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Physical and mechanical properties of lightweight concrete with incorporation of ceramic mold casting waste

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ABSTRACT

In the lost-wax foundry industry large amounts of ceramic mold casting waste (CMCW) are disposed of in landfills, which not only pollutes the environment but also leads to the loss of secondary resources. On the other hand, with the improvement of building style and performance, the demand for lightweight concrete is also increasing. Therefore, we recycle CMCW into lightweight concrete for environmental and economic reasons. In this study, two types of expanded clay with different sizes (2–10 mm and 10–20 mm) were used as reference aggregates. From the results, it can be seen that the density of CMCW is about four times higher than that of expanded clay, and the water absorption in 24 h is 1/4 of expanded clay. Then, expanded clay was replaced with three different weight percentages (30%, 60%, and 80%) of CMCW to prepare new lightweight concrete, which was tested for workability. After curing for 28 days at 90% humidity, four compositions were tested for their physical and mechanical properties. Finally, the results showed that with increasing CMCW content, mechanical performance also increased. With 80% CMCW in the lightweight concrete, a density of 1998 kg/m^3 and compressive strength of 36 MPa were achieved.

1. Introduction

Concrete is the most important material in the construction sector and has experienced a great demand in recent years. The Global Cement and Concrete Association [1] reported that global concrete consumption in 2020 was 14 billion m^3, 40% of which was used for residential construction. As the population grows, the global demand for concrete is increasing year by year. With the development of social productivity and the implementation of sustainable development goals, the development of concrete is getting a clearer direction, which is in the direction of lightweight, green and high strength concrete [2]. In particular, lightweight concrete with density below 2000 kg/m^3 [3], has significant applications in terms of thermal [4] and sound insulation properties compared to conventional concrete. It also reduces the weight of the structure, reducing the quantity of materials used. At the same time, the structure can be realized with large span, reducing the construction cost [5]. In recent years, due to environmental problems, researchers have tried to replace coarse or fine aggregates partially or totally with various waste products, such as fly ash [6,7], tire waste [8,9], agricultural wastes [10,11], plastics [12,13] and glass [14,15]. These studies are of great help for the practical application of recycled aggregates.

In the foundry industry the lost wax process is often used to obtain parts with high dimensional accuracy, for that many ceramic molds are used. In the casting process, the metal fluid is injected into the ceramic mold before it is allowed to cool. Finally, the ceramic mold is broken to release the casting [16,17]. Unfortunately, these broken ceramic molds become part of the solid waste generated by the foundry industry and eventually end up in landfills. According to the statistics [18], the production of lost wax casting in China in 2020 was about 5 million tons, accounting for 10% of casting production, and the demand for casting is increasing year by year. As reported [19], the lost wax casting output value of China in 2021 reached 3.3 billion dollars, an increase of 17.5% compared to 2020. The disposal of Ceramic Mold Casting Waste (CMCW) in landfills not only increases processing costs, but also has irreversible impacts on the environment, especially on the water quality of nearby water resources [20,21]. Recently, more and more attention has been paid to the waste from the industry foundry recovery. For example, Singh et al. [22] reported that the performance and strength of the concrete was improved when the fine aggregates were replaced with 15% waste foundry sand. Iqbal et al. [23] developed gene expression-based programming to predict the mechanical properties of green concrete containing waste foundry sand. The database includes

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234 compressive strengths, 163 splitting tensile strengths, and 85 elastic moduli. The model exhibits high generalization and prediction capability.

Regarding foundry waste, many researchers have investigated the performance of concrete with waste foundry sand, but few studies have been conducted on CMCW. Khatib et al. [24] replaced the fine aggregate of concrete with waste foundry sand (0%, 30%, 60%, and 100%) and found a linear relationship between water absorption by capillarity and strength. Behnood et al. [25], Siddique et al. [26], and Guney et al. [27] also studied the mechanical properties of concrete when waste foundry sand was used instead of aggregate. Hossiney et al. [28] reported on the use of waste foundry sand for brick making. Javed [29] and Tarek et al. [30] studied waste foundry sand for highway and sea barriers construction.

In this study, the water absorption and density of CMCW were characterized, the microstructure was observed, and the chemical composition was tested. The effects of different dosages of CMCW on the physical and mechanical properties of lightweight concrete were investigated (Table 1).

