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DOI

[10.2166/wrd.2021.031](https://doi.org/10.2166/wrd.2021.031)

Publication date

2021

Document Version

Final published version

Published in

Water Reuse

Citation (APA)

Gulamussen, N. J., Arsénio, A. M., Matsinhe, N. P., Manjate, R. S., & Rietveld, L. C. (2021). Use of reclaimed water for unreinforced concrete block production for the self-construction of houses. *Water Reuse*, 11(4), 690-704. <https://doi.org/10.2166/wrd.2021.031>

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Use of reclaimed water for unreinforced concrete block production for the self-construction of houses

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ABSTRACT

Experiments were conducted to evaluate the possibilities of using treated wastewater for the production of unreinforced concrete blocks. Compressive strength, water absorption and morphology tests of concrete blocks, produced from different makeups of mixing water, drinking water, drinking water spiked with ammonium and phosphate, and the effluent of the city's wastewater treatment plant, were evaluated. Results showed that the compressive strength of blocks manufactured using treated wastewater was as high as of the blocks produced using drinking water. Ammonium, phosphate and chlorine were found not to have a negative effect on the strength of the blocks. Water absorption tests confirmed the results of the compressive strength, as lower humidity was found in cases of higher strength. In the process of cement hydration, crystals of calcium silicate and calcium hydroxide were observed by morphology tests. From the variability in the results, it could be concluded that the quality of the mixing water was not the only factor that influenced the strength of the unreinforced concrete blocks. The observed differences in strength could, for example, also be attributed to the manufacturing process.

Key words: concrete, construction, industry, strength, wastewater, water reclamation

HIGHLIGHTS

- Water quality parameters, such as ammonium, phosphate and chlorine, have little influence on the quality of unreinforced concrete.
- The manufacturing process of unreinforced concrete is the most important factor that affects its quality.
- Treated wastewater can be used for concrete production.

INTRODUCTION

The use of reclaimed water, whereby treated wastewater is used for non-potable applications, is encouraged in situations where the demand for water is higher than the availability (Otoo *et al.* 2015). The agricultural sector, as the main water user, accounting for 70% of global consumption, has a great potential, also in the context of sub-Saharan Africa (Janeiro *et al.* 2020). However, industries are the second major users of water around the world, accounting for nearly 19% of the total abstracted water flows (Flörke *et al.* 2013), with the construction industry, with nearly 9% of that volume, being an important sector. In the construction industry, water is largely used for concrete production and curing, and, to a minor extent, for washing concrete mixers and concrete mixing trucks (Asadollahfardi *et al.* 2016). A volume of 0.7–2.2 m³ of water is needed to produce 1 m³ of concrete (Mack-Vergara & John 2017), with drinking water being the common source (Neville 2011).

In the case of severe water shortages, as in Maputo, Mozambique, alternative, low-cost, water sources for concrete manufacturing industries should thus be identified (Ofori 2007). These industries are often located relatively close to wastewater sources, making them an attractive source because of the reduced transport costs. Moreover, concrete production might allow for the use of a lower quality than drinking water. Finally, in a city served by poor sanitation services for most of its population (Bäuerl *et al.* 2015; Rietveld *et al.* 2016; Arsénio *et al.* 2018), water reclamation can be envisaged as a driving force to improve the city's sanitation services (Gulamussen *et al.* 2019).

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Previous studies around the world have shown the possibility of using non-potable water for concrete production, particularly treated wastewater (Kucche *et al.* 2015). However, when using water for producing and curing concrete, impurities in mixing water such as ammonium, sulfate, chloride, and phosphate (Kerkhoff 2007) can affect the setting time, strength and the durability of the concrete (Asadollahfardi *et al.* 2016). In addition, concerns about the safety of the workers can exist, resulting from exposure to pathogenic micro-organisms, when using reclaimed water (Silva & Naik 2010). Various authors have evaluated the use of non-potable water in concrete manufacturing, with different, and sometimes contradicting, conclusions. For example, studies by Nikhil (2014) and Obi Lawrence (2016), using different water sources to produce concrete samples, have indicated that the 28-day compressive strength of concrete samples produced with drinking water was significantly higher than that produced using wastewater, runoff water and salty water. However, Al-Ghusain & Terro (2003), Silva & Naik (2010), Asadollahfardi *et al.* (2016) and Shrilatha *et al.* (2017) did not find differences in compressive strength between concrete produced with drinking and treated wastewater. Tay & Yip (1987) found that the use of treated industrial wastewater, by means of coagulation-flocculation, sedimentation, filtration, aeration and chlorination, even improved concrete properties, in particular the compressive strength of the concrete. The presented studies, so far, did not include unreinforced concrete blocks for the self-construction of houses, which is an important industry in developing countries (Ofori 2007).

Since ammonium and phosphate are abundantly present in wastewater treatment plant (WWTP) effluents and are known compounds that could potentially affect concrete production, and the probable need for water disinfection, in this work, the influence of ammonium, phosphate and chlorine on the quality of locally produced (unreinforced) concrete blocks for house construction was investigated in the context of the sub-Saharan country Mozambique, with the support of a local construction company.

The quality of the blocks was assessed by their strength and water absorption, and, for the confirmation of the products formed during the hydration of cement that can confer the durability of the blocks, the type of crystals that were formed was analyzed by scanning electron microscopy (SEM) images.

METHODS

Experimental setup

The experimental studies covered the sampling of the effluent of the Maputo WWTP for the determination of the physical-chemical parameters of potential makeup water for concrete production, the manufacturing of concrete blocks using different makeups of mixing water (WWTP effluent treated with chlorine, drinking water and drinking water with various concentrations of ammonium, phosphate and chlorine) and the evaluation of properties such as strength and durability of produced blocks by measurements of compressive strength, water absorption and imaging for morphology determination.

Water quality tests were performed at the laboratory of Sanitary Engineering of the Eduardo Mondlane University (UEM). Tested blocks were produced at a local construction company, BRICOM. Compressive strength and water absorption percentages were measured at the Laboratory of Engineering of Mozambique, and morphology tests were executed at the Chemistry Department of UEM.

The results from the compressive strength tests were then analyzed statistically by t-tests for comparing two means with the same variance for the results of blocks produced with drinking water and WWTP effluent and by the observation of bar graph plots and SEM images.

Wastewater characterization

Samples of WWTP effluent were collected at the Maputo WWTP on a weekly basis during a period of 2 months. The pH was measured in the field. Methods used for laboratory tests are shown in Table 1.

Conditions for concrete block testing

Various batches were prepared using the conditions given in Table 2. The used concentrations of phosphate and ammonium were selected based on the concentrations that could be found in the WWTP effluent. The chlorine concentration (as $\text{Ca}(\text{ClO})_2$) used to disinfect the effluent from the WWTP was based on EPA's onsite manual (EPA 2002), being 40 mg/L. In addition, to further determine the threshold levels (i.e. the minimum concentration of the substances that could be present in water without effect) by plotting the calibration curves for each parameter, the concentrations of the above-mentioned parameters were 10–40 mg/L for chlorine, 20–120 mg/L for ammonium and 30–120 mg/L for phosphate, respectively.

