ENGLISH VERSION..........

Lightweight concrete masonry blocks produced with: tire rubber and metakaolin

Bloques de mampostería de hormigón liviano fabricados con caucho de neumáticos y metacaolín

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Abstract

This paper presents the evaluation of lightweight concrete masonry blocks, incorporated with tire rubber and metakaolin, aiming reduce its bulk density and obtaining dimensional values of compressive strength and water absorption in according to the Brazilian standard ABNT NBR 6136: 2016. Three mixtures of concrete were produced by the replacement of 9%, 18% and 27% (by volume) of the fine aggregate by tire rubber, and one mixture without rubber (reference). In all mixtures the procedure of replacing 10% (by weight) of cement to metakaolin was adopted. Family M-15x30 of concrete blocks were performed using an entirely manual process, with PVC molds and PET bottle devices to casting the hollow characteristic of blocks. The results indicated that the concretes produced with rubber and metakaolin provided bulk density values lower than 2000 kg/m³, thus featuring lightweight concrete characteristics. In the dimensional verification, all the blocks series produced reached of requirements of the current standard. Although only the R0, R1 and R2 series had structural function, however all mixtures achieved water absorption ratio lower than 13%. Therefore, the tire rubber as fine aggregate in concrete masonry blocks is thought to be a good alternative for reuse of this waste material.

Keywords: *Masonry block; lightweight concrete; waste tire rubber; metakaolin; alternative material*

Resumen

Este artículo evalúa bloques de mampostería de hormigón liviano, a los cuales se les ha incorporado caucho y metacaolín con el objeto de reducir su densidad aparente y obtener valores dimensionales de resistencia a la compresión y absorción de agua, en conformidad con la norma brasileña ABNT NBR 6136: 2016. Se fabricaron tres mezclas de hormigón, reemplazando el 9%, 18% y 27% (en volumen) del agregado fino por caucho de neumáticos y además una mezcla sin caucho (referencia). En todas las mezclas, se adoptó el procedimiento de reemplazar el 10% (en peso) de cemento por metacaolín. Los bloques de hormigón del tipo M-15x30 se fabricaron manualmente, utilizando moldes de PVC y elementos de botellas PET para moldear huecos de los bloques. Los resultados indican que los hormigones fabricados con caucho y metacaolín arrojan valores de densidad aparente menores a 2000 kg/m³, presentando así características de hormigón liviano. En cuanto al análisis de las dimensiones, todas las series de bloques producidas cumplieron con los requisitos de la norma vigente. Si bien solo las series R0, R1 y R2 tienen función estructural, todas las mezclas obtuvieron tasas de absorción de agua inferiores al 13%. Por lo tanto, se considera que el caucho de neumáticos como agregado fino en los bloques de hormigón es una buena alternativa para reutilizar este material de desecho.

Palabras clave: Bloque de mampostería; hormigón liviano; caucho de neumáticos de desecho, metacaolín; material alternativo

1. Introduction

At present the construction sector consumes large amount of raw materials in the accomplishment of its buildings generating a large volume of waste materials. Therefore, its common the interest in decrease the consumption of natural resources used by this sector, thus promoting constructive techniques which follow guidelines for sustainability.

In parallel, the use of tire rubber in concrete production contributes to resolve one of more crucial environmental problems, the deposition of solid waste. The accumulation of discarded tires in the environment is of great concern due to difficult degradation of the rubber. The concrete deserves detach in this scenario owing to this material being considered more use, due to versality, low cost, facility of manufacturing, higher mechanical strength and durability. Concerning to contributions to sustainability, the concrete presents huge potential due to ability to incorporate on it structure recycled materials and industrial waste, as well collaborates to reduce the CO_2 present in the atmosphere and can be infinitely recycled.

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Several papers about the concrete production with tire rubber shows the possibilities of this material replace partially aggregates of natural origin, contributing to the environment in function to the use of a polluting waste and replace it with materials from finite natural sources. However, changes of concrete behavior in the fresh and hardened state were observed, in relation to concretes without incorporation of tire rubber.

Upon these researches, generally, the results showed that the production of concrete with tire rubber implies in a significant decrease in bulk density, flexural and compressive strength. In another hand, occurs improvement of impact resistance and thermal isolation (Pelisser et al., 20011); (Fioriti et al., 2010).

(Rossignolo and Oliveira, 2007) affirms that lightweight concrete can be applied in several fields of construction, wherein their use can be justified for reduction of bulk density of concrete minimizing the loads applied to the buildings.