2. Materials and methodology

2.1. Materials preparation

Two different sizes of commercial expanded clay (EC), 2–10 mm and 10–20 mm (represented by EC2–10 and EC10–20), were used as coarse reference aggregates, obtained from Portuguese company. By comparison with the maximum particle size of commercially available expanded clay aggregates, the maximum particle size of the coarse aggregate was set at 20 mm. The main constituent of expanded clay is SiO_2 with a content of 63%, and the chemical composition is shown in

. The outer shape of expanded clay is smooth and round (Fig. 1a), and the internal microstructure, obtained after polishing in SiC abrasive paper followed by diamond suspension of 1 micrometer grain size, presents many porous structures (Fig. 1b).

The CMCW was obtained from a foundry company in northern Portugal. The chemical compositions were determined by X-ray fluorescence spectrometry (Table 2). Its main constituent is SiO_2, which accounts for 74.3% of its composition. The shape of the CMCW particles is irregular (Fig. 2a). The microstructure of the CMCW particles was studied by scanning electron microscopy (Fig. 2b). This showed that they consist of aggregates with a diameter of about 500 μm and colloids of bonded aggregates.

According to the standard EN 1097–6 [31], the density and water absorption of CMCW 0–20, EC2–10 and EC10–20 were determined, and the results are shown in Table 3.

The particle size gradation of the original CMCW was measured according to the standard EN 933–1 [32], and the results are shown in

Table 4 EC2–10, EC10–20, original CMCW and CMCW 0–20 mm size distribution

. To ensure uniformity of particle size, the obtained original CMCW that was larger than 20 mm was crushed in a crusher and then mixed with the original CMCW that was smaller than 20 mm. Then, the particle size gradation of the coarse aggregates was determined (

Table 4 EC2–10, EC10–20, original CMCW and CMCW 0–20 mm size distribution

). The aggregate gradation curve is shown in Fig. 3. These parameters play an important role in the subsequent design of the proportions of lightweight concrete.

The physical and mechanical properties of CEM I 42,5R, a type of Portland cement provided by the Portuguese company Secil, are given in Table 5. The fine aggregate used for the lightweight concrete was river sand with a particle size of 0–4 mm, with a density of 2580 kg/m^3 and a water absorption of 0.88%. Tap water from the CTAC laboratory (University of Minho) was used. MasterGlenium SKY 617 from the Portuguese company BASF [33] is a new generation superplasticizer (SP) with a density of 1041 kg/m^3, which was used to adjust the workability of the fresh lightweight concrete.

2.2. Design and preparation of specimens

Four compositions were prepared in this study. The water/cement ratio is 0.3, and the maximum particle size is 20 mm. Among these four compositions, the reference lightweight concrete (0% CMCW, represented by W0) was developed according to the method of Faury, which focuses on the gradation of different solid materials in the design of concrete proportions so that the concrete can obtain the most reasonable material proportions and better workability [35]. In the reference composition (W0), the aggregate consists of a mixture of natural sand (river sand) and lightweight aggregate (expanded clay), with two different granulometries.

Three lightweight concretes with 30%, 60%, and 80% CMCW (W30, W60 and W80) were designed. In these compositions, the river sand dosage was maintained. The expanded clay dosage (EC) was replaced in mass by Ceramic Mold Casting Waste (CMCW). The compositions of the four types of lightweight concrete are in Table 6. In addition, it should be mentioned that the amount of SP was fixed during the mixing process.