Table 1 | Methods for physical–chemical analyses

Parameter	Method	Reference
Sugar	Lane–Eynon	Silva <i>et al.</i> (2003)
Alcalis (Na ₂ O)	Flame photometer	APHA/AWWA/WEF (1999)
Chloride	Test kits mercury thiocyanate 4500-Cl ⁻ E APHA	APHA/AWWA/WEF (1999)
COD	Reflux colorimetry 5220-COD D	APHA/AWWA/WEF (1999)
Phosphates as P ₂ O ₅	Test kits ascorbic acid 4500-P E APHA	APHA/AWWA/WEF (1999)
Nitrates	Test kits 3,5-dimetil phenol 4500-NO ₃ -E APHA	APHA/AWWA/WEF (1999)
pH	pH-meter 3010 WTW	APHA/AWWA/WEF (1999)
Total solids	Gravimetric	APHA/AWWA/WEF (1999)
Ammonia–N	Test kits HACH TNT 835	APHA/AWWA/WEF (1999)
Sulfates	Turbidity meter 4500-SO ₄ ²⁻ E APHA	APHA/AWWA/WEF (1999)
Color	Visual	BS EN 1008 (2002)
Foam vanishing time	Visual	BS EN 1008 (2002)
Presence of oil and grease	Visual	BS EN 1008 (2002)
Odor	Sensorial	BS EN 1008 (2002)

Table 2 | Conditions for concrete blocks testing

Batch	Conditions
1	Drinking water (DW)
2	Drinking water + ammonium (80 mg/L) (DW + NH ₄)
3	Drinking water + phosphate (60 mg/L) (DW + PO ₄)
4	Drinking water + ammonium (80 mg/L) and phosphate (60 mg/L) (DW + NH ₄ + PO ₄)
5	Drinking water + ammonium (80 mg/L) and phosphate (60 mg/L) + chlorine (40 mg/L) (DW + NH ₄ + PO ₄ + Cl ₂)
6	WWTP effluent (WW)
7	WWTP effluent + chlorine (40 mg/L) (WW + Cl ₂)
8	Drinking water + chlorine (40 mg/L) (DW + Cl ₂)

Block manufacturing

In Mozambique, M15 blocks (400 mm length, 200 mm height and 150 mm width, see [Figure 1](#)) are commonly used for the self-construction of houses. For the laboratory tests, similar blocks were manufactured, with a proportion of cement:gravel:coarse sand:fine sand of 1:1.14:0.75:0.75, respectively, as normally used for the production of M15 blocks. The mixing was

**Figure 1** | Photograph of an M15 block.

done using the mixer and vibrational press presented in Figure 2(a). The blocks were then wrapped in plastic to keep the moisture for curing for 2, 7, 14 and 28 days (Figure 2(b)).

Most of the parameters, apart from water quality, that also can affect the quality of the blocks, such as accurate weighing of aggregates and water added, dryness of the aggregate, and weather conditions (temperature and precipitation) (Orozco *et al.* 2018), were not controlled on purpose, as we wanted to simulate real conditions of normal blocks' production.

Block testing

The blocks were tested on their compressive strength, water absorption and morphology, according to the experimental design presented in Table 3.

Compressive tests were performed using the Mozambican national standard NM 355/2011 (INNOQ 2011b), which consists of placing the block between compressive plates parallel to the surface. The specifications of the apparatus and the procedure are in accordance with the standard method ASTM C140-11a (ASTM C140-11a 2012). The blocks were then compressed at a rate of 15 kN/min. The maximum load was recorded along with stress-strain data. All tests were performed using a press King test, model Pat2001.

Water absorption of the blocks can give an indication for the durability and permeability of the concrete, with a higher absorption implying lower durability (Zhang & Zong 2014). It measures the volume of water-accessible pores in the concrete (Raza *et al.* 2020). In the process of block production, during cement hydration, calcium silicate hydrate (C-S-H) gel is formed (Neville 2011). A more compact C-S-H gel increases strength and lowers permeability and water absorption by virtue of the elimination of continuous capillaries (McCarter *et al.* 1992). Water absorption is thus also a good surrogate indicator for concrete durability (Misra *et al.* 2007). Water absorption tests were performed using the Mozambican national standard NM 355/2011 (INNOQ 2011b), which consists of drying a specimen to a constant weight, weighing it, immersing it in water for 24 h and weighing it again. The weighing was performed with a Karen balance with a maximum capacity of 60 kg and a precision of 0.014 kg, as indicated by the manufacturer. The results were presented as a percentage of water absorption by the blocks.



Figure 2 | (a) The equipment used to mix and mold the M15 concrete blocks. (b) The blocks wrapped in plastic to keep the moisture.

Table 3 | Experimental design of the experiments in Mozambique

	Drinking water			Spiked drinking water (ammonium and/or phosphate)			Effluent of WWTP			Effluent WWTP with chlorine		
After 3 days	C			C			C			C		
After 7 days	C			C			C			C		
After 14 days	C			C			C			C		
After 28 days	W	C	M	W	C	M	W	C	M	W	C	M

W, water absorption; C, compression resistance; M, morphology.

Finally, pore structure and morphology also affect concrete durability (McCarter *et al.* 1992). Three types of morphology can result from mixing cement with water and the amounts and characteristics of the principal solid phases in the hydrated cement paste, which were measured with SEM (Jeol, Model JSM-IT100), are as follows (Mehta & Monteiro 2006):

- C-S-H or tobermorite,
- Calcium hydroxide or portlandite and
- Calcium sulfoaluminates hydrates or ettringite.

Methods of data analysis

The results were presented considering a confidence limit of 95% taking the following into account:

1. Three replicates for the laboratory tests for compressive strength.
2. Three samples at each of the two discharge points of the WWTP.
3. Twelve replicates for compressive strength testing during field experiments where blocks were produced with drinking water and effluent of WWTP.
4. Six replicates for the compressive strength testing of field experiments with blocks produced with drinking water spiked with ammonium, phosphate and WWTP effluent with chlorine.
5. Three replicates for water absorption during field experiments for each mixture.

For comparison of the results of the compressive tests of the blocks, produced with drinking water and WWTP effluent at 28-day curing time, first the variances of the two groups of results were compared, using the Fisher test where the calculated F_{cal} , according to Equation (1), was compared with the critical tabulated value of F_{crit} for $n_1 - 1$ and $n_2 - 1$ degrees of freedom and the 95% level of significance to choose the appropriate t-test. Afterward, a t-test for comparison of two means with equal variance was used according to Equation (2) to calculate the t_{cal} , which is compared with the tabulated t_{crit} for $n_1 + n_2 - 2$ degrees of freedom, the two-tailed test and 95% of the level of significance (Miller & Miller 2010):

$$F_{cal} = \frac{s_2^2}{s_1^2} \quad (1)$$

$$t_{cal} = \frac{\bar{x}_1 - \bar{x}_2}{s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (2)$$

where \bar{x}_1 and \bar{x}_2 are the mean results of compressive strength for drinking and WWTP effluent, s_1 and s_2 are standard deviations of compressive strength for drinking and WWTP effluent, and n_1 and n_2 are the number of replicates of compressive strength for drinking and treated wastewater. s is calculated from the following:

$$s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 + n_2 - 2)} \quad (3)$$

The tested hypothesis was if the calculated value of t is greater than critical t with $n_1 + n_2 - 2$ degrees of freedom, 95% of significance level and $2T$, there is a significant difference between the means of the two groups of results.