In according to (Albuquerque et al., 2008), the characteristic concrete behavior with tire rubber in relation to flexural strength and elastic modulus is attributed to ability of rubber supports large elastic deformation before the concrete fracture. (Granzotto and Souza, 2013) reported the loss of compressive strength in concrete with tire rubber can be assign to the elastic modulus and the weak bond between the cement matrix and rubber.

(Selung et al., 2013), also observed a significant reduce of compressive strength in concretes up to 25% of tire rubber incorporating, and after, keeping practically constant up to 35%. The reduce of mean compressive strength of their mixtures with 15%, 25% and 35% of rubber, in relation with reference mixture was 51%, 88% and 89%, respectively. Thus, the authors concluded to mixture with 15% of rubber the compressive strength reached the minimum requirements to old Brazilian standard, in other words, the class C ($\geq$ 3,0 MPa) for use with structural function in masonry elements above ground level. While the other mixtures with 25% and 35% of rubber incorporation not reached of ABNT NBR 6136:2007 specifications.

Moreover regarding to the compressive strength decrease, (Peliesser et al., 2012) verified in order to make up the loss due to use of tire rubber, 10% of metakaolin in replacement of cement was introduced, thus enabling the facade panels fabrication process and reaching values of compressive strength higher than 20 MPa, this study was realized with mortar rather than concrete to allow thinner panels production.

(Rossignolo and Oliveira, 2007) verified the addition of 10% of metakaolin in replacement of cement, in which that addition increased compressive strength and diametral tensile strength performance, increased of durability of lightweight concrete and not promoted significant modifications in elastic modulus values, indicating that even in lightweight concrete, wherein the coarse aggregate is the main limiting factor of mechanical strength, the changes promotes by metakaolin presents in cement matrix resulted an improvement those properties performance.

(Xie et al., 2020) performed recycled concrete replacing the coarse aggregate with recycled concrete aggregate and cement with nano metakaolin and analyzed that the increase in the use rates of nano metakaolin improved the mechanical strength. For concrete with 100% recycled aggregate and 7% replacement of nano metakaolin, there was an increase of 27.1% in mechanical strength, presenting 45.9 MPa. Still, according to (Muduli and Mukharjee, 2020) the replacement of cement by 15% metakaolin in concrete with 50% recycled concrete aggregate replacing the natural coarse aggregate led to similar values of compressive strength when compared to reference concrete.

(Pelisser et al., 2012) concluded that in mortar or lightweight concrete the use of tire rubber and metakaolin contributes to reduction of raw materials consumption, as well to recycle those available materials and allows the construction materials production with higher thermal efficiency.

(Fioriti et al., 2010) performed interlocking blocks to paving replacing aggregates by tire rubber in 0%; 8%; 10%; 12% and 15% (by volume) and obtained 3,43%; 3,89%; 3,12%; 3,96% and 6,30%, respectively of average water absorption rates. The authors also mentioned that using different grade rubber size in concrete, the rubber particles influence straight in water absorption capacity lead to changes due to the lower water absorption by thinner grading size.

Regarding to the less porous structure of tire rubber and water repel property, (Santos et al., 2010) reported that when this material is incorporated in concretes, this incorporation is able to increase the durability.

However, the made concretes with tire rubbers presented permeability reduction due to non-hygroscopic aggregate, thus improve significant the durability of concretes which have degradation processes associated with the penetration of aggressive agents and CO_2. Although, they presented a loss of compressive strength with main problem leading to an increase of cement consumption for same strength class. Therefore, this study presents evaluation of lightweight concrete masonry blocks with tire rubber and metakaolin aiming reduce the bulk density, get dimensional values, compressive strength and water absorption in accordance to Brazilian standard ABNT NBR 6136:2016.

2. Materials and methods

The experimental study was developed with a physical characterization of used materials. Also, the concrete was produced and the slump test, air content and bulk density in fresh state were evaluated. Thus, was realized the casting of masonry blocks in order to evaluate the weight, dimensional analysis, compressive strength and water absorption in hardened state.

2.1 Materials properties

2.1.1 Cement

The cement used was CPV–ARI. This cement enables fast demolded and provide larger agility in production process. The achievement physical characterization of cement involved the following tests: specific surface – Blaine (ABNT NBR NM 76:1998), final setting (ABNT NBR 16607:2018), specific gravity (ABNT NBR 16605:2017) and cement compressive strength (ABNT NBR 7215:2019). (Table 1) shows the results obtained.