2.3. Methods

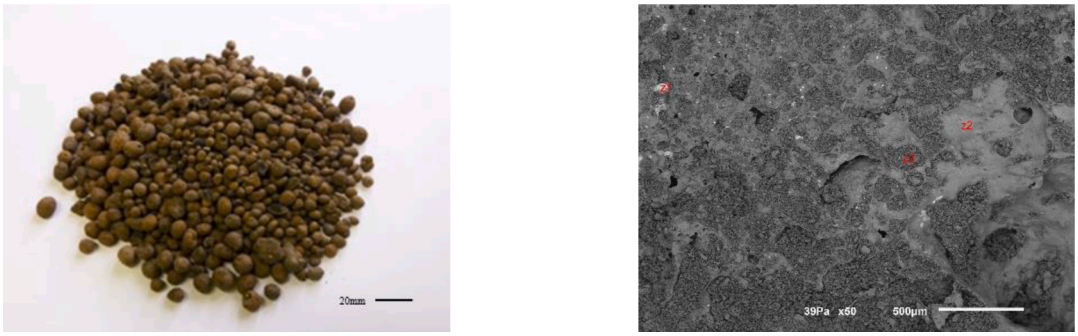
To avoid floating of the lightweight aggregates during the mixing process, the aggregates were soaked in water for 24 h before mixing. The dosage of SP is between 1% and 5% of the cement quantity, which mainly adjusts the workability of the lightweight concrete. A slump of 10–15 cm was considered, which corresponds to level S3 according to the standard EN 12,350–2 [36]. However, to ensure comparability, the value of 10 cm of the slumps of W30, W60 and W80 was maintained in the production.

The compositions were prepared in vertical shaft mixers at room temperature. Depending on the particle size of the material, from large to small, they were added and mixed in the vertical shaft mixers. After uniform mixing, water was slowly added. After a mixing time of 3 min, the slump of the fresh lightweight concrete was checked and adjusted with SP.

Lightweight concrete specimens were prepared for each composition according to requirements of standard of the physical and mechanical properties. For the physical experiments, twenty-four 100 mm cubic specimens were prepared for water absorption by capillarity and immersion tests according to standard LNEC E 393 [37] and LNEC E 394 [38]. For the determination of mechanical properties, twelve 150 mm cubic specimens were produced for 28-day compressive strength test according to standard EN 12,390–3 [39]; sixteen 100 × 100 × 425 mm prismatic specimens were considered for 28-day flexural strength test according to standard EN 12,390–5 [40]; sixteen Ø100 × 200 mm cylinders were prepared for the 28-day modulus of elasticity measurement according to standard EN 12,390–13 [41].

Table 1
Chemical composition of EC, obtained by X-Ray Fluorescence Spectrometry.

Constituent	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	K_2O	S	MnO	P_2O_5
Value (%)	64.36	23.46	1.12	8.82	0.04	1.89	0.03	0.13	0.16

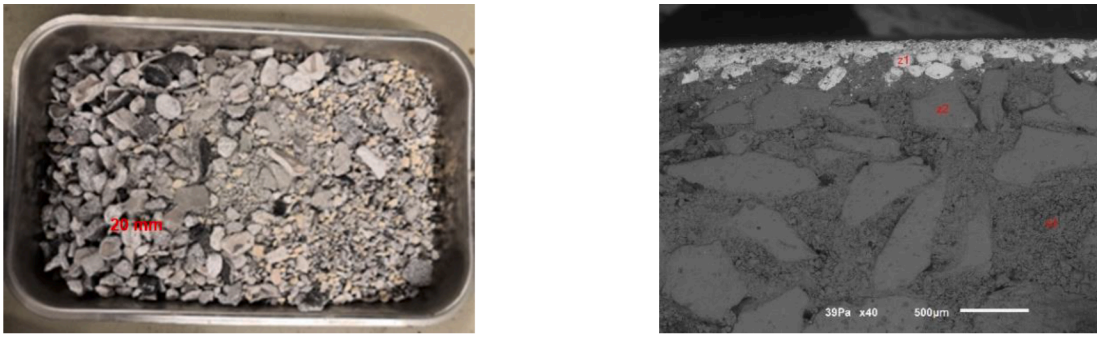


(a) EC (b) Microstructure of EC

Fig. 1. EC and microstructure scanning electron microscope.

Table 2
Chemical composition of CMCW, obtained by X-Ray Fluorescence Spectrometry.

Constituent	SiO_2	Al_2O_3	ZrO_2	TiO_2	Fe_2O_3	Na_2O	CaO	K_2O	Cr
Value (%)	74.3	20.0	4.2	0.66	0.66	0.12	0.07	0.08	0.02



(a) CMCW (b) Microstructure of CMCW

Fig. 2. CMCW and its microstructure obtained in scanning electron microscope.

Table 3
Physical properties of CMCW, EC2–10 and EC10–20.