The coefficient of variation (CV) of compressive strength was calculated using the following equation to estimate the variability of the results:

$$CV (\%) = \frac{s}{\bar{X}} * 100$$

where s is the standard deviation and \bar{X} is the mean result.

RESULTS AND DISCUSSION

Quality of wastewater treatment effluent of Maputo

Table 4 depicts the quality parameters of WWTP effluent of Maputo, Mozambique. This effluent, according to the standards (BS EN 1008 2002; ASTM C1602/C1602M 2012), was found to comply with concrete production standards for most of the

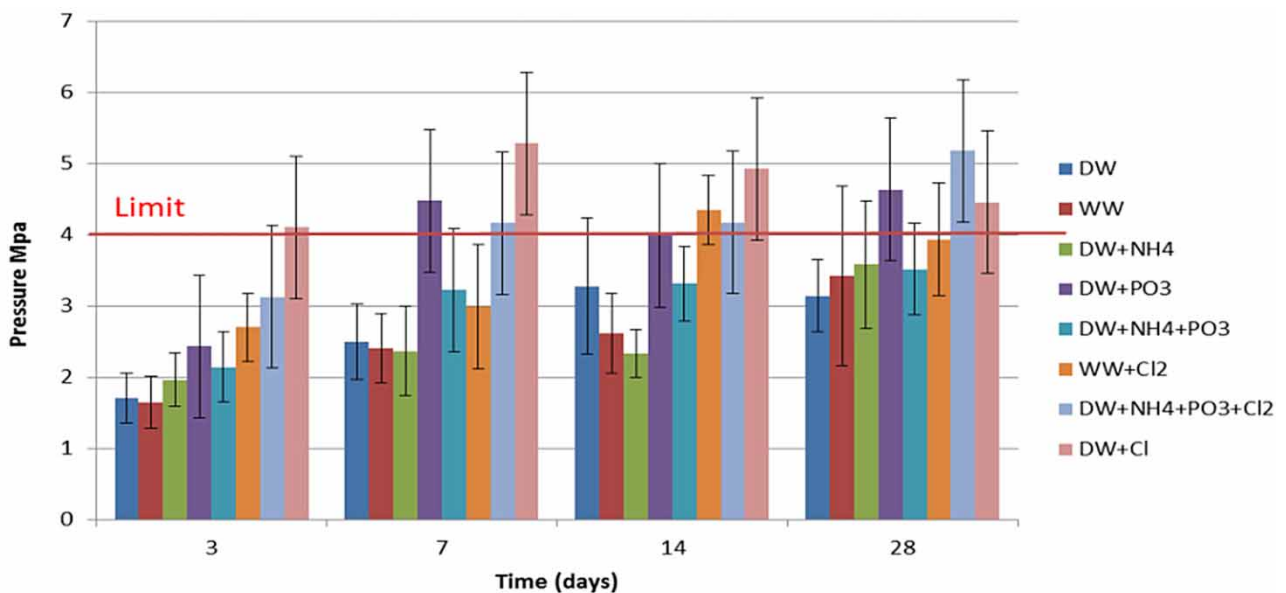
Table 4 | Quality of WWTP effluent and limits for concrete production according to norm BS EN 1008 (2002) and ASTM C1602/C1602M (2012)

Parameter	Measured value	BS EN 1008 (2002)	ASTM C1602/C1602M (2012)
Sugar (mg/L)	<50	100	No limit
Alcalis (Na ₂ O) (mg/L)	253.62 ± 20.93	1,500	600
Chloride (mg/L)	281.03 ± 83.40	1,000	500
COD (mg/L)	217.04 ± 92.66	500	No limit
Phosphates as P ₂ O ₅ (mg/L)	62.74 ± 6.42	100	No limit
Nitrates (mg/L)	0.79 ± 0.44	500	No limit
pH	7.08 ± 0.08	≥4	6.5 – 8.5
Total solids (mg/L)	873.90 ± 29.40	2,000	50,000
Ammonia-N (mg/L)	58.58 ± 3.92	No limit	No limit
Sulfates (mg/L)	21.48 ± 15.47	2,000	3,000
Color	Gray	Colorless or pale yellow	No limit
Foam vanishing time	After 6 min	After 2 min	No limit
Presence of oil and grease	Oil and grease visible	Not apparent	No limit
Odor	Characteristic of oil	Odorless or similar to potable water	No limit

important quality parameters, except for oil and grease and foam vanishing time. Compared to secondary treated wastewater used by [Arooj et al. \(2020\)](#) for concrete production and obtained from a WWTP, Maputo's WWTP effluent showed higher concentrations of sulfate and total solids and lower concentrations of chloride and COD, but all values were within the maximum permissible limits (see [Table 4](#)). [Swami et al. \(2015\)](#) found higher concentrations of total solids, pH, sulfates and alkalinity, and a lower concentration of chloride compared to this study, using extended aeration for the treatment of domestic wastewater, and alkalinity was above maximum permissible limits (see [Table 4](#)).

Compressive strength of M15 blocks

The compressive strength tests of the blocks, using different makeup waters, are depicted in [Figure 3](#). Overall, the strength of the concrete increased as a function of curing time, which is in accordance with the literature ([Uddin et al., 2012](#); [Piplewar](#)

**Figure 3** | Compressive strength of blocks produced with drinking water, spiked drinking water and treated wastewater, with the indication of the strength limit (4 MPa) according to norm NM 354 2011 (INNOQ 2011a).

et al. 2014), except for the conditions where chlorine was used in the absence of phosphate and ammonium. There, a higher compressive strength was observed at 7th and 14th days of curing time and decreased at 28 days. Chlorine is added as $\text{Ca}(\text{ClO})_2$ which reacts with water to form HClO and CaCl_2 . The chloride ions can be bound chemically in compounds like Friedel's salt (calcium chloroaluminate hydrate) or adsorbed physically at the surface of cement hydration product (Pargar *et al.* 2017). CaCl_2 has been known to accelerate both the setting and hardening of Portland cement concrete, the effect of strength decreases with time and the final strength can be reduced due to the formation of chloroaluminate hydrates, which is responsible for the concrete softening. However, it can also partially inhibit the cracking caused by drying and sorption-induced microcracking in the concrete system (Kishar *et al.* 2013).

