Using ready-mixed mortars in concrete block structural masonry

Uso de argamassas estabilizadas em alvenaria estrutural de blocos de concreto

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Abstract

Ready-mixed mortars have been increasingly used due to their potential for waste reductions and productivity increases. However, research regarding their use in structural masonry applications are practically non-existent. Thus, this work investigated the technical feasibility of using ready-mixed mortars with nominal compressive strengths of 6, 9 and 14 MPa and storage times of 0 and 36 hours in concrete block structural masonry. The fresh state properties of the mortars were evaluated at 0 and 36 hours through the slump test, consistency and plasticity by the Gtec test, and entrained air content. The compressive and flexural strengths of the mortars were determined at 28 days. In addition, three-row prisms were tested for compressive strength and modulus of elasticity, and four-row prisms for flexural strength in the bending test, all at 28 days. The results showed that the 6 and 9 MPa ready-mixed mortars showed satisfactory maintenance of the fresh properties from 0 to 36 hours and adequate hardened properties for both casting ages, in contrast to the 14 MPa mortar. Regarding the prism tests, the increase in storage time did not significantly affect the properties evaluated for a reliability of 95%.

Keywords: Ready-mixed mortar. Structural masonry. Concrete blocks.

Resumo

O uso de argamassas estabilizadas vem ganhando espaço devido ao seu potencial de reduções no desperdício e aumento na produtividade. Entretanto, estudos referentes ao emprego deste material em alvenaria estrutural são praticamente inexistentes. Assim, este trabalho investigou a viabilidade técnica do emprego de argamassas estabilizadas com resistências nominais à compressão de 6, 9 e 14 MPa e tempos de armazenamento de 0 e 36 horas, em alvenaria estrutural de blocos de concreto. As propriedades das argamassas foram avaliadas no estado fresco após 0 e 36 horas, através do abatimento do tronco de cone, consistência e plasticidade pelo Gtec teste, e teor de ar incorporado. As resistências à compressão e à flexão das argamassas foram determinadas aos 28 dias. Adicionalmente, foram ensaiados prismas de três fiadas para a determinação da resistência à compressão e módulo de elasticidade, e quatro fiadas para a determinação da resistência à flexão, aos 28 dias. As argamassas de 6 e 9 MPa apresentaram manutenção satisfatório nas propriedades do estado fresco de 0 para 36 horas, e no estado endurecido para ambas as idades de moldagem, opostamente a de 14 MPa. Em relação aos prismas, o aumento do tempo de armazenamento não alterou significativamente as propriedades investigadas, para uma confiabilidade de 95%.

Palavras-chave*: Argamassa estabilizada. Alvenaria estrutural. Blocos de concreto.*

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Introduction

Structural masonry is one of the oldest known building systems but has been changing over the years according to scientific and industrial evolution (MOHAMAD, 1998). In this type of structure, the walls are loadbearing elements comprising masonry units (bricks or blocks) joined by mortar joints and are capable of resisting loads beyond their own weight (PRUDÊNCIO JUNIOR; OLIVEIRA; BEDIN, 2002). This building system presents a few technical and economic aspects that makes it advantageous over traditional methods, such as the combination of reinforced concrete structures and brick masonry walls. The main advantage lies in the great potential of rationalisation of all construction stages, through the optimisation of temporal, material and human resources (HENDRY, 2001).

In order to rationalise the construction process, industrialised mortars were developed in the 1950s, which are previously dry-mixed mortars that require only the addition of water at the construction site. Later, the ready-mixed mortars appeared in the 1970s, which are ready-to-use mortars that can be used for up to three days, while maintaining their characteristics (PANARESE; KOSMATKA; RANDALL, 1991). This is feasible due to hydration controller admixtures. These can work in two ways: by reducing the solubility of Portland cement compounds (such as gypsum, which reduces the dissolution of aluminate phases), or by forming precipitates on the cement particles, thereby forming a low permeability layer over the grains and slowing their hydration. The first mechanism is associated with the commonly called "retarder" admixtures and have a faster effect, while the second mechanism is associated with "hydration inhibitors" admixtures, which have a longer effect (HEWLEET; JUSTNES; EDMEADES, 2019), and are conventionally used in ready- mixed mortars.

Some scientific papers investigated the properties of ready-mixed rendering mortars. Calçada *et al.* (2013) evaluated the compressive strength of ready-mixed mortars cast in metallic moulds and on absorbent surfaces (i.e. ceramic and concrete blocks), with storage times of 0 and 48 hours. The authors found higher strengths for the specimens cast on absorbent surfaces. In addition, they reported a trend of increasing the compressive strength and reducing the workability with the increase in the storage time, justified by the general reduction in the entrained air content over time.

Casali *et al.* (2011) and Macioski *et al.* (2013) evaluated the fresh and hardened properties of ready-mixed rendering mortars with up to 72 hours of storage times. In general, the increase in storage time reduced the mechanical strength of the mortars (in contrast to Calçada *et al.* (2013)), in addition to reducing the consistency index of the mixtures. Furthermore, Casali *et al.* (2011) found that the application of a water film over the mortar after its use resulted in lower workability losses from the previous day to the next one.

Bauer *et al.* (2015) evaluated 17 batches of ready-mixed rendering mortars produced in plants from Brasília – DF, proposing performance requirements for these materials. The authors evaluated the mixtures through cone penetration test, flow table test, water retention, air content, fresh and hardened densities, compressive, tensile and flexural strength, dimensional variation and capillary absorption. Finally, the authors proposed a standard performance profile for this type of mortar.

Oliveira *et al.* (2017) investigated the effect of the admixture type and content on the susceptibility to cracking of ready-mixed rendering mortars. The authors evaluated the flexural strength, modulus of elasticity and volumetric variation by drying shrinkage of the mortars. In general, they found that the contents of both air-entraining and hydration stabiliser admixtures affected the mortars susceptibility to cracking.

Finally, Casali *et al.* (2018) studied the influence of the type of cement and water content on the fresh state properties of ready-mixed rendering mortars with storage times of 0, 24 and 48 hours. The consistency index, fresh density, air content, and rheological behaviour through the squeeze-flow test were evaluated at different storage times. The authors found that the type of cement and storage time significantly affected the rheological properties of the mortars. However, the authors found that both the consistency index and entrained air content tests were not sensitive to evaluate the changes in the fresh state properties, even though these are the tests conventionally employed in production control.

In addition, some academic studies evaluated the properties of ready-mixed mortars, such as Mann Neto, Andrade and Soto (2010), Pereira (2012), Fernandes (2011) and Campos (2012). In general, these studies evaluated the properties of the mortars themselves or for the purpose of wall coatings.

Despite the list of works mentioned above addressing the use of ready-mixed mortars in rendering or bricklaying applications, this material is still rarely used in structural applications, such as in structural masonry. In fact, to the best of the author's knowledge, there are no scientific reports on the use of ready-mixed mortars for structural masonry production. Therefore, this work investigated the technical feasibility of using three ready-mixed mortars with two storage times in concrete block structural masonry.

Materials and methods

Materials

A Portland cement type CP IV-32 RS (ABNT, 2018) was used to prepare the mortars. Table 1 and Table 2, respectively, present the chemical and physical characteristics of the Portland cement used, provided by the manufacturer.

The aggregate fraction of the mortars consisted of a combination of a natural quartz sand, with a fineness modulus of 1.34 and a specific gravity of 2.65 g/cm³, and a granitic manufactured sand with fineness modulus of 2.60 and a specific gravity of 2.86 g/cm³. The sands were used in mass proportions of 70% natural sand and 30% manufactured sand. The composition of sands had a fineness modulus of 1.73 and specific gravity of 2.71g/cm³. Figure 1 shows the particle size distribution of the sands.