Table 1. *Physical characterization of cement* ***CPV-ARI***

Fineness mesh # 200 (% retained)			1,53
Fineness mesh # 350 (% retained)			6,14
Specific surface - Blaine (cm²/g)			3766
Apparent density (g/cm³)			1,05
Specific gravity (g/cm³)			3,03
Initial setting (h:min)			2:05
Final setting (h:min)			3:04
Uniaxial compressive strength (MPa)	**Consistency**	**Gram**	150
		w/c	0,48
	Strain (MPa)	**3 days**	38,70
		7 days	39,80
		28 days	51,70

2.1.2 Aggregates

The fine aggregate used was the river sand. The tests used to make the characterization were: determination of material finer than 75 µm sieve by washing (ABNT NBR NM 46:2003), apparent density and specific gravity (ABNT NBR NM 52:2009), water absorption (ABNT NBR NM 30:2001) and determination of content of the organic impurities (ABNT NBR NM 49:2001).

The coarse aggregates used was the gravel of basaltic origin. The tests used to make the characterization were: apparent density (ABNT NBR NM 45:2006), specific gravity (ABNT NBR NM 53:2009), water absorption (ABNT NBR NM 30:2001) and determination of clay lumps and friable materials content (ABNT NBR 7218:2010). (Table 2) presents the results obtained of those aggregates characterization.

Table 2. *Characterization of aggregates*

Aggregates	**d.s.s. (g/cm³)**	**Apparent density (g/cm³)**	**Specific gravity (g/cm³)**	**Water absorption (%)**	**Organic impurities (%)**	**Pulverulence (%)**
Fine	2,627	1,532	2,644	0,38	+ light	0,40
Coarse	2,945	1,585	3,014	1,15	–	1,20

**d.s.s = dry saturated surface*

2.1.3. Metakaolin

The metakaolin used was provided of a company located in Jundiaí-SP, which (Table 3) shows the characterization values and are in according to the limits established by Brazilian standard ABNT NBR 15894-1:2010.

***Table* 3.** Characterization of metakaolin

Waste mesh # 325 (% retained)	*5*
Specific surface (cm²/g)	*240000*
Apparent density (g/cm³)	*0,62*
Specific gravity (g/cm³)	*2,58*
Performance with cement – 7 days (%)	*115*
Chapelle's methods for determination of pozzolanic activity (mg $Ca(OH)_2$ / g)	*1000*

2.1.4 Tire rubber

The tire rubber used was provided by a company retreading in located in Ilha Solteira-SP, which realize mechanical process of retreading of tire exclusively of trucks and heavy machines.

Aiming to observe the influence of this material in concrete mixtures, the tire rubber was submitted by sieving process, in which was used the passing material in mesh #6,3 mm, shown in (Figure 1).

Figure 1. *Sieving process*

(Table 4) presents results of test of apparent density (ABNT NBR NM 45:2006) and specific gravity (ABNT NBR NM 52:2009) of the tire rubber.

Table 4. Characterization of rubber

Apparent density (g/cm³)	***Specific gravity (g/cm³)***
0,348	*1,090*

2.1.5 Mixture procedure and mix proportion

The campaign was designed in use mixtures in volume of dry materials with replacement of 9%; 18% and 27% (by volume) of fine aggregate by tire rubber. The content of rubber used represents a significant quantity, due to the specific gravity of rubber is lower than the fine aggregate. Regarding another researches of cement composites with tire rubber, that researches used 3% up to 30% volume content (Pelisser et al., 2011); (Fioriti et al., 2010); (Sukontasukkul and Chaikaew, 2006).

In all mixtures also was adopted the replacement of 10% (by weight) of cement for metakaolin in order to obtain a lightweight concrete with bulk density less of 2000 kg/m³. The study had a reference (without rubber) mixture in order to make comparation. The cement consumption was fixed in 350 kg/m³, this value was investigated in four factories of precast elements in State of São Paulo, in which the cement consumption proximally varies of 250 up to 425 kg/m³ on the factory process of masonry blocks. Although that consumption limit is variable due to the equipment type used by blocks factory moreover the materials qualities.

Initially was realized the transformation of mixture in volume by mass, with used the values of specific gravities of cement, fine and coarse aggregates, metakaolin and rubber. The relationship of w/c was fixed in 0,70 in order to facility the blocks casting without vibro-compactor equipment. Moreover, for all mixtures the workability of concrete was fixed in 140 ± 20 mm without change the w/c relationship, thus using polycarboxylate-based superplasticizer. Lastly, the campaign included the casting of four concrete mixtures, in which three mixtures used rubber and one without rubber (reference). (Table 5) and (Table 6) shows the materials dosage of all mixtures in volume and mass, respectively.