Blocks produced with drinking water with phosphate and drinking water with chlorine showed a large increase in strength from the 3rd day to the 7th day. Blocks produced with drinking water with chlorine had already the required strength for use in self-construction on the 3rd day of curing. The rapid increase in strength can be explained by the capacity of chloride and phosphate ions which have the quick setting capability to be adsorbed in C-S-H, forming hydroxyapatite and calcium chloroaluminate, respectively, which are highly insoluble (Naus *et al.* 2008).

Comparing blocks produced with drinking water with the other makeup waters at 28 days of curing time, it was found that the addition of ammonium, phosphate, to the same concentrations found in WWTP effluent, and chlorine at a concentration of 40 mg/L, even increased the strength of the blocks. The strength of the blocks produced with drinking water with additional phosphate and ammonium was at the same level as that of the blocks produced with WWTP effluent. The highest strength was obtained when drinking water was used with a combination of ammonium, phosphate and chlorine.

According to the Mozambican norm NM354:2011, M15 blocks must have a resistance of above 4 MPa at 28 days of curing time in order to be classified as 'Category B with a structural function' for use in masonry elements above the ground level for buildings of at most two floors. Only the blocks produced with drinking water with phosphate, drinking water with chlorine, WWTP effluent with chlorine and drinking water with a mixture of ammonium, phosphate and chlorine can, on average, be considered as category B. However, when comparing blocks produced with drinking water with blocks produced with WWTP effluent, the t-test (using Equation (2), was 0.11 and the critical t was 2.09) did not show a significant difference. These results are in accordance with the results of Asadollahfardi *et al.* (2016), Ghrair & Al-Machaqbeh (2016), Manjunatha & Dhanraj (2017) and Arooj *et al.* (2020), who found that treated wastewater using various treatment methods is suitable for concrete production.

Although the parameter oil and grease and foam vanishing time did not comply with concrete production standards, no adverse effects were detected during the experiment.

High variations in compressive strength (see the error bars in Figure 3 and the CV of more than 50% of the results is higher than 20%, see Table 5) were observed, which indicates that another important factor when manufacturing concrete blocks was probably the manufacturing process rather than the quality of the used water as found by Orozco *et al.* (2018) in their study.

After increasing the concentrations of ammonium, phosphate and chlorine in the makeup water, see Figures 4–6, the curing time of the blocks showed different trends. The blocks produced with drinking water and ammonium did not reach the required compressive strength, while the blocks produced with drinking water with phosphate and chlorine achieved the required compressive strength at 7th and 14th days, respectively. This is in accordance with the results of Kucche *et al.* (2015) who found that impurities (organic and inorganic compounds) in water react differently affecting the setting time and the compressive strength, also depending on their concentration. The lower strength of blocks produced with drinking

Table 5 | Coefficient of variation of compressive test results

Curing time	CV%							
	DW	WW	DW + NH ₄	DW + PO ₃	DW + NH ₄ + PO ₃	WW + Cl ₂	DW + NH ₄ + PO ₃ + Cl ₂	DW + Cl
3	21	22	19	15	23	18	28	5
7	21	20	27	15	27	29	23	20
14	29	21	14	28	16	11	25	6
28	16	37	25	25	18	20	13	22

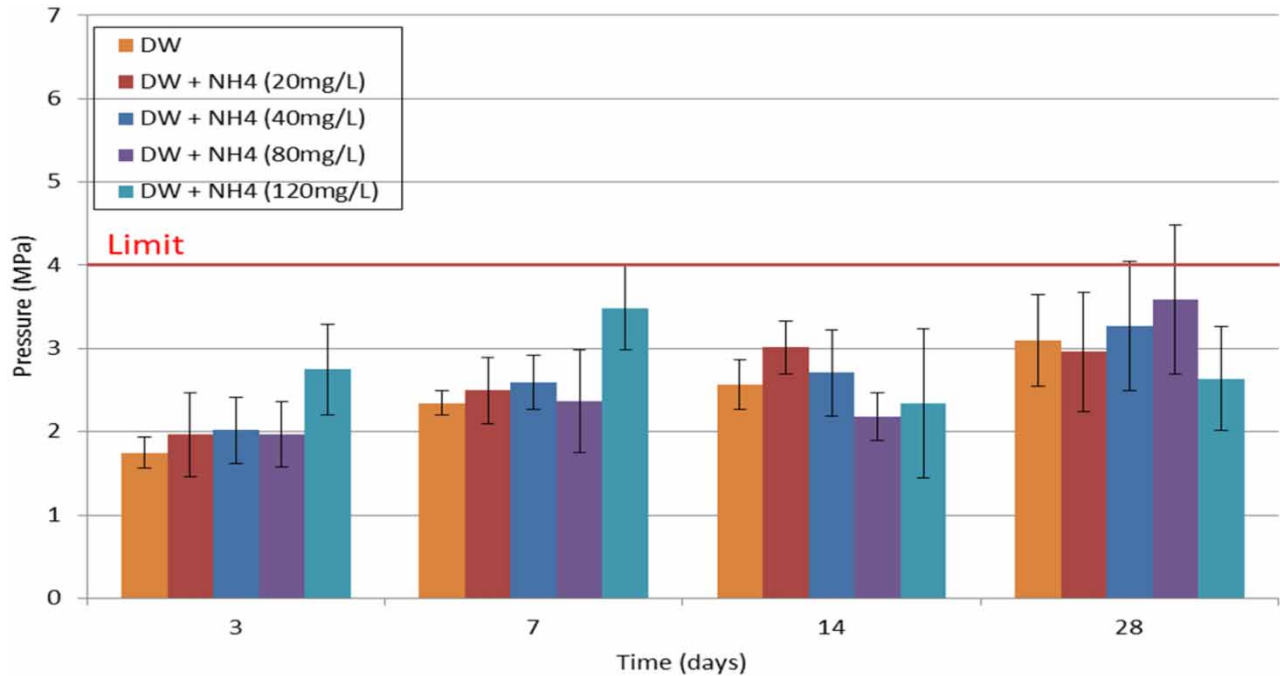


Figure 4 | Compressive strength of blocks produced with increasing concentration of ammonium, with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