Property	CMCW	EC2–10	EC10–20
Grain size original (mm)	0–20	2–10	10–20
Apparent particle density (kg/m^3)	2545	714	672
Particle density on an oven-dried basis (kg/m^3)	2036	542	511
Particle density on a saturated and surface-dried basis (kg/m^3)	2236	783	751
(Water Absorption,%)			
2 h	8.35	28.2	28.66
24 h	8.98	33.05	34.19
7 days	9.81	44.2	47.03

Table 4
EC2–10, EC10–20, original CMCW and CMCW 0–20 mm size distribution.

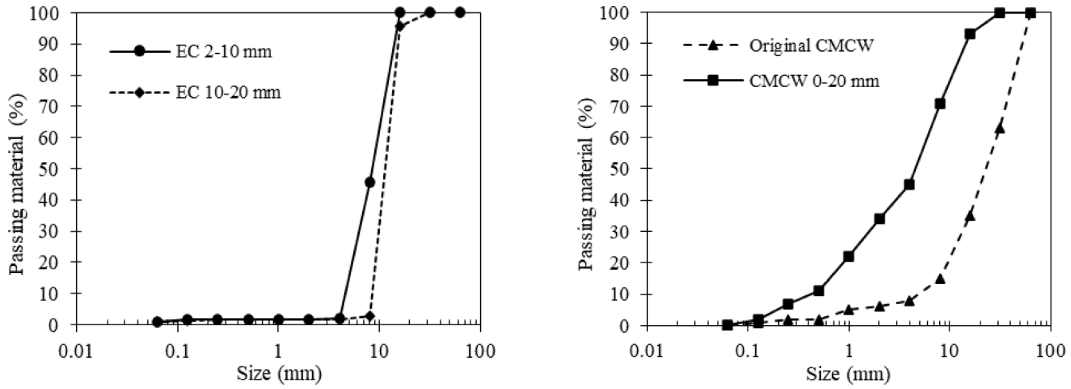
Sieve size (mm)	Accumulated retained (%)			
	EC 2–10	EC 10–20	Original CMCW	CMCW 0–20
63.0	0	0	0	0
31.5	0	0	37	0
16.0	0	4	65	0
8.0	0	97	85	7
4.0	54	98	92	29
2.0	98	98	94	55
1.00	98	98	95	66
0.50	98	98	98	78
0.25	98	98	98	89
0.13	98	99	99	94
0.063	100	100	100	100

3. Physical characterization results

3.1. Workability

In this study, slump was used to evaluate the workability of lightweight concrete. The SP content was calculated as a percentage of the cement weight. The worse the workability of the lightweight concrete, the more SP was added to keep the slump of the lightweight concrete the same. According to the standard EN 12,350–2 [36], the results of slump were determined and the amount of SP in each composition was recorded, as shown in Fig. 4.

From Fig. 4, it can be seen that as the amount of CMCW increases, the content of SP also increases. By W80, the amount of SP is 3.5 times greater than that of W30 needed to have the same effect on the slump of the lightweight concrete. Comparing the compositions of W0 and W30, the dosage of SP is the same, but the slump is 30% lower. The irregular shape of CMCW increases the friction of the slurry, and the microparticles adsorbed on the surface also difficult the flowability of the slurry to some extent. As the CMCW content increases, the phenomenon of decreasing slump becomes more evident, and has been studied by Siddique [42] and Ganesh [43].



(a) EC 2-10 mm and EC 10-20 mm (b)Original CMCW and CMCW 0-20 mm

Fig. 3. The particle gradation curve of coarse aggregates.

Table 5
Physical and mechanical properties of the CEM I 42,5R [34].

Property		Standard	Value
Sulfate content (in SO_3)		EN 196–2	≤ 4,0%
Chloride content		EN 196–21	≤ 0,10%
Set Principle		EN 196–3	≥ 60 min
Expandability		EN 196–3	≤ 10 mm
Compressive strength (MPa)		Compressive strength (MPa)	Density (kg/m^3)
2 days	7 days	28 days	3120
≥20	–	≥42,5 *e* ≤ 62,5	

Table 6
Compositions of the lightweight concretes (kg/m^3).

