Environmentally friendly interlocking concrete paver blocks produced with treated wastewater

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ABSTRACT

This study aimed at supporting processes and techniques for minimization of water consumption in the production of concrete. For this purpose, the use of treated wastewater from a wastewater treatment plant (WWTP) in interlocking concrete paver block (ICPB) production was evaluated. The treated wastewater was added in various dosages (0%, 50%, 75% and 100%) to the water used to produce cylindrical concrete samples. These samples were evaluated for compressive strength and water absorption tests. After these evaluations, the dosage of 100% treated wastewater for concrete production was established and ICPB were produced with this water composition. Subsequently, an area in a parking lot was replaced by ICPB produced with treated wastewater, and an equal area was replaced by ICPB produced with potable water. A comparison between parameters obtained for cylindrical samples and ICPB samples prepared with treated wastewater and those prepared with potable water indicated that wastewater reuse would be a good alternative for potable water consumption reduction in the concrete industry.

Key words | concrete, sustainable, trickling filter, UASB, wastewater, water consumption

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INTRODUCTION

Brazil has the largest fresh water reserve on Earth, accounting for almost 16% of the total (UN 2011), but uneven distribution of population and fresh water have led to water scarcity in some regions, such as São Paulo, its most industrialized and most populated state.

Since the end of 2013, southeastern Brazil has been struggling through the worst drought in 55 years. Cities such as São Paulo, Rio de Janeiro and Belo Horizonte are facing water shortages, putting a total of 40 million people at risk in the region. Reservoirs that supply water to these cities have been at dangerously low levels, due to a deficient rainy season accompanied by record high temperatures and subsequent increase in water demand by the population (Nobre *et al.* 2016).

The International Resource Panel of the UN states that governments have tended to invest heavily in largely inefficient solutions: mega-projects like dams, canals, aqueducts, pipelines and water reservoirs, which are generally neither environmentally sustainable nor economically viable. The most cost-effective way of decoupling water use from economic growth, according to the scientific panel, is for governments to create holistic water management plans that take into account the entire water cycle: from source to distribution, economic use, treatment, recycling, reuse and return to the environment (United Nations Environment Programme 2016).

So, water saving has been encouraged and many alternatives have been studied, such as replacing potable water by treated wastewater in situations where it does not present any harm to human and animal health.

The production of concrete requires large amounts of water, which may be burdensome in regions where there

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is low availability of fresh water. Concrete production was responsible for 9% of global industrial water withdrawals in 2012 (this is approximately 1.7% of total global water withdrawal) (Miller *et al.* 2018). In 2050, 75% of the water demand for concrete production will likely occur in regions that are expected to experience water stress (Miller *et al.* 2018). The urgency of reducing potable water consumption has boosted research on the use of treated wastewater in concrete production all over the world.

Some of these results indicate positive changes in concrete characteristics, such as higher compressive strength (Al-Ghusain & Terro 2003; Duarte *et al.* 2019). Other studies indicated no differences or, in some cases, a slight decrease in compressive strength values for concrete and mortar samples produced with wastewater, but in these cases the values were within international regulations for concrete, indicating treated wastewater reuse was possible and safe (Al-Jabri *et al.* 2011; Asadollahfardi & Mahdavi 2018).

Al-Ghusain & Terro (2003) cast concrete samples produced with tap water, preliminary treated wastewater, secondary treated wastewater and tertiary treated wastewater and concluded that the compressive strength of concrete produced with tertiary treated wastewater was higher than that of concrete made with tap water after 3 and 7 days, and similar for both concretes after 3 months, so tertiary treated wastewater was considered suitable for mixing concrete with no adverse effects.

Al-Jabri *et al.* (2011) prepared high-strength concrete samples with various proportions of car washing station wastewaters and tap water, with a water-to-cement ratio of 0.35. They concluded that the concrete strength was similar for the samples prepared with wastewater and the control samples.

In Brazil, regulations on water quality for concrete production (NBR 15900-1 2009) state clearly that wastewater and treated wastewater are not adequate for concrete production. That reflects the widespread prejudice against concrete artifacts produced with treated wastewater, which hinders this reuse practice. The USA, on the other hand, is an example of a country that allows this practice, as long as pH, biochemical oxygen demand (BOD), total suspended solids (TSS), fecal coliforms and residual Cl_2 values are within defined limits (USEPA 2012).