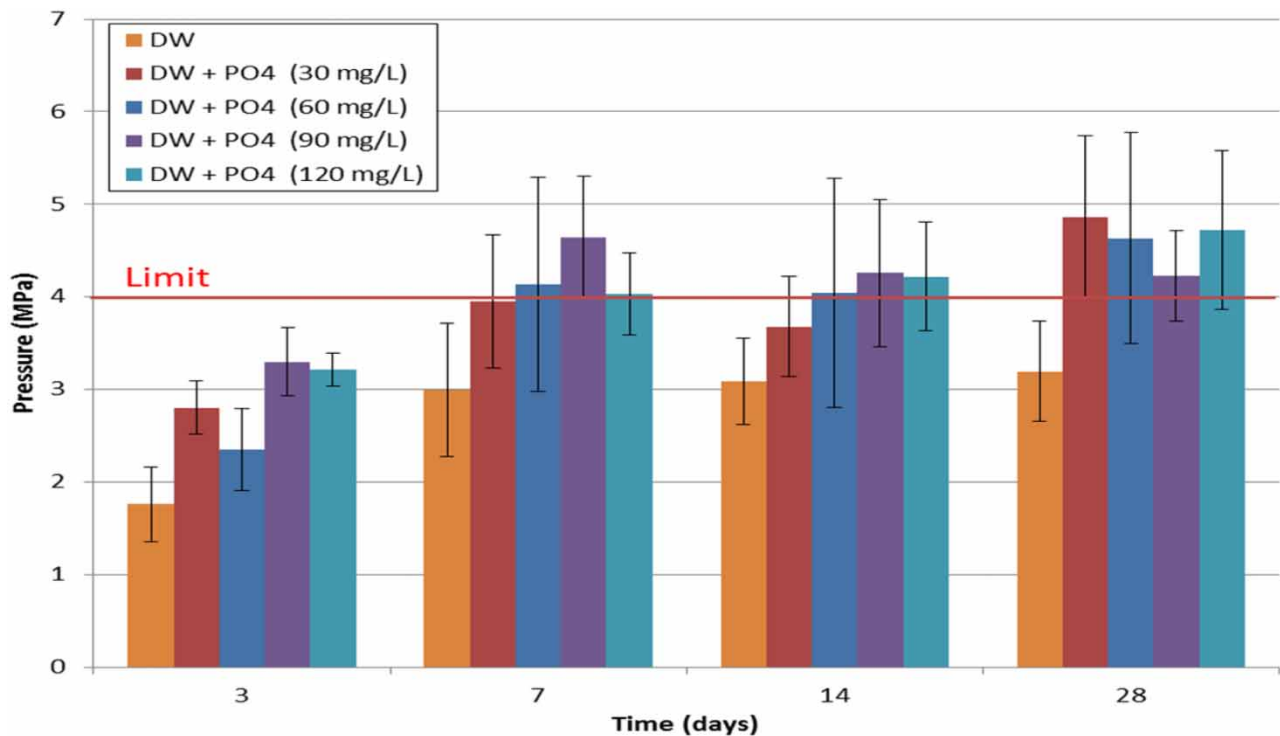


Figure 5 | Compressive strength of blocks produced with increasing concentrations of phosphate with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

water containing ammonium ($pka = 9.24$) (Vogel & Mendham 2000) can be explained by the fact that at the considered concentrations, the water is acidic with pH varying from 5.7 to 6.0. Since, during the process of concrete hardening, silicates and lime ($Ca(OH)_2$) crystals are formed, the water of a pH lower than 6.5 can attack concrete by dissolving and removing part of

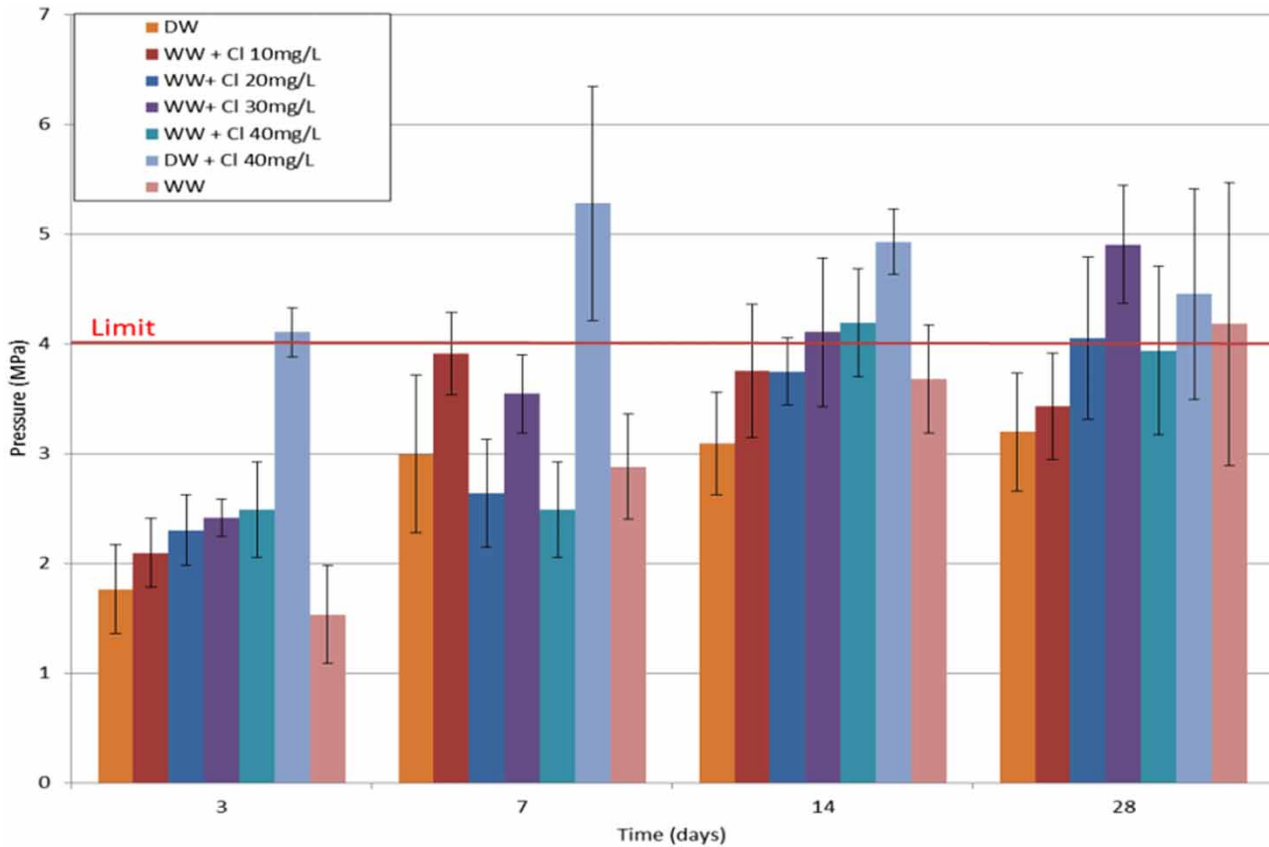


Figure 6 | Compressive strength of chlorine at different concentrations with the indication of the strength limit (4 MPa) according to norm 354 2011 (INNOQ 2011a).

the hydrated cement paste and leaving a soft and weak mass. Because the acidity increases with increasing ammonium concentration, the decline of the strength was observed from concentrations of 80–120 mg/L

The compressive strength values at 28 days indicate that the highest strength of the blocks was obtained at concentrations of 80, 30 and 30 mg/L for ammonium, phosphate and chlorine, respectively.

Water absorption tests of M15 blocks

Water absorption is a durability parameter of concrete. High water absorption causes the corrosion of reinforcement and allows harmful chemicals to penetrate the concrete and possibly react with the ingredients of the cement, thus changing the properties of the concrete (Raza *et al.* 2020).