When preparing the mortars, an air-entraining admixture (Rheomix 701, BASF) and a hydration stabiliser admixture (Rheomix 702, BASF) were used. The characteristics of the admixtures provided by the manufacturer are shown in Table 3.

Finally, concrete blocks of three nominal compressive strengths (6, 9 and 14 MPa) were used in the prism production. All blocks had nominal dimensions of 140 x 190 x 390 mm (width x height x length), and a wall thickness of 25 ± 3 mm.

Mortar mix composition

Three ready-mixed mortars, provided by a plant from Florianópolis – SC, were investigated in this work. They were respectively designed for 28-day compressive strengths of 6, 9 and 14 MPa, and for a maximum storage time of 48 hours. The mass unitary compositions of the mortars were provided by the plant and are shown in Table 4.

Experimental procedures

Concrete blocks

For each block strength class, eighty units were collected. It is known that the weight of the block affects its mechanical strength. Since the blocks had the same volume, heavier blocks have greater compactness, thus resulting in greater strengths (PRUDÊNCIO JUNIOR; OLIVEIRA; BEDIN, 2002). Therefore, in order to reduce the variability of the results, the blocks of each strength class were weighed and classified according to their weight. Thirty-three blocks with "intermediate" weight were selected, six of which were used for the blocks´ compressive strength test, eight for the central rows of the compression prisms, sixteen for the central rows of the bending prisms, and three for the water absorption test. The blocks classified as "light" and "heavy" were respectively used in the lower and upper rows of the compression and bending prisms. This procedure is further explained in item "Prisms".

Table 1 – **Chemical composition of the Portland cement**

Composition (%)								Property (%)		
SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	LOI	IR	Free CaO
28.99	9.79	4.07	45.45	*1.18		4.97	2.34	3.17	28.67	0.67

Note: *Na_2O equivalent = Na_2O + 0.64 K_2O;
LOI = loss on ignition; and
IR = insoluble residue.

Table 2 – **Physical properties of the Portland cement**

Property		Value
Density (g/cm³)		2.82
Blaine fineness (cm²/g)		4583
Fineness (% retained)	# 200	0.56
	# 325	1.91
Setting time (min)	Start	255
	End	328
Compressive strength (MPa)	1 day	14.71
	3 days	24.55
	7 days	29.65
	28 days	42.03

Figure 1 – **Particle size distribution of the sands**

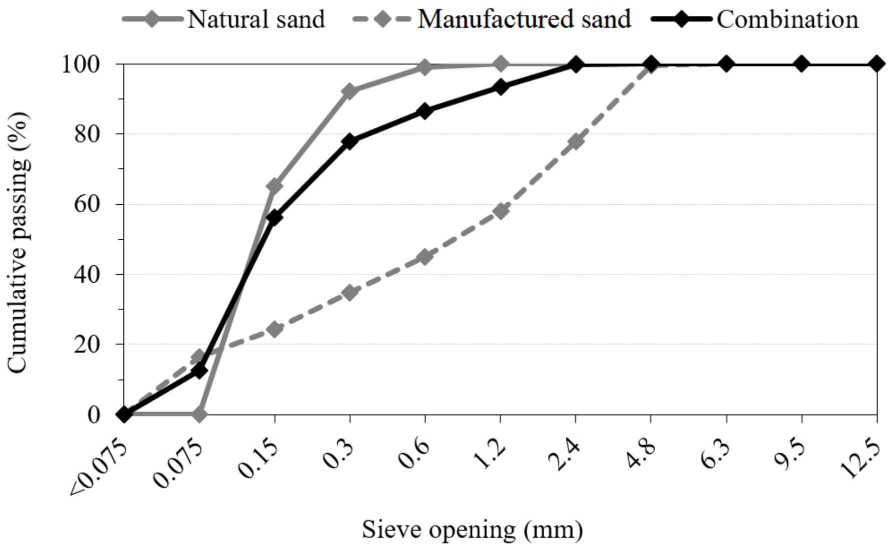


Table 3 – **Properties of the chemical admixtures**

Property	Admixture	
	Air-entraining	Hydration stabiliser
Chemical Base	Synthetic resins	Polysaccharides
Colour	Reddish brown liquid	Yellow liquid
pH (at 23°C)	10 – 12	8 – 11
Density at 23°C (g/cm³)	1.000 – 1.040	1.160 – 1.200
Solid content (% by mass)	4.0 – 6.0	38.0 – 42.0

Table 4 – **Mass unitary composition of the mortars investigated**

Constituent	Unitary composition		
	6 MPa	9 MPa	14 MPa
Portland cement	1.00	1.00	1.00
Natural sand	6.43	5.41	4.54
Manufactured sand	2.79	2.35	1.97
Water	1.50	1.21	1.07
Air-entraining admixture (%)	0.23	0.20	0.18
Hydration stabiliser admixture (%)	0.70	0.70	0.70
Water/dry material ratio (% by mass)	14.7	13.8	14.2

The compressive strength of the blocks was determined according to NBR 12118 (ABNT, 2013). For each strength class, six units were tested, and the characteristic strength (f_{bk}) was calculated through Equation 1 prescribed by NBR 6136 (ABNT, 2016a), where $fb_{(1)}$, $fb_{(2)}$, ..., $fb_{(i)}$ are the individual compressive strength values in increasing order; *n* is the number of blocks tested; and *i* = *n*/2 if *n* is even, or *n*/2 - 1 if *n* is odd. Moreover, this standard prescribes that, for n = 6 (adopted in this work), the f_{bk} value should not be lower than 0.89 × f_{b1}. For this test, the upper and lower faces of the blocks were previously capped with cement paste for surface regularisation.

$$f_{bk} = 2\left[\frac{f_{b(1)}+f_{b(2)}+\ldots+f_{(i-1)}}{i-1}\right] - f_{b(i)} \qquad \text{Eq. 1}$$

Finally, the water absorption (*a*) was determined following the NBR 12118 (ABNT, 2013) and calculated by Equation 2. The procedure consists of drying the block in an oven at 110 ºC for 24 hours and then determining its weight (m_1). After cooling it, the block is immersed in water at 23 °C for 24 h. Finally, the block is weighed in a saturated surface dry condition (m_2). For each strength class, three units were tested, and the mean values were adopted.

$$a = \frac{m2-m1}{m1} \times 100 \qquad \text{Eq. 2}$$

Mortars

The mortars were delivered by the plant in a plastic container of 1/3 of a cubic meter (333 liters), similar to a water tank. The container was kept inside the laboratory throughout the study, protected from the sun and wind. After performing the tests on the first day (referred to as "0 hours"), the mortars were covered with a waterproof plastic sheeting in addition to a water film over it, similarly to that suggested by Casali *et al.* (2011). This procedure avoided changing the water content of the mixtures, either by evaporation or incorporating additional water by applying the water film directly onto the mortar. After 36 hours, both the sheeting and water film were removed, and the mortars were manually homogenised according to the procedure conventionally adopted on site, which consists of mixing the mortar with a paddle until obtaining a homogeneous material. Finally, the "36-hour" tests were performed. The tests performed in the fresh and hardened mortars are described below.

Fresh state

The mortar consistency is commonly evaluated using the flow table test (ABNT, 2016b). However, in this study we chose to use the slump test (ABNT, 1998) to evaluate this property as it is the test conventionally used by the plants, and it is adopted as acceptance criterion on the construction site.

The entrained air content was determined by the pycnometer method, developed by Schankoski *et al.* (2012). In this method, the air content is determined by the volume variation of a mortar sample added to a pycnometer, which contains a solution of 50% ethyl alcohol + 50% distilled water, before and after the removal of the air by shaking the sample with a glass rod.