Table 5. *Quantity of materials used in mixtures in volume*

Mixture	Mixture in volume	
	Cement : fine aggregate : rubber : coarse aggregate : w/c	Rubber (%)
R0	1 : 4,95 : 0,00 : 0,68 : 0,629	0
R1	1 : 4,43 : 0,50 : 0,68 : 0,629	9,2
R2	1 : 3,94 : 1,00 : 0,68 : 0,629	18,0
R3	1 : 3,44 : 1,50 : 0,68 : 0,629	26,8

Table 6. *Quantity of materials used in mixtures in mass*

Mixture	Mixture in mass (kg/m³)							
	Cement	Metakaolin	Sand	Rubber	Gravel	Water	Additive	Rubber (%)
R0	315,00	35,00	1506,28	0,00	228,14	222,72	1,89	0,00
R1	315,00	35,00	1349,63	64,78	228,14	222,72	0,95	9,00
R2	315,00	35,00	1199,00	127,07	228,14	222,72	0,95	18,00
R3	315,00	35,00	1048,37	189,36	228,14	222,72	0,95	27,00

2.1.6 Molds manufacturing and casting of masonry blocks

The molds used to manual casting of blocks were made with a smooth PVC (Polyvinyl Chloride) slabs and PET (Polyethylene Terephthalate) bottle as device to casting the hollow characteristic of blocks. The dimensional of molds were the same of blocks M-15x30 family (14 cm x 19 cm x 29 cm) thickness, height and length, respectively according to ABNT NBR 6136:2016. (Figure 2) presents the molds and samples of masonry blocks with measures in millimeters.

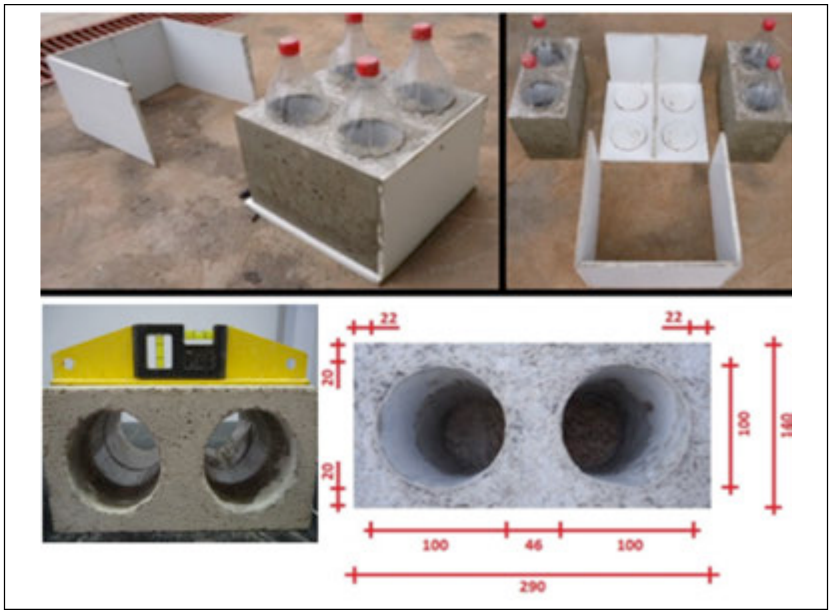

Figure 2. *PVC molds and PET bottle devices, as well masonry block with measures in millimeters*

The blocks densification process was realized in a vibro-compactor table during two steps, first with 50% fill of mold height and second with full fill of mold and keeps in laboratory condition. The blocks were demolded after 24 hours, like this the blocks were placed in a wet chamber with 23 ± 2ºC temperature for 21 days.

2.2 Experimental programme

2.2.1 Slump test

The slump test was realized in according to ABNT NBR NM 67:1998. (Figure 3) shows the measuring of slump test.

Figure 3. *Slump* test evaluation

2.2.2 Air content

The air content was realized in all mixtures by pressure method in according to ABNT NBR NM 47:2002. (Figure 4) exposes this test.