	Quantity of material in one m^3							
	Cement	River sand 0/4	water	w/c	EC		CMCW	SP
					2/10	10/20		
W0	350	346	101	0.3	76	398	0	3.5
W30					69	361	184	3.5
W60					52	274	490	5.1
W80					34	176	838	12.3

3.2. Density

The density of cementitious composites plays an important part in the self-load of the structures. Especially for lightweight concrete, density is an important identification criterion. According to Fig. 5, it was found that the incorporation of CMCW leads to an increase in the density of the compositions. With the addition of 80% CMCW, the density of W80 is 1998 kg/m^3. Thus, it reaches the limit value for lightweight concrete. At a CMCW content of 0 to 30%, the density of lightweight concrete increases by 2.8%; at a CMCW content of 30% to 60%, the density of lightweight concrete increases by 18.7%. This behavior can be explained by the higher density of the CMCW compared to the EC density, which justify the increase in the concrete density with the higher content replacement of the EC by CMCW.

3.3. Water absorption by capillarity

According to the standard LNEC E 393 [37], the water absorption by capillarity of four compositions cured for 28 days was tested from 10 min to 340 h The water absorption by capillarity of the four compositions was determined. It was found that the four compositions had two water absorption periods, and their cutoff line was around the 70th hour for all cases. In the study by Alexandre [44], the water absorption rate of each composition in the initial absorption period is faster than the secondary absorption. However, in general, regardless of the initial or secondary absorption period, as the CMCW content increases, the water

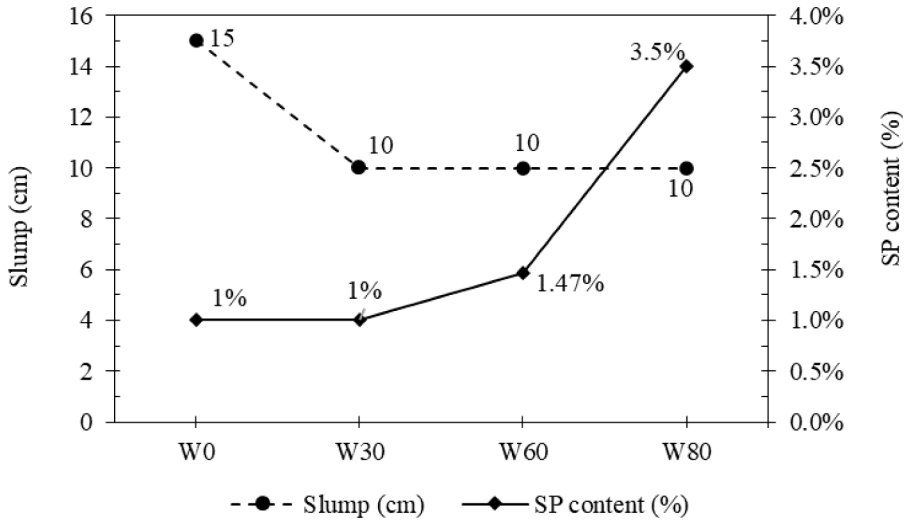


Fig. 4. Variation of slump and SP content for the different compositions.

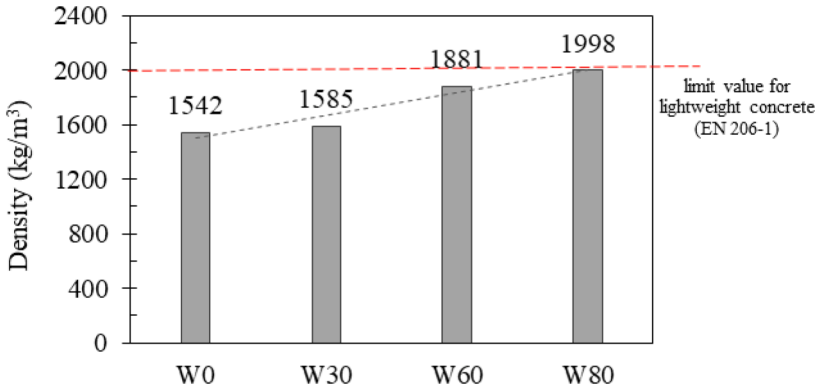


Fig. 5. The density of each composition (kg/m^3).

absorption by capillarity of the lightweight concrete decreases (see Fig. 6). This phenomenon also shows that a larger proportion of dense aggregate not only increases the density (Fig. 5) of the lightweight concrete, but also reduces the porosity within the lightweight concrete. This is due to the high degree of hydration originated by the presence of high quantity of SP. This behavior can also be explained by the lower porosity of the Ceramic Mold Casting Waste compared to the expanded clay (Table 3), which also justify the decrease of the concrete water absorption by capillarity with the higher content replacement of the EC by CMCW.