According to the Mozambican norm NM354:2011, unreinforced blocks can be considered as category B when the percentage of water absorption is less than 10%, which was confirmed for all samples, as can be seen in Figures 7 and 8. The results confirm that the conditions that gave the highest durability (and thus the lowest water absorption) were drinking water with phosphate and drinking water with a mixture of ammonium, phosphate and chlorine. Considering the inverse relation between strength and humidity (Mehta & Monteiro 2006), it was found that the concrete blocks made of drinking water with ammonium and phosphate (with lowest humidity at concentrations of 80 and 60 mg/L, respectively) were the most durable. Water containing ammonium is acidic which can attack concrete but the attack depends on the ability of hydrogen ions to be diffused through the cement gel (C-S-H), after which $\text{Ca}(\text{OH})_2$ have been leached out (Lea 1965; Neville 1987). Additionally, ammonium chloride salts present in the mixing water interacts with $\text{Ca}(\text{OH})_2$, which is included in the pores and forms CaCl_2 and volatile NH_3 . The quick removal of NH_3 will adversely affect the concrete (Yilmaz *et al.* 2002). $\text{Ca}(\text{OH})_2$ appears in relatively large crystals, and they will leave larger voids after being leached, resulting in a greater impact on the compressive strength and durability. The diffusivity of ammonia reduces along the process (Tyra *et al.* 2001) and counteracts the voids, created by the leaching of lime, creating the opportunity to rearrange the microstructure

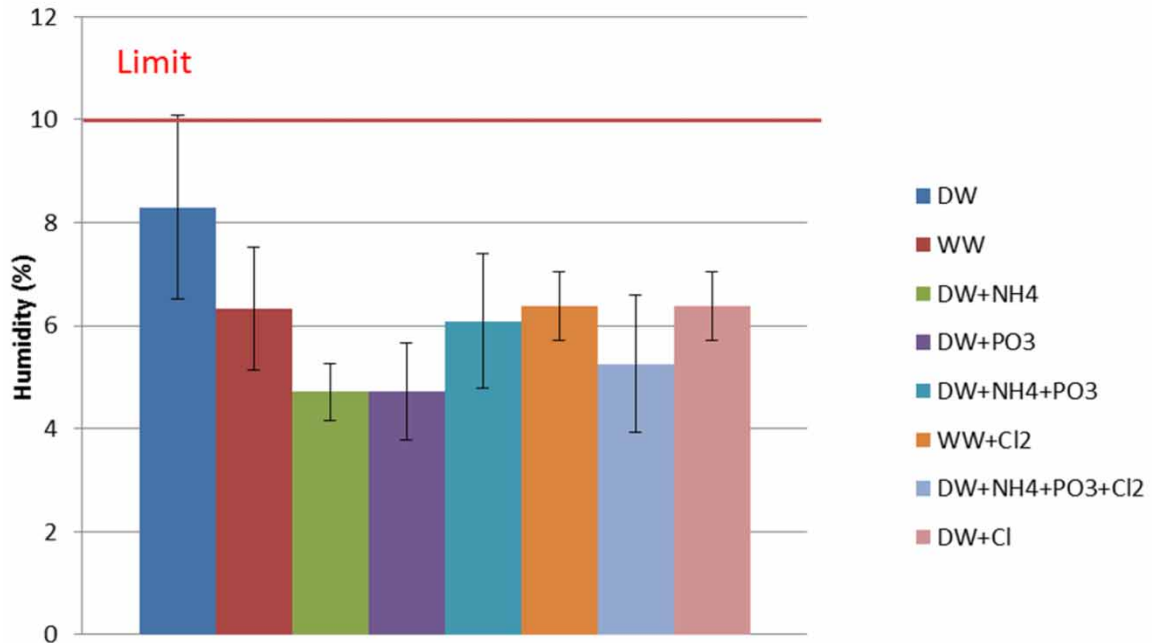


Figure 7 | Water absorption of blocks produced with drinking water, spiked drinking water and WWTP effluent, with the indication of the limit according to norm NM 354 2011 (INNOQ 2011a).

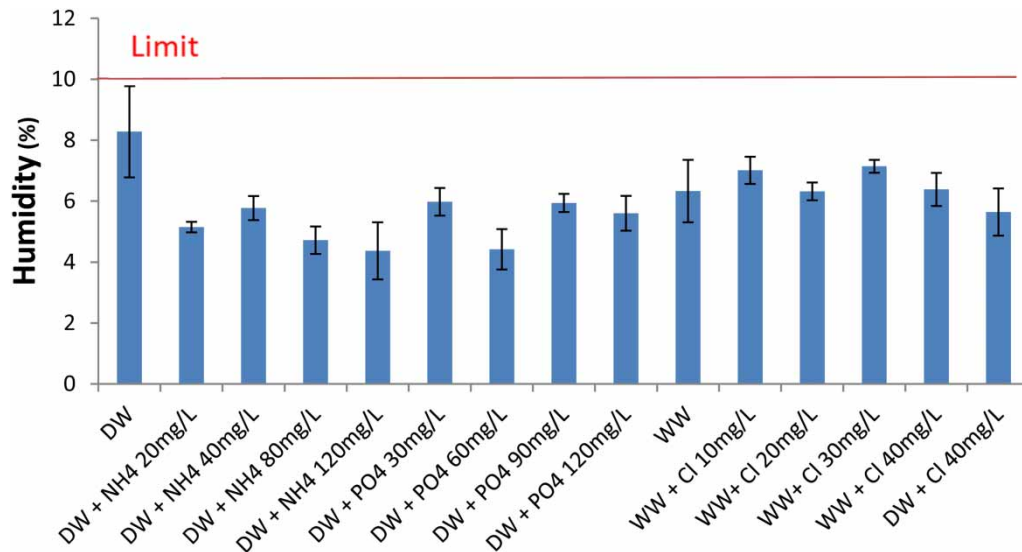


Figure 8 | Water absorption of blocks made with increasing concentration of ammonium, phosphate and chlorine, with the indication of the limit according to norm NM 354 2011 (INNOQ 2011a).

of the hardened paste, reduce the pores in the structure and, therefore, reduce the possibility of water absorption. The low humidity of the produced blocks with drinking water and phosphate probably results from the formation of a dense coating of hydroxyapatite, as a result of the reaction of C-S-H and phosphate, which reduces the water penetration.