Additionally, the consistency and plasticity of the mortars were evaluated through the Gtec test, developed by Casali and Prudêncio Junior (2008), which is also presented by Carasek (2017). The apparatus is illustrated in Figure 2. The test simulates the application of a real block over a mortar fillet, and consists of the following steps:

(a) a mortar fillet of 20 mm is cast in the *F* mold and positioned over the *E* base. Then, the mortar fillet + *E* base set is positioned over the *A* base;

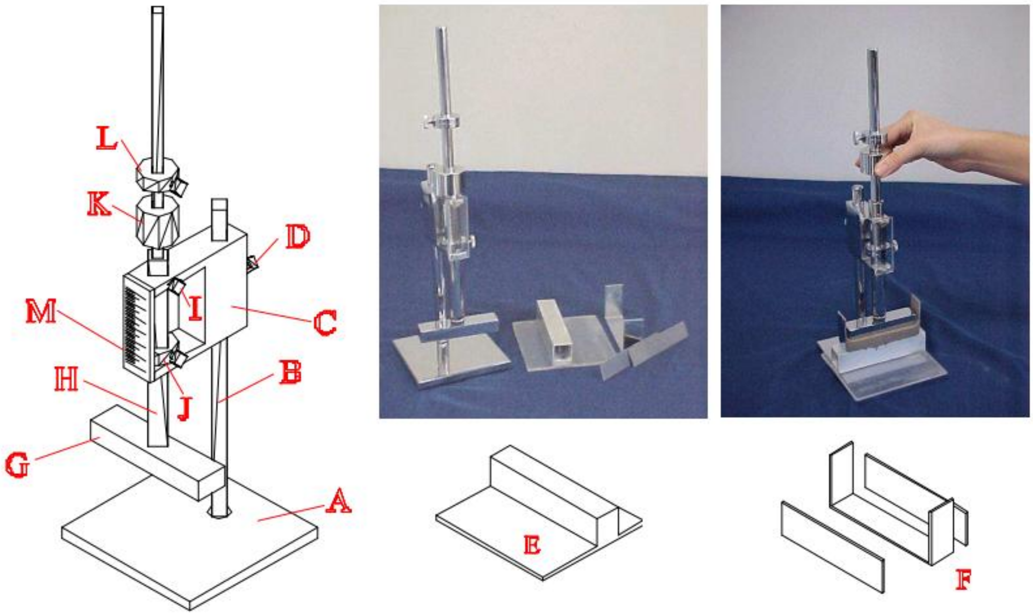
(b) the *GH* probe is placed in its initial position at 20 mm height of the *E* base, resting over the mortar fillet;

(c) the *GH* probe is released, and the deformation suffered by the mortar sample is measured; and

(d) the *K* sliding mass is dropped from a standard height (from the *L* ring) until the mortar fillet reaches a thickness of 10 mm.

The consistency of the mortar is taken as the deformation of the mortar fillet after releasing the probe, and the plasticity as the number of drops required for the mortar fillet to reach the thickness of 10 mm. According to Casali and Prudêncio Junior (2008), a mortar suitable for concrete block structural masonry applications should have a consistency between 15.0 and 18.0 mm, and a plasticity between 7 and 15 drops. These values were used as acceptance criterion for mortar workability, for both storage times.

Figure 2 – **Gtec test apparatus**



Source: Casali, Prudêncio Junior (2008).
Note: A: support base;
B: support column;
C: sliding support;
D: bracket fixing column;
E: support base of the mortar mould;
F: fillet mould;
G: probe base;
H: probe rod;
I: probe holder screw;
J: probe holder ring 1;
K: sliding mass;
L: standard height ring; and
M: sample measurement scale.

Hardened state

For each mortar and storage time, three cylindrical specimens of 50 x 100 mm were cast for the compressive strength test, following the NBR 7215 (ABNT, 2019). In addition, three prismatic specimens of 40 x 40 x 160 mm were cast for the bending test, according to NBR 13279 (ABNT, 2005). After the bending test, the specimen halves were submitted to the compression test following the NBR 15961 (ABNT, 2011), which prescribes the compressive strength determination in cubic specimens of 40 x 40 x 40 mm.

Prisms

For each mortar and storage time, four prisms of three rows were produced for the compressive strength and modulus of elasticity tests, according to Prudêncio Junior, Oliveira and Bedin (2002), and four prisms of four rows were produced for the bending tests. The mortars were applied with wooden trowels over the whole web of the blocks. Some care was taken at this step, following the recommendations of Prudêncio Junior, Oliveira e Bedin (2002):

(a) the blocks were previously air dried and kept in the laboratory before the tests;

(b) before producing the compression prisms, the blocks for the top and bottom rows had one face capped with cement paste for surface regularisation;

(c) the mortar joints had a final thickness of 10 ± 3 mm; and

(d) the blocks classified as "heavy" were applied in the upper rows and the "light" blocks in the lower rows.

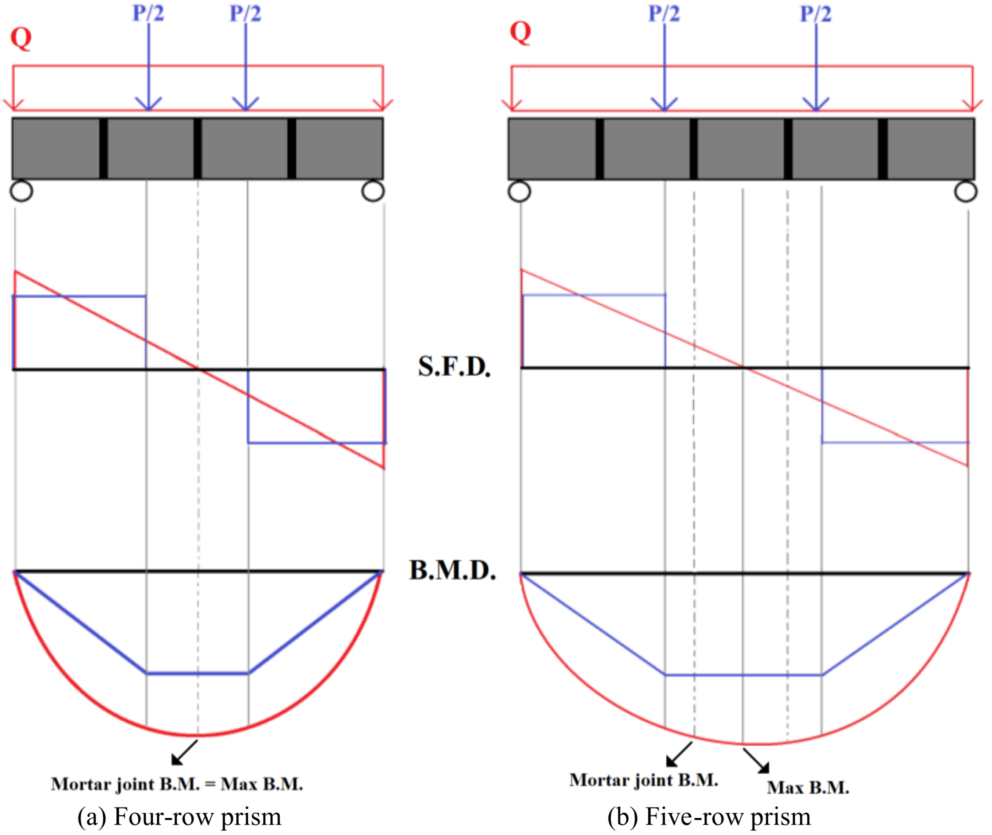
This procedure aimed to compensate for the absence of subsequent rows, present on a real wall. The weight of the wall applies pressure on the mortar that assists its penetration into the pores of the substrate. This provides a mechanical bonding between the mortar and the block and is essential to achieve a proper adhesion between them (CARASEK, 2017). For the same purpose, an additional block was positioned at the top of each prism (without mortar application), which was maintained until the test age.