In Fig. 7, it can be seen that the capillary water absorption coefficient curve of W30 and W0 essentially overlap when the EC was replaced with 30% CMCW, indicating that the replacement of 30% CMCW has little effect on the capillary water absorption coefficient. When the CMCW replacement reaches 60%, the effect on the capillary water absorption coefficient of lightweight concrete starts to become significant. At a CMCW content of 80%, the capillary water absorption coefficient of lightweight concrete decreases by 53% compared to the reference concrete (W0), which is directly related to the higher content of EC replacement by CMCW and the lower porous microstructure of the CMCW (Fig. 2).

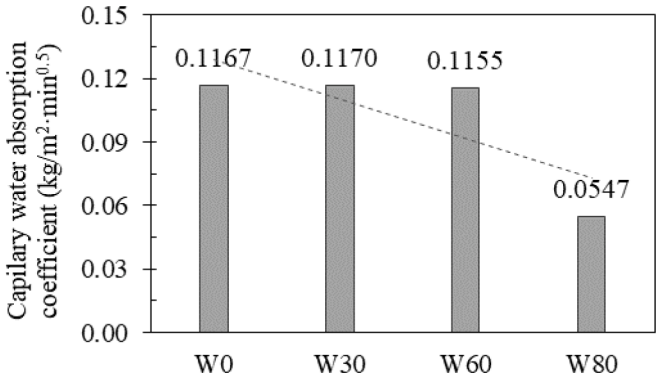


Fig. 7. Capillary water absorption coefficient of the compositions.

3.4. Water absorption by immersion

Fig. 8 shows the values of water absorption by immersion obtained for the four compositions. It was found that the water absorption by immersion decreased with the incorporation of CMCW. A CMCW content of 30% did not cause much change in water absorption by immersion of lightweight concrete. In particular, when the CMCW content reaches 80%, the water absorption by immersion is 21.5% lower than W0, which is due to the higher hydration degree. Once again, this behavior is related to the fact that the CMCW has a lower water absorption capacity than EC (Table 3), which justifies the lower water absorption capacity by immersion in concrete with a higher content of CMCW in EC replacement, as already seen for water absorption by capillarity tests (Figs. 7 and 8). This also proves that replacing EC with CMCW provides an advantage in water absorption by immersion, which means a reduction in the porosity of the lightweight concrete.

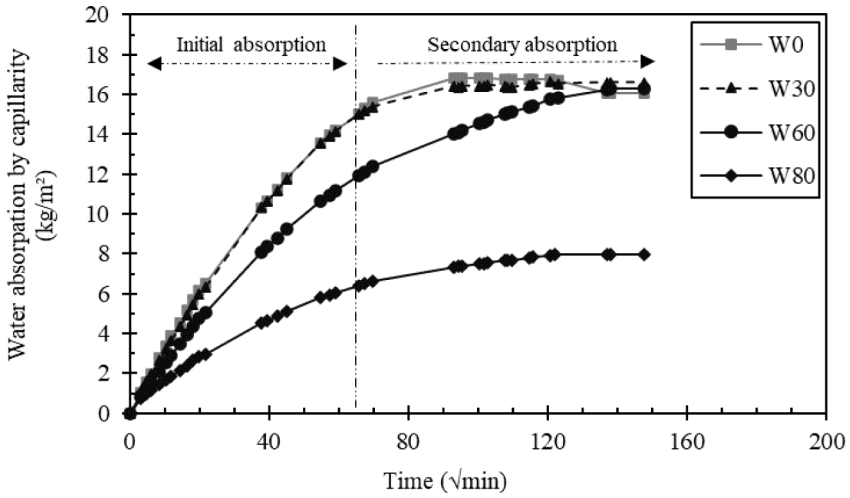


Fig. 6. Water absorption by capillarity of the compositions.

