravel	Sand	Stone powder
CMD[a] (mm)	9.50	4.80	2.40
Fineness modulus (FM)	5.32	2.59	2.14
Unitary mass ($g.cm^{-3}$)	1.54	1.46	1.43
Specific gravity ($g.cm^{-3}$)	2.67	2.59	2.79
Teor de material pulverulento (%)		0.21	2.40
Teor de umidade (%)	0.10	0.22	0.10

[a]Characteristic maximum diameter.

Table 4
Physical characteristics of aggregates

2.2 Moulding of test specimens

Plates (250mm x 250mm x 25mm) of concrete were shaped, aiming to simulate the action of rainfall on the exposed flat face of the blocks.

The concrete was compacted by using a pneumatic press (20t) yielding, thus, plates had a similar density to those of molded factory plates.

The test started after 28d of curing, and during the first 24 h in a humid chamber.

The remaining test period was conducted at ambient temperature. The amount of material for each evaluated composition is described in Table 5.

Mixture	Cement [kg]	Metakaolin [%] [kg]		Gravel [kg]	Sand [kg]	Stone powder [kg]	Ratio A/(C+M)*
A Cement = 18%	375	0	0	770	833	479	0,52
	337	10	38	770	833	479	0,53
	319	15	56	770	833	479	0,54
	300	20	75	770	833	479	0,56
B Cement = 15%	322	0	0	794	858	494	0,54
	290	10	32	794	858	494	0,57
	274	15	48	794	858	494	0,58
	258	20	64	794	858	494	0,60
C Cement = 12%	266	0	0	820	887	510	0,56
	239	10	27	820	887	510	0,57
	226	15	40	820	887	510	0,58
	213	20	53	820	887	510	0,60

* Water / (cement + metakaolin).

Table 5
Amount of material for each trait evaluated (kg/m^3 of concrete)

The consumption of calcium hydroxide resulting from the addition of metakaolin, confirming the existence of pozzolanic reaction, was evaluated through analysis by X-ray diffraction of samples in all compositions after 28 days of curing prior to the start of the test by simulating rainfall erodibility.

2.3 Simulation of rainfall run-off

Used was a Basic Hydrology System - BHS, manufactured by Armfield Corporation, England (Figure 1), which is composed of an array of eight nozzles with adjustable water flow and area of 2m^2 (2m x 1m) and used in soil permeability studies.

Figure 1
Equipment utilized for rainfall simulation

The water supply to this equipment is cyclical, done through a tank and a circulation pump, and the water sprayed, but not absorbed by the plates, returns through channels and pipes to the reservoir restarting, in this way, the whole process. The plates were placed upon brackets, supported so as to be tilted 30° from the horizontal and 10mm high from the base, so asnot to obstruct the flow of water. In order to minimize the effects caused by the difference as to the location of the plates in relation to the spray lines, columns are alternated along each cycle. The quantitative flow and exposure time have been determined based on the data of average annual precipitation in Paraíba (GALVÍNCIO and RIBEIRO, 2005), and on the DRI Brazilian mapas found in Lima and Morelli, (2005). Table 6 describes the data used for the test.

Table 6
Calculation of flow rate and exposure time to simulate rainfall

Annual distribution	Minimum (12%)	Average (50%)	Maxim (38%)
Driven Rain Index - DRI	3	7	11
Flow [$L.m^{-1}$]	7	17	27
Average annual rainfall – 1300mm*	163	340	517
Equipment area [2 m^2]	326	680	1034
Time [min]	45	40	39

*1 mm of rainfall corresponding to $1L.m^{-2}$

According to the data presented in Table 5, this was standardized to 40min exposure for all ranges, ie, 160min (2h:40min) equivalent to the average precipitation in a year. After this period, the samples were weighed (wet weight) and placed in a stove (71 ± 2°C) to dry for 20h:20min, and re-weighed (dry mass), after which a new cycle was restarted.

The weight variation (Eq. 2) was the parameter used to evaluate resistance to erosion by rain, the results being compared to those found for the reference boards with no metakaolin.

Eq. 2

$$Vms=(msi - msc).m_{si}^{-1}.100$$

Where: V_{ms} - variation in dry matter (%); m_{si} - dry initial mass; m_{sc} - dry cycle mass rated.

3. Results and discussion

The results of weight loss after 20 cycles of exposure are shown graphically in Figure 2.