As Brazil, just like many other countries, has been going through a severe water crisis (Nobre *et al.* 2016), it is possible that in a near future, the country's regulations will become softer, allowing treated wastewater reuse for activities such as concrete production, as a way of saving potable water for other activities and avoiding effluent release in water bodies, preventing pollution (United Nations Environment Programme 2019).

Along with this, in many developing countries the upflow anaerobic sludge blanket reactor (UASB) is commonly used for domestic sewage and industrial wastewater treatment. According to Noyola *et al.* (2012), the UASB reactor is the third most used for sewage treatment in the analysis of 2,734 municipal plants in six Latin American and Caribbean countries. In Brazil, it is the second most used technology, corresponding to approximately 30% of the plants studied. More recently, India has become a front-runner in using UASB reactors for sewage treatment (Bressani-Ribeiro *et al.* 2018).

It is worth mentioning the most frequently applied flow sheets of the so-called combined systems (anaerobic/aerobic), such as: UASB + polishing ponds; UASB + overland flow system; UASB + wetlands; UASB + trickling filter (TF); UASB + activated sludge (AS); and UASB + flotation unit (von Sperling & Chernicharo 2005; Chernicharo *et al.* 2015).

In many developing countries there has been a major development of the association of UASB + trickling filter. A recent survey carried out in Brazil has shown that amongst 333 investigated sewage treatment plants comprising UASB reactors followed by post-treatment units, trickling filters accounted for 25% (82 plants). The operational simplicity and performance stability of TFs are key aspects in their worldwide application, especially in developing countries (Bressani-Ribeiro *et al.* 2018).

The BOD removal efficiencies of trickling filters fed with effluent from UASB reactors (median of 65%) are typically lower than those for traditional TFs following primary settlers (65%–80%) (Bressani-Ribeiro *et al.* 2018). This was to be expected, since most of the readily biodegradable organic matter was consumed in the anaerobic step. From the operational results indicated it was observed that the UASB–trickling filter systems produced effluents with BOD and TSS concentrations below 40 mg BOD L^{-1} and 30 mg TSS L^{-1}, respectively (Bressani-Ribeiro *et al.* 2018).

Whereas the characteristics of treated wastewater generated by the association of UASB + trickling filter have been well discussed, when it comes to reclaiming the main resource produced by this combination of reactors, which is the water present in the treated wastewater, no extensive evaluations can be found in the literature. Thus, this study consists in an evaluation of cylindrical concrete samples and interlocking concrete paver blocks produced with treated wastewater from the wastewater treatment plant (WWTP) Barão Geraldo located in Campinas, Brazil. It consists of the association of UASB + trickling filter. The research aimed at providing further data on concrete quality as a way of supporting a sustainable production of concrete artifacts.

MATERIALS AND METHODS

The treated wastewater used in this experiment was obtained at WWTP Barão Geraldo, located in the city of Campinas (Brazil). This WWTP treats the wastewater from a fixed population of 55,000 people and a floating population of 20,000 people, resulting in an average of 80 Ls^{-1}. The treatment system consists of a combination of a UASB reactor and a trickling filter.

In the first stage of the research the treated wastewater from WWTP Barão Geraldo was collected and disinfected with calcium hypochlorite at a concentration of 12.0 mgL^{-1} and 30-minute contact time to guarantee its safety for interlocking concrete paver block (ICPB) production. This value was enough to maintain total coliforms and *Escherichia coli* concentrations below detection limits (>1 organism 100 ml^{-1}). The presence of these microorganisms was analyzed immediately after disinfection and also at the end of the experiment in which the treated effluent was used for concrete sample production.

Subsequently, treated wastewater was characterized by the following physical, chemical and biological parameters: pH, alkalinity, conductivity, dissolved oxygen, turbidity, total solids, chemical oxygen demand (COD), nitrogen compounds and phosphorus. All analyses were based on APHA *et al.* (2012).

Concrete sample production

In the second stage of the research, effluent was used to produce cylindrical concrete samples measuring 0.20 m height and 0.10 m diameter (Figure 1), with cement type CP II, medium sand and gravel zero. Proportions were 1:2:3 (cement:sand:gravel) and the water:cement ratio was 0.45.

The water for concrete production was a combination of potable water and treated wastewater, in various proportions (Table 1). For each composition of this water mixture ten concrete samples were cast.