The compressive strength and modulus of elasticity tests were performed simultaneously in each prism according to NBR 15961 (ABNT, 2011), 28 days after their production. The prisms were submitted to axial compression, and the strain was measured by digital extensometers (ID-C112B, Mitutoyo) with instant readings every 20 kN until the mortar yielded. After this, the strain measurement apparatus was removed, and the prisms were tested until the breaking load.

The flexural strength of the prisms was evaluated at 28 days through the four-point bending test in four-row prisms, following the NBR 8798 (ABNT, 1985). This test differs from the NBR 15961 (ABNT, 2011) standard, currently in effect, which prescribes the test in five-row prisms. This choice is justified below. Figure 3 shows the loads, shear force diagrams and bending moment diagrams in prisms during the bending test, for four- and five-row prisms. In the four-row prism (Figure 3a), the central section consists of a mortar joint which is subjected to pure bending, i.e., it does not undergo shear stress. In contrast, in the five-row prism (Figure 3b), both mortar joints of the central block are subjected to shear stress, and are not subject to the maximum bending moment (which occurs in the middle of the central block, and is used to calculate the flexural strength). Therefore, the four-row prisms were chosen for the bending tests.

In order to handle the prisms preventing the blocks from detaching and applying loads before the tests, they were placed on confining supports developed by Schankoski *et al.* (2012), illustrated in Figure 4a. The bending test is conventionally performed by placing concrete blocks over the load distribution apparatus, as prescribed by NBR 15961 (ABNT, 2011). However, for a greater accuracy of the results, the loading was applied through a hydraulic press (UH-A, Shimadzu), as shown in Figure 4b.

Figure 3 - **Loads, shear force diagram (S.F.D.) and bending moment diagram (B.M.D.) in the prism bending test**



Note: the diagrams are illustrative only, thus they are not to scale.Q represents the uniformly distributed load relative to the prism's own weight, and P represents the applied load for prism rupture.

Figure 4 – **Prism flexural test**

(a) Confining support for handling the prisms (b) Loading through hydraulic press

Statistical analysis of the results

Based on the experimental results obtained in the laboratory, the statistical analysis of the data was performed through comparison of means. To do this, a chi-squared test was used for a significance of 5% (i.e. reliability of 95%). This test evaluates the mean, standard deviations and number of data from two groups, accepting the hypothesis of difference between the means if the dispersions are small enough for the given reliability.

Results and discussion

Concrete blocks

Table 5 shows the compressive strength and water absorption of the blocks. The average compressive strengths exceeded the characteristic strength values (f_{bk}) by 61%, 93% and 66%, respectively for the 6, 9 and 14 MPa blocks, well above the expected. Regarding the absorption test, the average results were below the maximum limit of 9% prescribed by NBR (ABNT, 2016a) for blocks with strength between 4 and 8 MPa, and 8% for blocks with strength greater than 8 MPa. According to Parsekian *et al.* (2019), high absorption values can lead to high moist absorption over time, facilitating the incidence of mould, fungi, lichens, and vegetation in the masonry. There was a progressive reduction in water absorption as the block strength increased. These reductions were of 5.0% and 7.0% respectively for the 9 and 14 MPa blocks compared to the 6 MPa blocks. This confirms that increasing the block strength increases its compactness, consequently reducing the water absorption, as reported in the literature (PARSEKIAN *et al.*, 2019). This behaviour was also reported by other authors for compressive strengths different from those found in the current work (MARTINS *et al.*, 2018; FONSECA *et al.*, 2019). Since the adhesion between the mortar and the block can be largely affected by the mechanical bonding provided by the mortar penetration into the block pores, this trend may lead to progressive reductions in adhesion as the block strength increases, as discussed later.

Fresh state

The results of the mortar fresh state tests are shown in Figure 5 and Table 6. The 14 MPa mixture was not workable at 36 hours. Thus, water was gradually added to this mixture until it reached the Gtec test target range values for consistency and plasticity. This procedure increased the water/cement ratio of the mixture, tending to reduce its mechanical strength. However, this procedure is conventionally adopted on the construction site for the workability adjustment of the ready-mixed mortars.

Table 5 – **Compressive strength and water absorption of the concrete blocks**

Nominal strength (MPa)	Block						Average (MPa)	SD (MPa)	CV (%)	F_{bk} (MPa)	Absorption (%)
	1	2	3	4	5	6					
6 MPa	9.78	9.93	10.08	10.30	11.18	11.64	10.49	0.75	7.16	9.63	6.97
9 MPa	18.06	19.44	20.16	21.77	23.71	24.07	21.20	2.40	11.34	17.34	6.62
14MPa	23.48	23.64	23.95	26.68	27.75	29.31	25.80	2.47	9.56	23.17	6.48

Note: SD = standard deviation;
CV = coefficient of variation; and
F_{bk} = characteristic compressive strength.

Ready-mixed mortar

In general, the mortars showed consistency and plasticity within the limits proposed by Casali and Prudêncio Junior (2008) for the Gtec test (consistency between 15.5 and 18.0 mm and plasticity between 7 and 15 drops). According to this test, the 9 MPa mortar had a slight variation in the fresh state properties from 0 to 36 hours, maintaining the plasticity and varying the consistency by 3%. The 6 MPa mortar had greater variations on those properties in the same period but remained within the proposed limits after 36 hours. The workability loss (i.e. increases in the consistency and plasticity values) over time observed for the 6 MPa mortar is in line with the results reported by Casali *et al.* (2018), who found reductions in the flow table test values over time for ready-mixed mortars produced with different types of Portland cement. The authors justified this behaviour by a possible start in the cement hydration reactions. Finally, the 14 MPa mortar showed very high plasticity on the first day, which was compensated by the water incorporation on the second day. It worth noting that the limit values proposed by Casali and Prudêncio Junior (2008) refer to concrete blocks, and those values may vary depending on the material and geometry of the blocks. Dafico (2007), for example, proposed consistency values between 3 and 13 mm for the Gtec test, for clay blocks of 90 x 190 x 190 mm (width x height x length).

Regarding the air content of the mortars, the 6 and 9 MPa mixtures showed values between 5.9% and 7.2% at both storage times. According to Prudêncio Junior, Oliveira and Bedin (2002), an air content lower than 10% usually does not cause significant losses in compressive strength and in the adhesion between the mortar joint and the block. In contrast, the 14 MPa mortar had air contents of 9.0% at 0 hours and 10.7% at 36 hours. These values are respectively 43% and 70% higher than the average of the other mortars and may lead to reductions in mechanical strength and adhesion. This was confirmed by Santamaría-Vicario *et al.* (2015), which reported that increasing the mortar air content from 8% to 22% reduced its adhesive strength by 61% in ceramic-based masonry. Furthermore, it can be noted that both the 6 MPa and 14 MPa mortars had increases in the air content from 0 to 36 hours. This probably occurred due to the homogenisation process performed after 36 hours, which may have incorporated air into the mixture. Thus, it can be stated that the 6 and 9 MPa ready-mixed mortars had satisfactory maintenance of both consistency and plasticity from 0 to 36 hours. One can expect a greater air content for this type of mortar, which usually ranges from 10 to 20%. However, the values found in the current work (7.5% on average) are in line with those reported by Lozovey (2018) (down to 8.0%) for this material.