With increasing concentrations of the targeted compounds, different trends in water absorption were observed (Figure 8), while for ammonium the humidity decreased with increasing concentration, phosphate and chlorine did not show any trend. In solids, there exists a fundamental inverse relationship between porosity and strength, but sometimes, this is not observed because of the presence of microcracks in the interfacial transition zone between the coarse aggregate and the concrete matrix (Mehta & Monteiro 2006). This porous zone, where cracks often originate, prevents efficient load transfer between

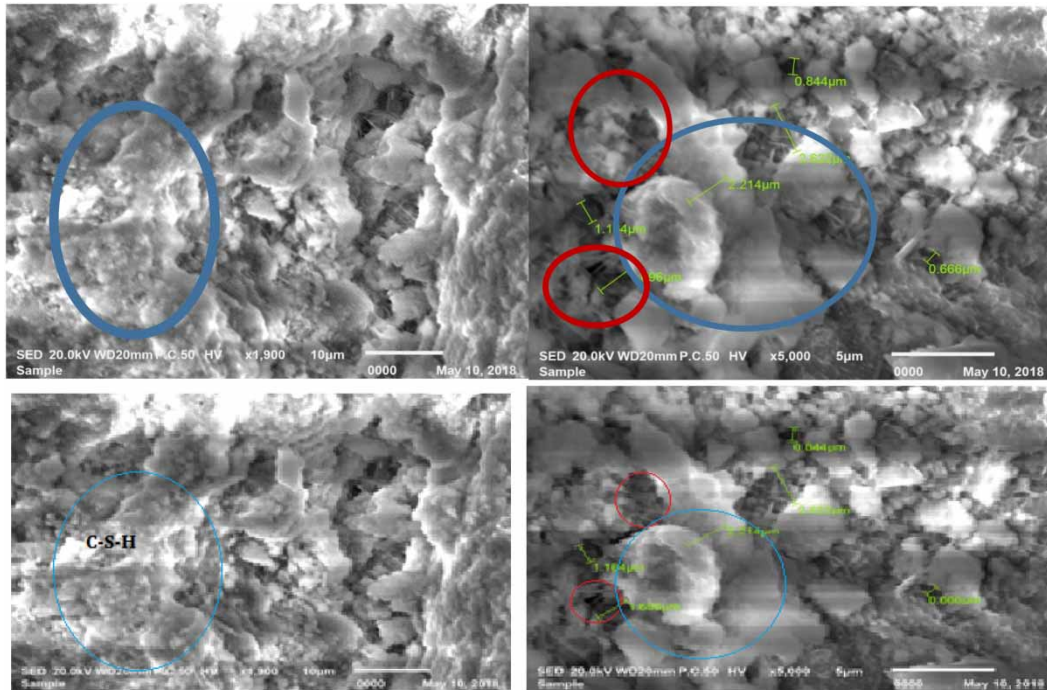


Figure 9 | SEM images of blocks produced with drinking water (DW). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wrd.2021.031>.

the coarse aggregate and the cement mortar (Neville 1987). This can be the reason why differences in behavior are observed when analyzing various compounds.

Block characterization with SEM

The types of the formed minerals and their relative percentages influence the quality of the produced concrete blocks and thus could confirm the strength and durability of the concrete. Depending on the added water mixtures to produce concrete blocks, different and complex microstructures are formed.

In concrete blocks produced with drinking water, spherical crystals of C-S-H (tobermorite) were observed, rounded by the blue circle, and long needleless crystals of ettringite, in red circles (Figure 9). As a result of the interaction between calcium, sulfate, aluminate and hydroxyl ions, present on cement, and aggregates that get saturated in water forming small fibrous crystals, tobermorite makes 50–60% of the volume of solids in a completely hydrated Portland cement paste and is the most important phase determining the properties of the paste, while ettringite occupies 15–20% of the solid volume in the hydrated paste and, therefore, plays only a minor role in the microstructure–property relationships. During the early stages of hydration, the sulfate/alumina ionic ratio of the solution phase favors the formation of trisulfate hydrate, which forms these needle-shaped prismatic crystals of ettringite (Mehta & Monteiro 2006).

In the blocks made with WWTP effluent (Figure 10), crystals of apatite (phosphate mineral), portlandite (calcium hydroxide mineral), in the yellow circle, and tobermorite (red circle) were observed. Portlandite constitutes 20–25% of the volume of solids in the hydrated paste. It tends to form large crystals with a distinctive hexagonal-prism morphology like the ones presented in the yellow circle.

In blocks made with WWTP effluent with chlorine, mainly ettringite crystals were observed (red circle, Figure 11). The WWTP effluent has a mean chloride concentration of 281 mg/L (Table 4), which is increased by the addition of $\text{Ca}(\text{ClO})_2$. Friedel's salt is the main reaction product of chemical binding of chloride ions in concrete. It is formed due to the reaction between the chloride ions and hydration products. It is assumed that all aluminate hydrates transform to Friedel's salt with increasing chloride concentration in the pore solution (Birnin-Yauri & Glasser 1998). In general, the tendency of sulfate ions to bind in hydration products is higher than that of chloride and hydroxide. However, the concentration of sulfate ions in the pore solution of mature (28 days) cement paste is low compared to chloride. Therefore, chloride ions can react with the

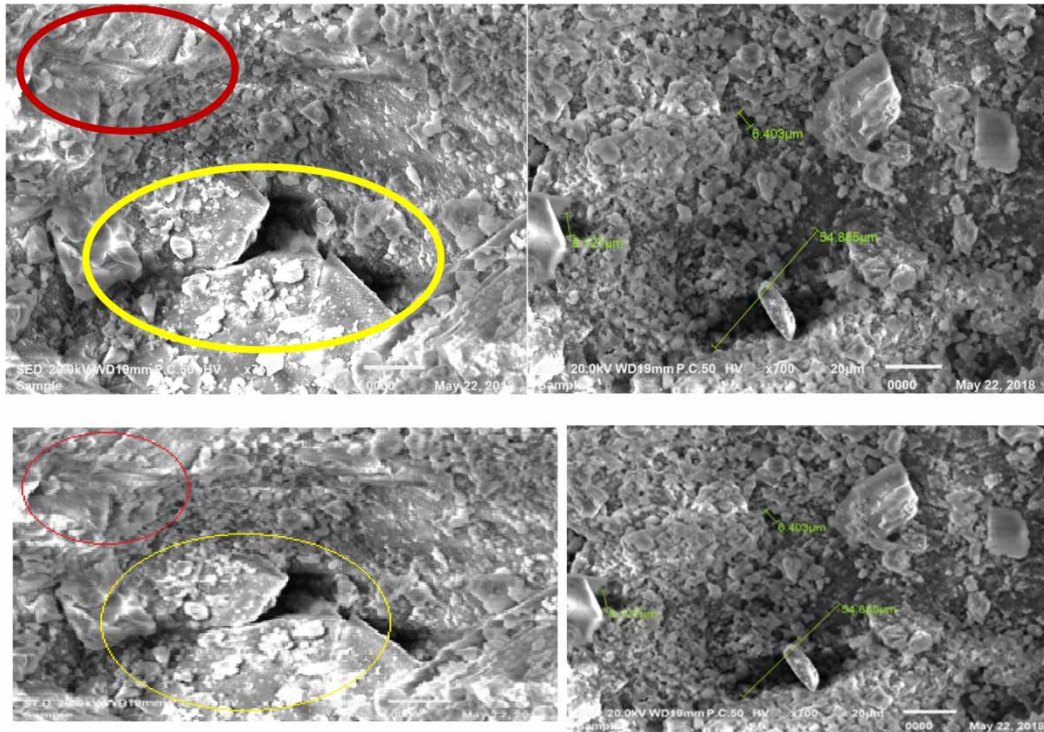


Figure 10 | SEM images of blocks produced with wastewater (WW). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wrd.2021.031>.