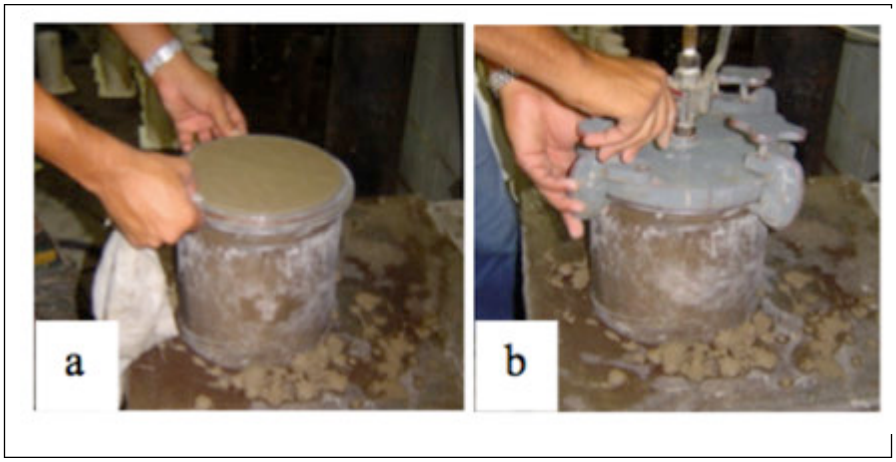

Figure 4. *a) Initial test; b) Pressure application*

2.2.3 Dimensional analysis

The dimensional analysis was realized in according to ABNT NBR 12118:2014, for this test was used a ruler and pachymeter to measure the width, length, height and thickness of blocks, also to was used a digital scale to verify the mass. The test was realized in eight blocks for each mixture at 28 days. (Figure 5) shows of dimensional analysis.

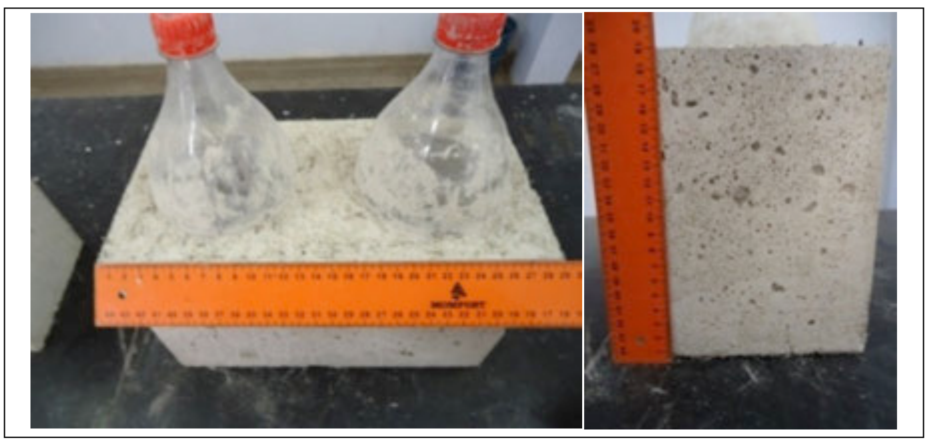

Figure 5. *Measuring of dimensional analysis*

2.2.4 Weight and bulk density

The evaluation of weight of blocks was made weighing up each specimen at 28 days and was investigated the bulk density of concretes.

2.2.5 Compressive strength

The test was made in according to ABNT NBR 12118:2014. Due to the top face of blocks present irregularities was made capping with gypsum paste, as shown in (Figure 6). Also was used eight blocks by mixture and carried out at 28 days. The characteristic compressive strength of the block (f_{bk}), referred to gross area, was determined by (Equation 1).

$$f_{bk} = f_{bm} - 1{,}65 \cdot sd \qquad (1)$$

where:
f_{bm} = average compressive strength of the block;
sd = standard deviation.

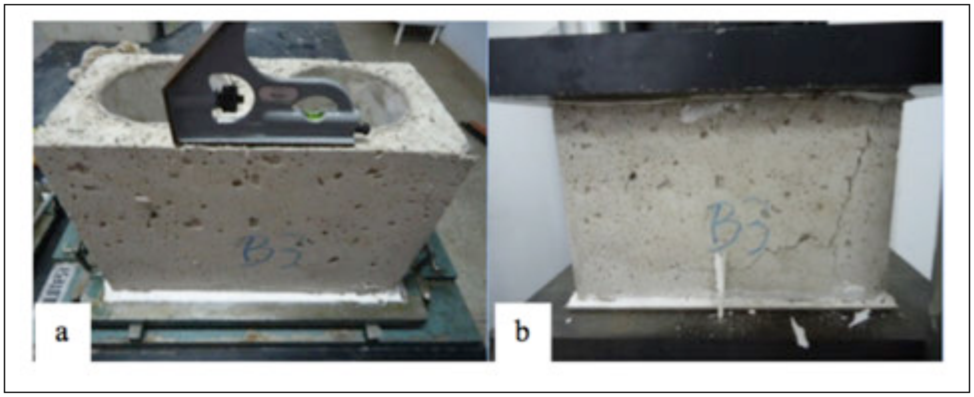

Figure 6. *a) Capping of blocks; b) Blocks being carried out*

2.2.6 Water absorption

The water absorption was realized in according to ABNT NBR 12118:2014, which was used eight specimens by mixture at 28 days. The absorption percentage was obtained by the ratio of water absorbed to oven-dried mass in greenhouse. (Figure 7) shows the steps of this test.