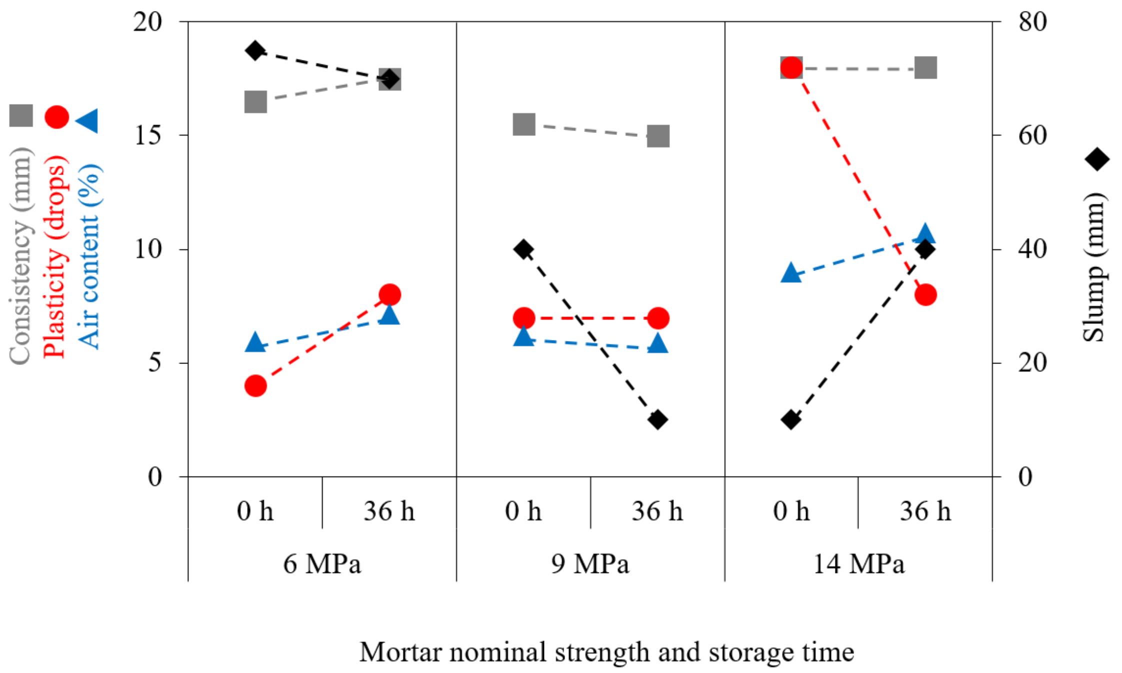
The slump results did not show good correlations with the consistency and plasticity values of the Gtec test ($R^2 < 0.38$). For example, the 14 MPa – 36h mixture showed the same consistency value as the 14 MPa – 0h, but slump was 4 times higher. Moreover, the 9 MPa – 36h and 14 MPa – 0h mixtures had similar slump, but very different plasticity. This probably resulted from the sum of two factors. Firstly, the Gtec test evaluates the mortar fresh behaviour through a combination of static and dynamic loads, respectively related to the plasticity and consistency of the mortar. In turn, the slump test evaluates the fresh behaviour only through a static loading condition (i.e. the sample own weight). In addition, the compaction process performed during the slump test may remove part of the entrained air of the mixtures, while the Gtec test is performed in a mortar sample that is practically undisturbed, which is closer to a real condition. Casali *et al.* (2018) also reported the limitation of some empirical tests on the evaluation of fresh state properties of mortars. The authors evaluated the influence of the cement type and storage time on the fresh properties of ready-mixed mortars. They observed significant differences in the rheological behaviour of the mixtures through the squeeze-flow test, while the consistency index (measured by the flow table test) was not sensitive enough to evaluate such differences.

Table 6 - **Summary of the fresh state tests results**

Mortar		Slump (mm)	Gtec test		Air content (%)
			Consistency (mm)	Plasticity (drops)	
6 MPa	0 h	75	16.5	4	5.94
	36 h	70	17.5	8	7.18
9 MPa	0 h	40	15.5	7	6.22
	36 h	10	15.0	7	5.89
14 MPa	0 h	10	18.0	18	9.00
	36 h*	40	18.0	8	10.72

Note: *additional water incorporation.

Figure 5 - **Mortar fresh properties**



Hardened state

Figure 6 shows the compressive and flexural strength of the mortar at 28 days. Error bars correspond to ± 1 standard deviation. Except for the 6 MPa – 36h and 14 MPa – 36h mixtures, the compressive strength values of the cylindrical specimens were 2% higher on average compared to those of the cubic specimens. This behaviour was not expected as cubic specimens generally provide values from 5 to 10% higher than the cylindrical ones (GREYBEAL; DAVIS, 2008; KUSUMAWARDANINGSIH; FEHLING; ISMAILB, 2015; ALSELMAN; DANG; HALE, 2017). In the current study, the bending test previously performed on the cubic specimens may have caused internal cracking, thus resulting in mechanical strength reductions. Nonetheless, a good linear correlation was found between the strengths of the cylindrical and cubic specimens (shown in Figure 7), with $R^2 = 0.88$.

The compressive strengths of the 6 and 9 MPa mortars were respectively 80% and 62% higher than their nominal values on average, for cubic specimens. In contrast, the 14 MPa mortar did not reach the nominal strength, regardless of the storage times. This can be explained mainly because the 14 MPa mortar had an air content greater than the 6 and 9 MPa mortars and required the addition of extra water at 36 hours, both leading to strength reductions. In addition, the 14 MPa mortar mixture had a high consistency in 0 hours (18 drops in Gtec test and 10 mm in slump), which may have resulted in casting failures.

Figure 6 - **Compressive and flexural strength of the mortars at 28 days**

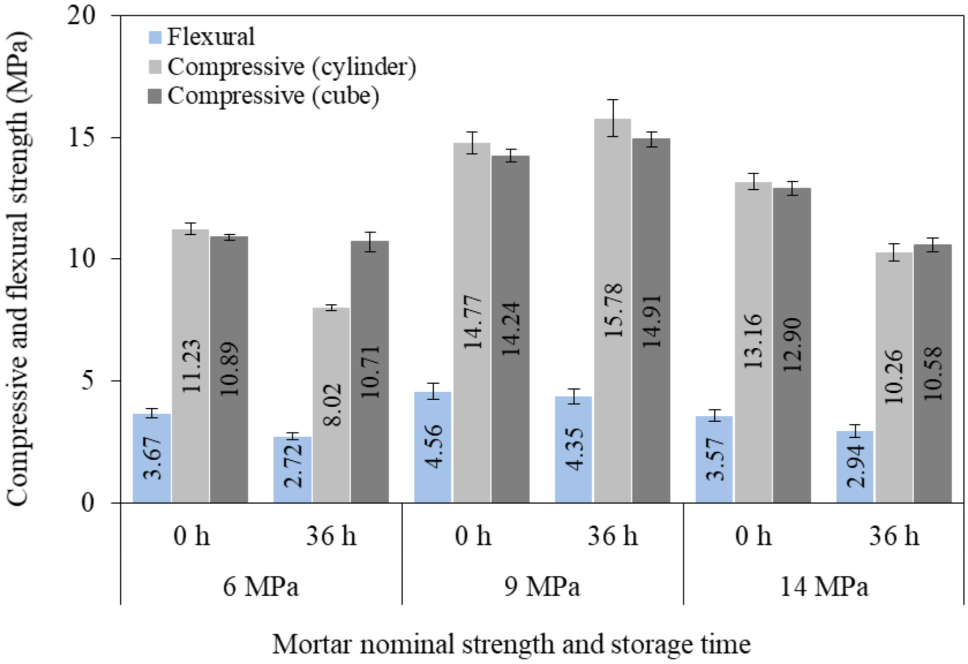


Figure 7 - **Correlation between the compressive strength of the mortars in cubic and cylindrical specimens**