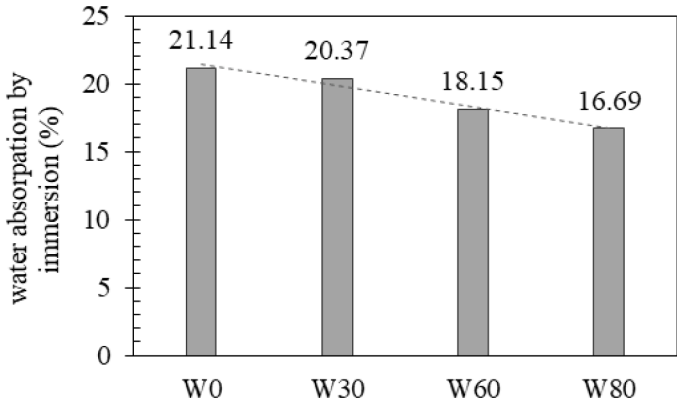


Fig. 8. Water absorption by immersion of the compositions.

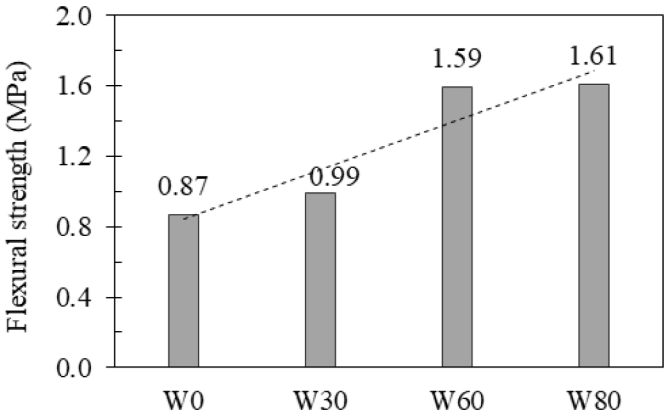


Fig. 10. Flexural strength of the compositions.

4. Mechanical characterization

4.1. Compressive strength

Compressive strength increases when EC was replaced with CMCW (see Fig. 9). The results of Fig. 9 show that the compressive strength of the lightweight concrete with 30% CMCW is slightly lower than that of the reference lightweight concrete. From Figs. 7 and 8, it can be seen that when the CMCW content is 30%, the porous mass EC still occupies most of the volume, which does not contribute to the compactness of the lightweight concrete. When the CMCW content is increased from 30% to 60%, the compressive strength of the concrete increases up to 65.9%. At 80% CMCW, the compressive strength of the lightweight concrete reached 36.3 MPa, the highest value of all compositions. Referring to the standard EN 206–1 [3], the compressive strength of lightweight concrete with 80% CMCW reached the level of LC25/30, indicating that the use of this lightweight concrete in structures is feasible.

It can be seen from Fig. 5 that the density of the reference lightweight concrete is 1542 kg/m^3, which corresponds to a compressive strength of 17.7 MPa. When 80% CMCW was used, the density of the lightweight concrete increased by 29.6%, but the compressive strength increased by 105.1%. The results shown in Fig. 9 can also be explained by the reduction of the porosity of the concrete (Figs. 6–8), due to the replacement of EC by CMCW (Table 6) and also due to the higher hydration degree.

4.2. Flexural strength

Fig. 10 shows that the flexural strength of lightweight concrete increased with the addition of CMCW. Similar to compressive strength (Fig. 9), the value of flexural strength increased up to 61% when the CMCW content was increased from 30% to 60%. The incorporation from 60% to 80% did not cause much change in the flexural strength of the compositions, but the flexural strength with the incorporation of 80% CMCW increased by 85.1% compared to the reference lightweight concrete (W0). This is due to the reduction in porosity caused by the incorporation of a higher content of CMCW (Figs. 6–8) and to the higher adhesion between the aggregates and the cement paste, due to the more angular shape and irregular surface of the CMCW (Fig. 2).

4.3. Elastic modulus

According to the standard EN 12,390–13 [41], to determine the elastic modulus of the compositions, three loading and unloading cycles were performed on the specimens in the range of 1 MPa and 1/3 of the compressive strength of the composition. Three specimens of each composition were tested and then the average value was calculated as the elastic modulus of the composition (see Fig. 11). It can be clearly seen that the modulus of elasticity of the lightweight concrete increases with the incorporation of CMCW. The lightweight concrete with the largest elastic modulus is W80 with a value of 19.7 GPa. It is 49% higher than the elastic modulus value of reference lightweight concrete (W0).