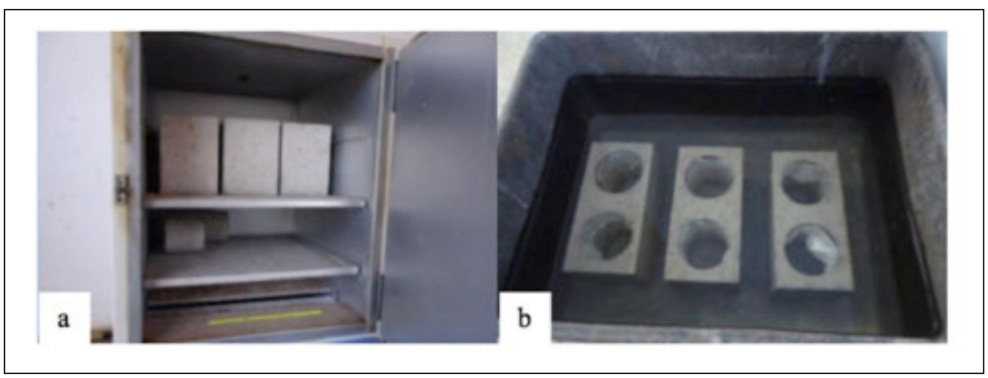

Figure 7. *a) Blocks in greenhouse for drying; b) Blocks immersed in water*

3. Results and discussion

3.1 Slump test

(Table 7) shows that the slump test decreased with an increase of tire rubber ratio consequently decreasing the workability of mixture, which the reference achieved slump of 21,95% more than R3.

This reduction in workability also can be explained due to shape and texture of tire rubber leading to difficulty in packaging the particles. However, all mixtures reached the slump (S) expected of 140 ± 20 mm, thus the mixtures can be specifying by flowability class S100 (100 ≤ S < 160 mm) in according to ABNT NBR 7212:2012. Besides that, this increased not muddled the blocks casting.

(Granzotto and Souza 2013) verified that rubber incorporation in concrete decrease the workability due to rubber specific surface be higher than sand specific surface, thus the authors when necessary, increased the w/c to maintain the same workability.

3.2 Air content

(Table 7) evidence the higher the rubber ratio lead to higher air content in the mixtures. Mixtures with rubber (R3; R2 and R1) shows larger percentage of air content of 47%; 27% and 13% respectively in relation to reference, these results agree with (Santos et al., 2010); (Granzotto and Souza, 2013). In respect of the air content amount, although improving the workability and contribute to decrease the bulk density, this amount affects directly the compressive strength (Cintra et al., 2014).

Table 7. *Slump test and air content results*

Mixture	R0	R1	R2	R3
Slump test (mm)	150	149	134	123
Air content (%)	15	17	19	22

3.3 Dimensional Analysis

The dimensional analysis presented in (Table 8) and (Table 9) attended all the requirements of ABNT NBR 6136:2016.

After the demolding of the blocks, it is possible to verify the uniformity in all points, sharps edges and cracks absence or other defects.

Table 8. *Average results of dimensions of blocks*

Mixture	Width (mm)	Height (mm)	Length (mm)
R0	140,0	189,0	291,0
R1	140,0	189,0	290,0
R2	141,0	188,0	290,0
R3	139,0	190,0	291,0

Note: In according to ABNT NBR 6136:2016 the tolerances allowed to width are ± 2,0 mm; to length and height are ± 3,0 mm.

Table 9. *Average results of dimensions of blocks walls*

Mixture	Longitudinal walls (mm)	Transverse walls	
		Walls (mm)	Equivalent thickness (mm/m)
R0	20,1	29,0	300,0
R1	20,1	30,0	310,3
R2	19,5	29,3	303,4
R3	20,0	29,7	306,9

Note: In according to ABNT NBR 6136:2016 the Class C – M15x30 to the minimal thickness to longitudinal and transverse walls is 18,0 mm and the equivalent thickness of transverse walls is 135 mm/m. The tolerance allowed to wall dimensions for each individual value is ±1,0 mm.

3.4 Weight and bulk density

In accordance to the results showed in the (Figure 8) can be observe that the higher rubber content in concrete block provides a decrease of the weight. Still, verified that weight decrease of rubber concrete blocks R1; R2 and R3 were 16%; 20% and 29%, respectively compared to the reference.