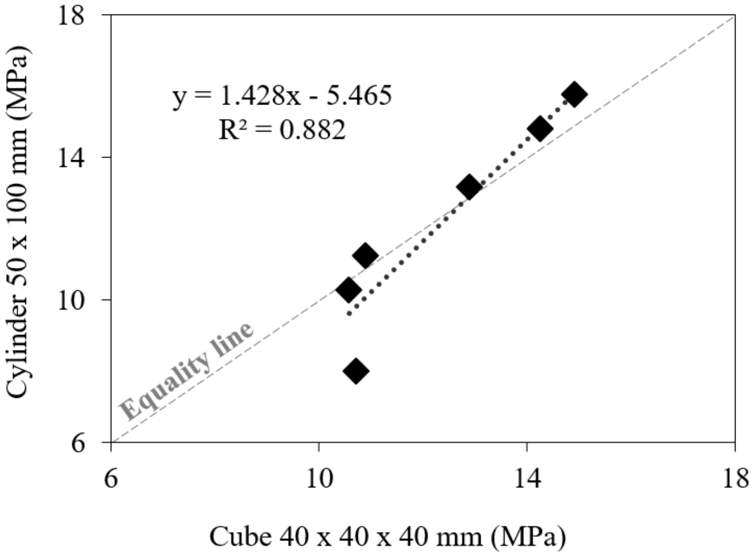


Table 7 - **Comparison of means between the compressive strength of mortars with different storage times (in cubic specimens)**

Combination	Sp^2	t(Sp)	t α/2 (Nx+Ny - 2)	Result
6 MPa - 0h vs. 6 MPa - 36h	0.0885	0.7686	-2.7764	Equal
9 MPa - 0h vs. 9 MPa - 36h	0.0920	2.6779	-2.7764	Equal
14 MPa - 0h vs. 14 MPa - 36h	0.0819	9.9333	-2.7764	Different

Regarding the compressive strength variation from 0 to 36 hours, the 6 and 14 MPa mortars showed strength reduction trends, while the 9 MPa mortar showed a slight increase trend over time (Figure 6). These trends can be explained by the air content of the mortars (Table 6). Both 6 and 14 MPa mortars showed increases in their air content over time, in addition to the extra water incorporation in the latter at 36 hours. This would result in mechanical strength losses due to increases in the porosity of the mortar. In contrast, the 9 MPa mortar had a slight decrease in its air content over time, resulting in the opposite behaviour to other mortars, i.e., mechanical strength gains. Nonetheless, the comparison of means showed that the storage time did not significantly change the compressive strength of the 6 and 9 MPa mortars for a reliability of 95%, as can be seen in Table 7. In contrast, the comparison of means confirmed that the increase in the storage time significantly reduced the 14 MPa mortar strength, which can be related to the fact that this was the only mixture that required extra water addition at 36 hours.

Regarding the flexural strength obtained by the bending test, the mortars showed strengths from 2.7 to 4.6 MPa, which corresponds to 30% on average of its respective compressive strengths. This value is similar to the average of 32% reported by Schankoski, Prudêncio Junior and Pilar(2015) for industrialised and mixed mortars of 6 to 16 MPa and is well above the 10% average generally reported for conventional mortars and concretes (MEHTA; MONTEIRO, 2015). Figure 8 shows that a satisfactory linear correlation was found between the flexural and compressive strength values in the cubic specimens, with R^2 = 0.79. As in the compressive strength, the 14 MPa mortar showed lower flexural strength than expected for both storage times, justified by the same reasons previously presented.

Comparing the flexural strength of each mortar with different storage times, all the mortars had reductions in their average strength from 0 to 36 hours. However, for a reliability of 95%, the storage time did not significantly change the flexural strength of the 9 MPa mortar, while it changed the strengths of the 6 and 14 MPa mortars (Table 8). Despite these reductions, the flexural strengths of these mortars were 29% of their compressive strength values.

Prisms

Figure 9 shows the compressive strength of the prisms at 28 days. Error bars correspond to ± 1 standard deviation. A substantial variability in the results can be observed with a coefficient of variation of 20% on average. This variability is inherent to the prism tests and is compatible with the average coefficient of variation of 17% reported by Schankoski, Pridêncio Junior Pilar (2015) for concrete block prisms of 6 to 16 MPa. The 6 MPa prisms showed strengths similar to the nominal value, while the 9 and 14 MPa prisms had strengths, respectively, higher and lower than their nominal values, as observed in mortars.

Figure 8 – **Correlation between the flexural and compressive strength (in cubic specimens) of the mortars**

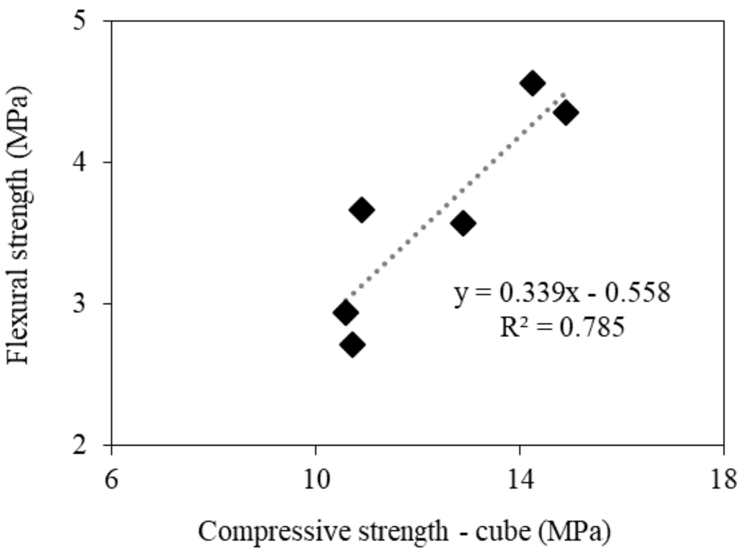


Table 8 – **Comparison of means between the flexural strength of mortars with different storage times**

Combination	Sp²	t(Sp)	t α/2 (Nx+Ny - 2)	Result
6 MPa - 0h vs. 6 MPa - 36h	0.0260	7.2257	-2.7764	Different
9 MPa - 0h vs. 9 MPa - 36h	0.1032	0.7880	-2.7764	Equal
14 MPa - 0h vs. 14 MPa - 36h	0.0681	2.9413	-2.7764	Different

Figure 9 – **Prism compressive strength at 28 days**

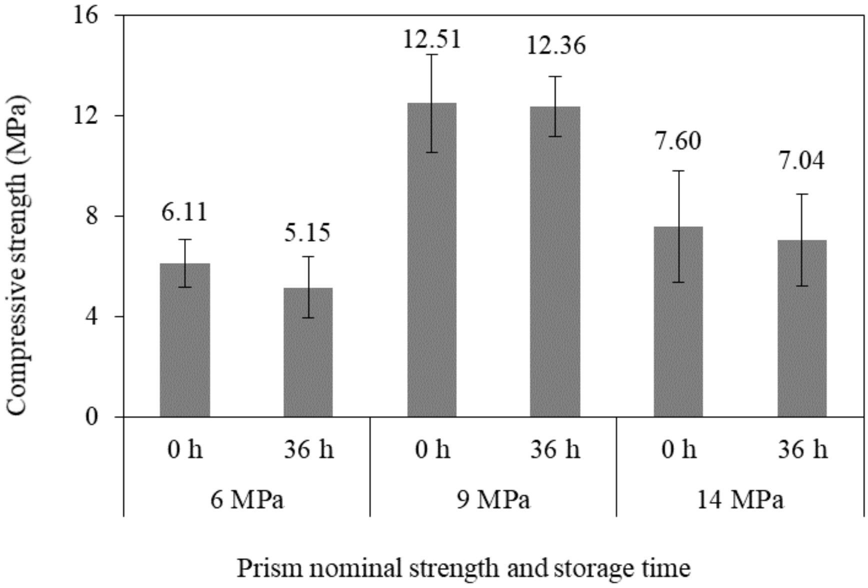


Table 9 – **Comparison of means between the compressive strength of prisms with different storage times**

Combination	Sp²	t(Sp)	t α/2 (Nx+Ny - 2)	Result
6 MPa - 0h vs. 6 MPa - 36h	1.2527	0.8111	-2.7764	Equal
9 MPa - 0h vs. 9 MPa - 36h	2.8467	0.1112	-2.7764	Equal
14 MPa - 0h vs. 14 MPa - 36h	4.1131	0.3362	-2.7764	Equal

Regarding the effect of storage time on the compressive strength of the prisms, an overall trend of strength reduction over time is observed (Figure 9). However, for a reliability of 95%, no significant differences were found in the compressive strength of the prisms with the same nominal strength as the storage time increased, as can be seen in Table 9.