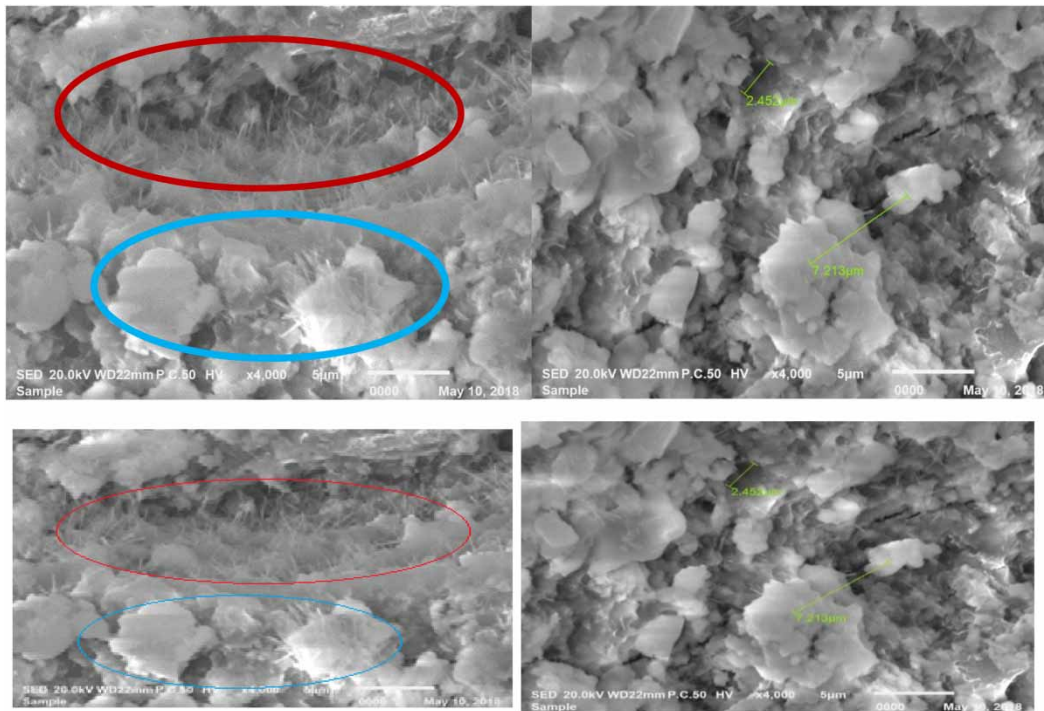


Figure 11 | SEM images of blocks produced with chlorinated wastewater (WW + Cl₂). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wrd.2021.031>.

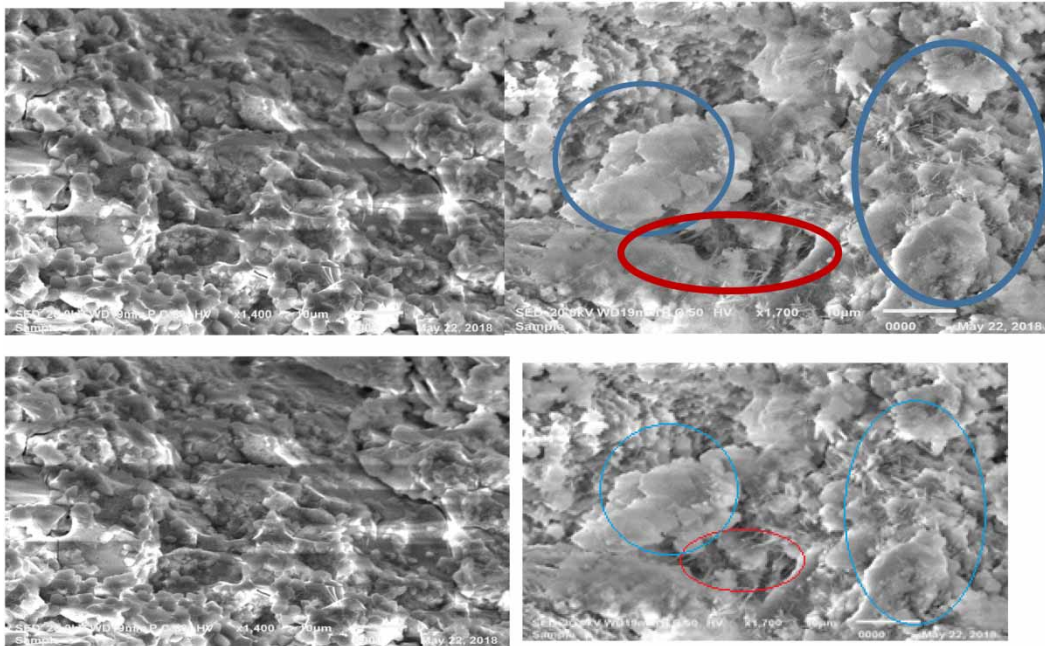


Figure 12 | SEM images of blocks made with phosphate added to drinking water (DW + PO₄). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wrd.2021.031>.

aluminate compounds to form Friedel's salt. Even the sulfate-containing hydration products convert into Friedel's salt if the chloride concentration in the pore solution is sufficiently high (Pargar *et al.* 2017). The formation of ettringite in the fresh concrete is the mechanism that controls stiffening and improves strength development, and also reduces drying shrinkage. This can be the reason why an increase in the strength of the concrete is observed when chlorine is used.

Blocks made with phosphate looked more compact and thus were more durable (see Figure 7). This can be explained by the presence of crystals of tobermorite (blue circle) and apatite (red circle) in Figure 12. These calcium salts are highly insoluble and therefore readily form a dense coating in the vicinity of hydrating cement particles creating a compact structure of hydroxyapatite (Naus *et al.* 2008). It is expected that hydroxyapatite is formed as a product of the reaction of phosphate ion and C-S-H and this is the expected morphology.

CONCLUSIONS

Field experiments were conducted to evaluate the possibility of using WWTP effluent for concrete production in low-cost applications, in particular of M15 blocks that are commonly used during the self-construction of houses in Mozambique.

The water quality experiments showed that the parameters foam vanishing time, oil and grease, and oily characteristic odor did not comply with the limits for concrete production but they did not affect the strength and durability of produced blocks. These parameters are therefore not expected to limit the use of reclaimed water for block production.

From the experiments, it was concluded that the strength and durability of M15 blocks produced with WWTP effluent did not show a significant difference with blocks produced with drinking water. The quality of reclaimed water for concrete mixing was thus sufficient for adequate strength development, and related water absorption and crystal formation. In addition, considering other makeup water, where drinking water was spiked with phosphate, ammonium and chlorine, the impurities had a slightly positive effect on concrete block manufacturing. However, it could also be concluded that the results were highly variable, indicating that the quality of the mixing water was not the only factor that influenced the strength of the M15 blocks, but could also be attributed to the manufacturing process.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 29 April 2021; accepted in revised form 3 August 2021. Available online 30 August 2021