From Figs. 9 and 11, it can be seen that the same trend exists between the value of elastic modulus and compressive strength of the compositions (Fig. 9). In particular, when the CMCW content increases from 30% to 60% (W30 and W60), the elastic modulus and compressive strength increase the most, which, once again, is associated with the lower porosity of concrete compositions with CMCW incorporation. This phenomenon indicates a positive correlation between the strength and the modulus of elasticity of lightweight concrete, as reported by Beushausen [45] and Nath [46].

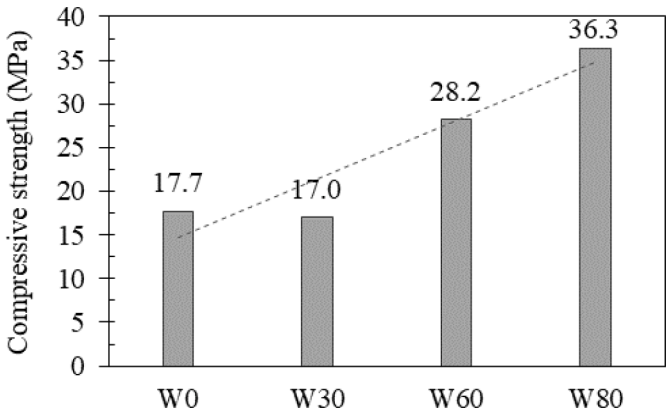


Fig. 9. Compressive strength of the compositions.

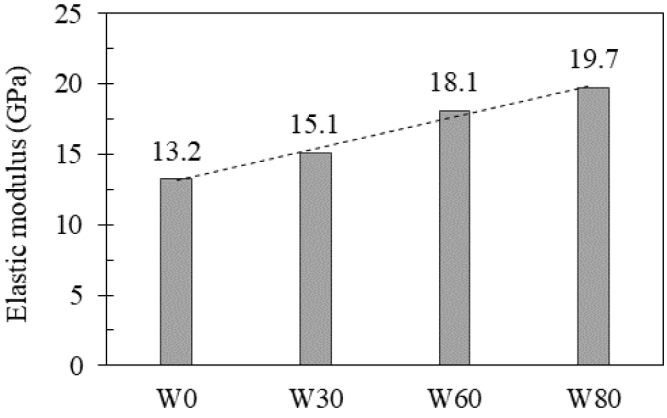


Fig. 11. Elastic modulus of the compositions.

5. Conclusions

This study evaluates the effect of different dosages of CMCW on the physical and mechanical properties of lightweight concrete. It is important note that the reutilization of CMCW as aggregate in concrete is still a subject with great research needs, since little is known about possible applications of these materials in the construction industry. Thus, in the context of environmental protection and sustainable development, is important explore the possibility of the use of CMCW as a substitute for lightweight aggregate in lightweight concrete.

The replacement of EC by CMCW in concrete lead to different behaviors in the main properties of concrete. Regarding to the:

- Slump tests, it was observed a decrease of the resulting value with the replacement of a higher content of EC by CMCW, due to the irregular shape of CMCW increases the slurry friction, and the microparticles adsorbed on the surface also difficult the slurry flowability;
- Density, it was verified an increase with the presence of a higher CMCW content, due to the higher density of the material;
- Water absorption, it was detected a decrease with the higher content of EC replacement by CMCW, which can be explained by the lower water absorption capacity of the CMCW;
- Mechanical behavior (compressive strength, flexural strength and elastic modulus), it was observed an increase in the different properties, due to the concrete reduction in the porosity and higher hydration degree related with the replacement of EC by CMCW.

When the CMCW content was increased from 30% to 60%, both the physical and mechanical properties of lightweight concrete improved significantly compared to CMCW from 0% to 30% and from 60% to 80%. This shows that in the case of reference lightweight concrete, a large amount of CMCW promotes the improvement of physical and mechanical properties of lightweight concrete. Porosity was shown to be negatively correlated with mechanical properties. The results also show that a lightweight concrete with a CMCW content of 80%, a compressive strength of 36 MPa and an elastic modulus of 19.7 GPa, can be used for structures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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