Figure 10 shows the breaking mechanism of some of the prisms tested. In general, the failure occurred by crushing the mortar joint. This probably occurred because the actual strengths of the blocks were much higher than the nominal values, especially for the 9 and 14 MPa blocks. In fact, the average strengths of these blocks were respectively 31% and 55% higher than the strengths of their respective mortars. Once the prisms breaking occurred due to the collapse of the mortar joints, the strength of this element commanded the strength of the masonry. Thus, a correlation between the compressive strength of the prisms and their respective mortars was proposed, as shown in Figure 11. The R^2 coefficients obtained were 0.85 and 0.89, respectively, for the compressive strength in cylindrical and cubic specimens. These values are in line with the R^2 of 0.84 reported by Schankoski, Prudêncio Junior and Pilar (2015) for the same correlation. It can also be noted that the correlation between the strengths of the prisms and mortars in cubic specimens had the highest R^2 coefficient. This indicates a better prediction of the strength of prisms by this specimen geometry and corroborates with the NBR 15961 (ABNT, 2011), which prescribes the test in cubic specimens.

Figure 12 shows the prisms flexural strength obtained by the bending test. Error bars correspond to ± 1 standard deviation. Although the NBR 15961 (ABNT, 2011) does not prescribe minimum values for this property, it provides characteristic strength values (ftk) in the case of not having tests to determine it. Those values are 0.20 MPa for mortars with compressive strength from 3.5 to 7.0 MPa, and 0.25 for mortars with compressive strength above 7.0 MPa. In the case of bending tests, the ftk calculation is prescribed by this standard as follows:

(a) the test is performed following the Annex C – Part II of the standard;

(b) the values lower than 30% of the average of the 50% highest values are excluded; and

(c) for 4 specimens (which is the number of samples tested in this work), the ftk value is given by 0.84 × ft_1, where ft_1 is the lowest valid values obtained.

Figure 10 – **Breaking mechanism of the prisms:(a) 6 MPa – 0h; (b) 6 MPa – 36h; (c) 9 MPa – 0h; (d) 9 MPa – 36h**

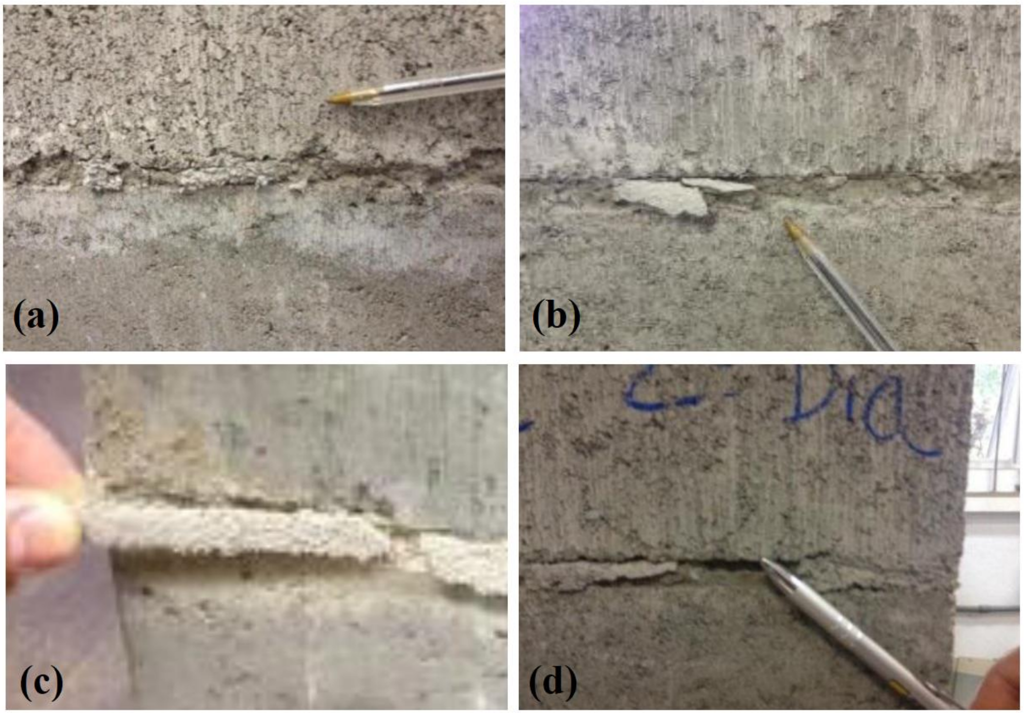
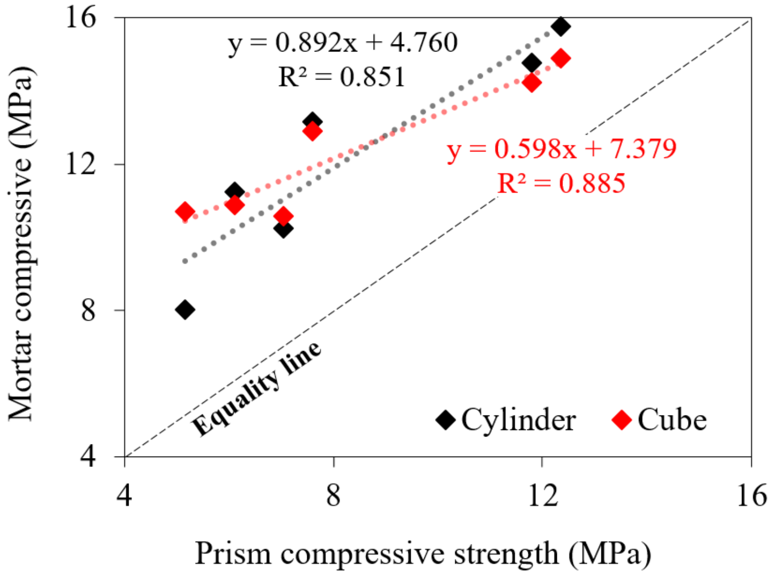


Figure 11 – **Correlation between the compressive strength of the prisms and the respective mortars in cylindrical specimens (in black), and in cubic specimens (in red)**



Since the referred standard does not prescribe limit values for this property, the results experimentally obtained were compared with those provided by the standard in the absence of the bending tests. Figure 12 also shows the ftk values of the prisms in red. None of the prisms reached the values proposed by the NBR 15961 (ABNT, 2011), even at 0 hours of storage time. This is similar to that reported by Schankoski, Prudêncio Junior and Pilar (2015), who found flexural strengths of about 0.05 MPa for industrialised and mixed mortars in prisms with compressive strengths of 6 to 16 MPa (close to those investigated in the current work). This indicates the difficulty of meeting such standard values, especially for high strength masonries (i.e. above 9 MPa). It may occur because of the high compactness of these units, which may lead to a reduction in the adhesion strengths between the mortar joint and the block. Such compactness hinders the percolating of water from the mortar to the block, which carries cementitious materials to the pores of the substrate and promotes the mechanical bonding between the parts.

Regarding the effect of the storage time on the prism flexural strength, the comparison of means indicated that the storage time did not significantly influence the flexural strength of the prisms for a reliability of 95%.