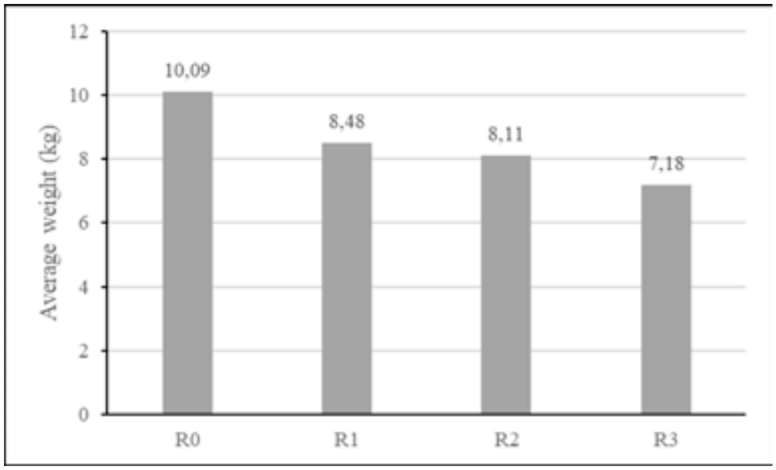

Figure 8. *Average weight of blocks*

As shown in (Figure 9) the bulk density of concretes remained below than 2000 kg/m³ obtain lightweight concrete characteristics. In addition, observes a decreased of bulk density of blocks (R1; R2 and R3) of 14%, 18% and 20%, respectively compared to reference.

Those properties are linked by the rubber and metakaolin incorporation which has lower specific gravity than the sand and cement, respectively, that lead to decrease the bulk density of concretes. Moreover, the air content amount, as shown in § 3.2., leads to decrease of these values. Thus, evidencing the possibility of rubber and metakaolin use for lightweight concretes production. These results agree with (Santos et al., 2010); (Granzotto and Souza, 2013).

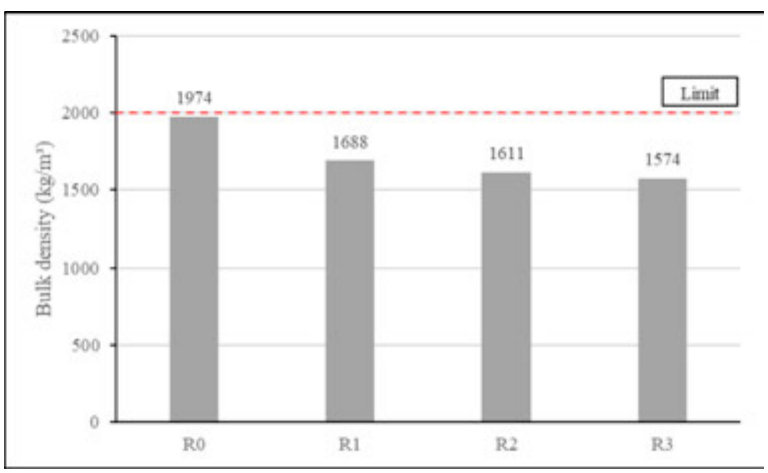

Figure 9. *Bulk density of concretes in fresh state*

3.5 Compressive strength

The (Figure 10) presents the average compressive strength of blocks (f_{bk}) in which only the mixtures R0; R1 and R2 achieved the ABNT NBR 6136:2016 requirements to structural masonry use for presenting f_{bk} above than 3 MPa. Thus, the series classifications are: R0 – class A (≥ 8,0 MPa, with structural function); R1 – class B (4,0 ≤ f_{bk} < 8,0 MPa, with structural function); R2 – class C (≥ 3,0 MPa, with structural function) and R3 – class C (< 3,0 MPa, with non-structural function).

Moreover, the averages results of f_{bk} with rubber content presented decrease with increased of rubber content, in which the R0 series reached the higher value. The maximum decrease in percentage is between R0 and R3, in which had 81% of decrease. In addition, the percentage between R0; R1 and R2 also decreased in 67% and 76%, respectively. The f_{bk} loss can be attributed to the weak bond between the cement matrix and the rubber. These results agree with (Sukontasukkul and Chaikaew, 2005). Also, (Fioriti and Akasaki, 2004) evaluated masonry blocks and concluded that the ideal amount of rubber ratio is the 13% (in volume), in which that mixture consume 245 kg/m³ of cement and reach results up to 5,0 MPa.