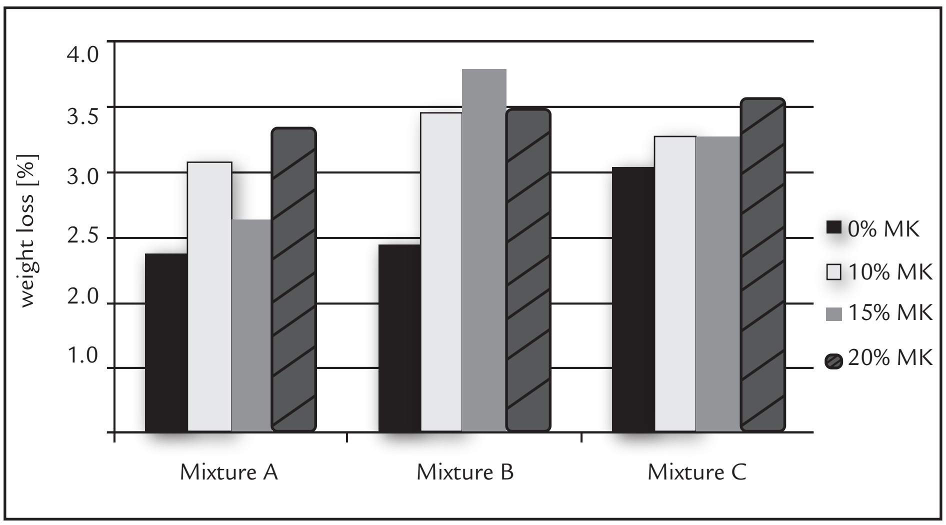

Figure 2
Mass loss of concrete specimens with 0, 10, 15 and 20% metakaolin after 20 cycles of rainfall intensity

Comparing the results showed in Figure 2, it was found that the concrete slabs with a metakaolin were more susceptible to erosion caused by splashes of water from the sprinkler than the reference plates without the addition of metakaolin. It also appears that an increase in the content substitution produced greater amounts of weight loss, which may be related to reduced cement content, and the performance of metakaolin to replace it by increasing the content of aggregates. The permeability of the concrete behavior was also observed by Oliveira et al. (2006) and Lima (2010).

After 20 cycles of exposure, all the compositions showed a mass loss of less than 4% which, can be considered when comparing to the value of 3.8% reported by Heathcote (2002) for soil-cement blocks after 25 cycles of exposure to driving rain intensity. The higher scores for weight loss, obtained in the current study may be justified by the degree of compression of the plates which tends to be lower at the edges, thus making these regions more susceptible to erosion.

The results of the chemical analysis of the water tank after 0, 5, 10, 15 and 20 cycles are shown in Table 7.

Quantity of cycles	0	5	10	15	20
pH	6.77	7.32	8.05	8.60	9.47
Electrical conductivity [μS.cm^{-1}]	15.37	105.00	212.00	262.00	416.00
Calcium [mec.L^{-1}]	0.06	0.87	1.02	0.62	0.33
Magnesium [mec.L^{-1}]	0.55	0.81	0.97	1.21	1.02
Sodium [mec.L^{-1}]	0.01	0.37	0.51	0.90	2.00
Potassium [mec.L^{-1}]	0.01	0.29	0.32	0.88	2.64
Carbonates [mec.L^{-1}]	-------	0.43	0.53	0.98	1.18
Bicarbonates [mec.L^{-1}]	0.26	1.13	1.28	0.84	0.35
Chlorides [mec.L^{-1}]	0.01	0.25	0.31	0.65	0.75
Sodium adsorption ratio (SAR)	0.01	0.29	0.57	0.96	2.43
Class of water	C1	C1	C1	C2	C2

Table 7
Chemical analysis of water sprayed and collected in the reservoir.

For the chemical analysis, the parameter taken into account was as a parameter the use of water for irrigation. The results obtained from sodium concentration, shown in Table 6, allows us to include it in the group of low (C1) and medium (C2) salinity according to ABNT specifications, in which case the first one (up to 10 cycles) can be used in various different crops and soils without causing salinity, and the second one (10-20 cycles) can be considered in case of moderate leaching. As the equipment was initially subjected to a six-hour water flow, and renewed before beginning the test on the concrete plates, the results of the water chemical analysis at the end of the experiment accounts for the changes as a result of leaching.

The data presented in Table 7 demonstrate that there has been an increase in sodium content along with a decrease in the pH levels, chemically unbalancing the CSH which is then decomposed, resulting in larger mass loss where the pozzolanic reaction occurs at some minor intensity. As from the tenth cycle, a decrease in the values de calcium was verified, revealing that there has been a carbonate reaction favoring mass weight losses as a result of the cement desegregation verified in the samples.

4. Conclusions

- The concrete slabs with metakaolin showed a higher susceptibility to erosion caused by water spray from sprinklers than the reference design boards without metakaolin. Increasing the level of substitution led to increased mass loss values. For all compositions measured, the weight loss was less than 4%;
- Erosion rates, measured by weight loss tend to decrease with increasing exposure time, which can be related to greater densification of the folder occurring with an increasing degree of hydration of the cement during curing ;
- The water used for the test, after 20 cycles, showed that either the chemical composition was classified as suitable for use in irrigation, or the resulting water leaching represented no risk of contamination to the soil.

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