Figure 13 shows the modulus of elasticity of the prisms. Error bars correspond to ± 1 standard deviation. Table 11 presents the statistical comparison of means of the modulus of elasticity of the prisms. Trends of increasing the modulus of elasticity over time can be noted for the 9 and 14 MPa mortar, while the opposite is observed for the 6 MPa mortar. However, the comparison of means indicated that the increase in storage time did not lead to significant differences in this property for a reliability of 95%.

Finally, it is worth noting that both mortars and prisms of 6 and 14 MPa had compatible strengths (difference of 20% on average), while the modulus of elasticity of the 14 MPa prisms were up to 150% higher than those of 6 MPa prisms. This occurred because the blocks used in the 14 MPa prisms had an average strength of 25.8 MPa, compared to 10.5 MPa of the 6 MPa blocks (Table 5). Since the rigidity of the masonry is directly related to the rigidity of its composing elements, the use of blocks with higher compactness (i.e. with higher mechanical strength and lower water absorption) led to higher modulus of elasticity values in the 14 MPa prisms.

Conclusions

This paper evaluated the technical feasibility of using three ready-mixed mortars in concrete block structural masonry. The mortars had nominal strengths of 6, 9 and 14 MPa, and were used at storage times of 0 and 36 hours. Based on the results presented in this paper, the following conclusions were established.

Figure 12 – **Prism mean flexural strength (in grey) and characteristic flexural strength – ftk (in red)**

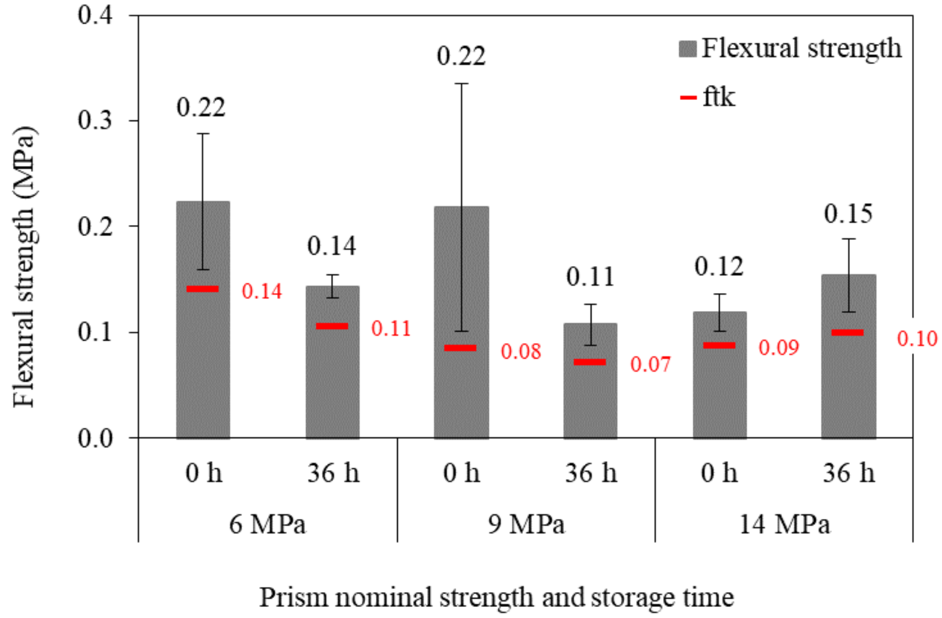


Table 10 – **Comparison of means between the flexural strength of prisms with different storage times**

Combination	Sp²	t(Sp)	t α/2 (Nx+Ny - 2)	Result
6 MPa - 0h vs. 6 MPa - 36h	0.0021	2.1246	-2.7764	Equal
9 MPa - 0h vs. 9 MPa - 36h	0.0070	1.6161	-2.7764	Equal
14 MPa - 0h vs. 14 MPa - 36h	0.0007	1.5515	-2.7764	Equal

Figure 13 – **Modulus of elasticity of the prisms at 28 days**

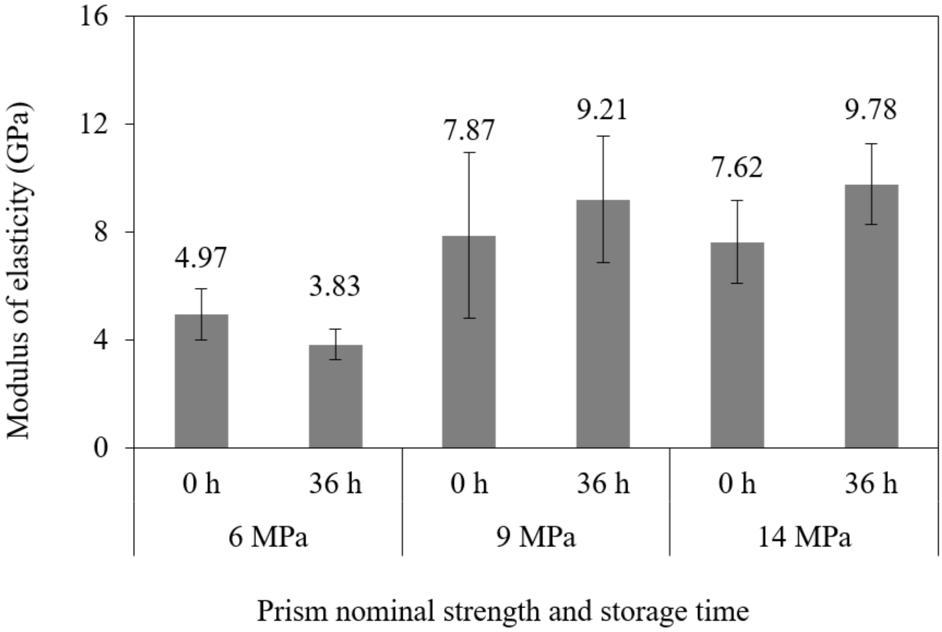


Table 11 – **Comparison of the means between the modulus of elasticity of prisms with different storage times**

Combination	Sp²	t(Sp)	t α/2 (Nx+Ny - 2)	Result
6 MPa - 0h vs. 6 MPa - 36h	0.6044	1.5662	-2.7764	Equal
9 MPa - 0h vs. 9 MPa - 36h	8.5610	0.2944	-2.7764	Equal
14 MPa - 0h vs. 14 MPa - 36h	2.3032	1.7378	-2.7764	Equal

The 6 and 9 MPa mortars presented satisfactory workability maintenance from 0 to 36 hours. In contrast, the 14 MPa mortar was not workable after 36 hours, thus requiring the addition of water. The slump test, which is conventionally used both by the plants for the consistency control and as an acceptance criterion on site, was not adequate to evaluate the mortars´ fresh state properties.

The storage time did not significantly change the compressive strength of the 6 and 9 MPa mortars for a reliability of 95%. In contrast, both the water incorporation and the increase in the entrained air content reduced the compressive strength of the 14 MPa mortar as the storage time increased. Regarding the mortars´ flexural strength, only the 9 MPa mortar did not show a significant reduction in this property as the storage time increased for a reliability of 95%. Nevertheless, the 6 and 14 MPa mortars showed flexural strengths of about 29% of those compressive strengths, even after 36 hours. Thus, increasing the storage time did not result in great losses in this property.

Regarding the prisms, neither the compressive strength, the flexural strength in the bending test, nor the modulus of elasticity were significantly influenced by the storage time with a reliability of 95%. For the set of mortars and blocks used, none of the prisms reached the standard flexural strengths even at 0 hours of storage time, similarly to that reported by the authors in previously published research.

Taken as a whole, the 6 and 9 MPa ready-mixed mortars investigated in this work did not present significant impairments in fresh and hardened properties after 36 hours, thus enabling its use in concrete block structural masonry.

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