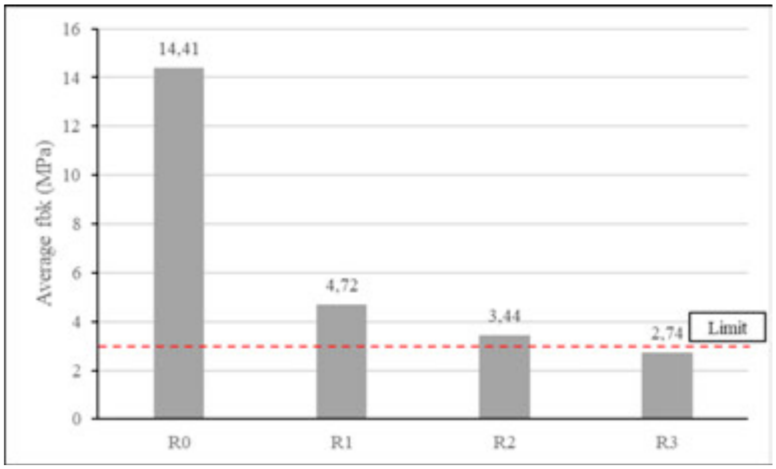

Figure 10. *Average compressive strength of blocks (f_{bk})*

In generally the concrete blocks with and without rubber presented different behavior on compressive strength test. The rubber concrete blocks presented volume increase, which despite of they carried out with lower stress capacity, thus holding up higher deformations, that is, maintained almost their integrity. In another hand, the concrete blocks without rubber has abrupt failures, shatter the concrete.

3.6 Water absorption

(Figure 11) presents the results of the average water absorption of concrete blocks, allows conclude that all mixtures presented absorption ratio lower than 13% specified by ABNT NBR 6136:2016. Also shows the non-significant difference between the rubber concrete blocks. Comparing the concrete blocks, the higher percentage difference is between R0 and R2, evidencing that water absorption capacity of R2 was 21% higher than R0 with value of 8,10% of water absorption. This increasing behavior is natural due to the air content increased, as shown in § 3.2.

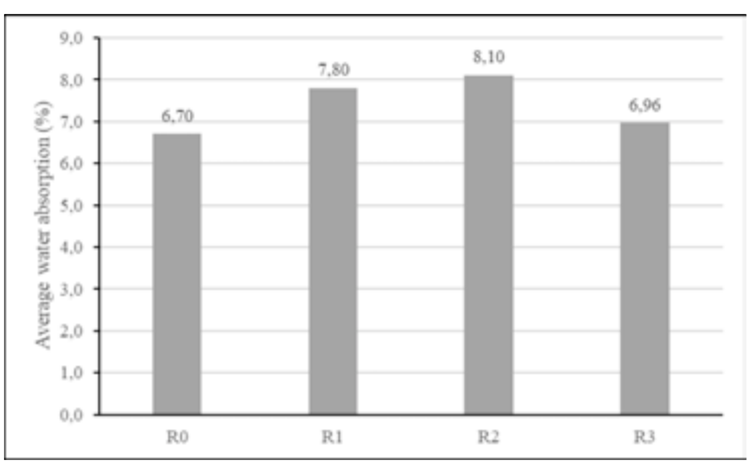

Figure 11. *Average water absorption of concrete blocks*

The increased of water absorption also was evaluated in (Fioriti et al., 2010) and in (Selung et al. 2013) in which the incorporating of rubber in concrete blocks with 15%, 25% and 35% increased the average water absorption of 4,7%, 6,1% and 6,4%, respectively. Therefore, the incorporating of rubber not evidenced significant changes.

4. Conclusions

The main points observed in this paper were:

a) Due to the decrease of workability whenever increasing the rubber incorporation on the concrete the polycarboxylate-based superplasticizer was used to obtain the workability 140 ± 20 mm desired.

b) The increase of rubber in mixture leaded to decreasing of slump test and increased of air content, those results are associated to the shape and texture of tire rubber.

c) The concrete produced with rubber and metakaolin provided bulk density values lower than 2000 kg/m³, characterizing lightweight concrete. The mixture R3 obtained the smallest bulk density of 1574 kg/m³, that is, 20% reduction comparing to R0. Therefore, conclude with higher rubber content leads to lower bulk density values, this occurs due to the rubber has lower specific gravity than the sand.

d) In terms of the dimensional analysis, all blocks produced showed dimensions within the requirements established by ABNT NBR 6136:2016.

e) Concerning to compressive strength of concrete blocks, the R0 reached the higher value of 14,41 MPa, however the decreasing of strength was verified with more rubber rate. That behavior is attributed to the weak bond between the cement matrix and the rubber. Regarding to structural function only R0, R1 and R2 had this characteristic, meanwhile the R3 had 2,74 MPa not obtaining structural function as established by ABNT NBR 6136:2016.

f) The water absorption test shown that all mixtures achieved the requirements established by ABNT NBR 6136:2016 due to average water absorption was less than 13%. Although the results not showed changes significantly the water absorption property.

g) Lastly, upon the results and behaviors shown, other studies must be performed to confirm the feasible of the tire rubber use in concrete masonry blocks.

5. Acknowledgments

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