Concrete curing occurred for 30 days, with concrete samples totally submerged in water. This water had the same composition as the one used to produce the concrete, for each group (Table 1). Molding and curing were according to Brazilian regulation NBR 5738 (2015).

Concrete samples were then characterized by visual inspection, dimensional measurements, water absorption, compressive strength and abrasion resistance, according to Brazilian regulations for concrete pavements (NBR 9781 2013; NBR 5739 2018). In characteristic compressive strength tests, the results were compared with required values for pedestrian and vehicular traffic. In this case, this value must be higher than 35 MPa.

For water absorption determination, saturated concrete samples were taken to the drying oven for 24 hours (105 °C). The mass increment was obtained by the difference between the mass of the saturated sample and the mass of the sample after drying in the oven. Water absorption, in percentage, corresponds to the ratio between mass increment and mass after the oven, multiplied by 100. Concrete samples had to present average water absorption less

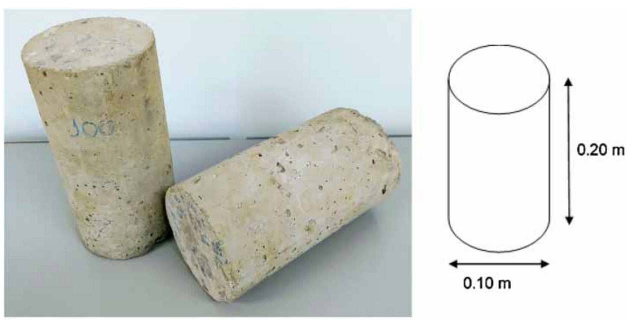

Figure 1 | Concrete samples.

Table 1 | Compositions of water used for concrete sample production

Group	Potable water (% in volume)	Treated wastewater (% in volume)
1	0	100
2	25	75
3	50	50
4	100	0

than or equal to 6% and no samples should have presented values higher than 7%.

Concrete samples were visually inspected to identify defects that might hinder floor laying, structural performance or pavement aesthetics. Slight variations in color were accepted due to manufacturing process and raw material variations. The aspect of the floor pieces had to be homogeneous, with regular edges and right angles and be free of burrs, defects, delamination and flaking.

Production of interlocking concrete paver blocks and real situation assessment

After evaluation of cylindrical concrete samples the most adequate potable water:treated wastewater relation was chosen and 4 m^2 of interlocking concrete paver blocks were produced with this water composition, and another 4 m^2 were produced with potable water. Proportions of cement:sand:gravel were the same as for cylindrical concrete samples.

The ICPB were cured for 3 weeks with the same water composition used for their production, in order to prevent them from losing moisture. At the end of this period the ICPB were evaluated for compressive strength, water absorption, visual inspection and dimensional measurements, the same tests that were carried out for the cylindrical concrete samples.

Finally, the last stage of the project consisted in replacing a part of the ICPB from the parking lot of the School of Civil Engineering, Architecture and Urban Design from Unicamp with the ICPB produced with potable water and with treated wastewater. This place was chosen for presenting extreme conditions: there is a substantial flow of vehicles (abrasion) and, as it is exposed to temperature and humidity, there is higher degradation and a higher chance of alkali–aggregate reaction occurrence.

Statistical comparison was performed using analysis of variance (ANOVA) and the post hoc Tukey's test. A p value of <0.05 was considered statistically significant.

RESULTS AND DISCUSSION

Treated wastewater from the trickling filter as post-treatment and UASB reactor effluents (Table 2) showed BOD and SS concentrations lower than 60 mgL^{-1}, confirming the values found by Chernicharo *et al.* (2018). In a review published by Bressani-Ribeiro *et al.* (2018), it was found that in 28 papers that discussed the application of a trickling filter in operation in demo, pilot and real conditions, BOD values ranged from 2 to 35 mgL^{-1} and TSS from 1 to 45 mg L^{-1}. The system studied in this article has always presented results within this range of values. Thus, it can be stated that it represents typical wastewater for this type of treatment system.

The results for potable water and treated wastewater analyses (Table 2) showed that both meet Brazilian (NBR 5739 2018) and European (EN 1008 2002) regulation requirements for water quality for concrete pavement production, which suggests that the treated wastewater from a UASB reactor associated with a trickling filter can be used in concrete mixtures offering no risks to concrete quality or to human health.

After treated wastewater characterization, the concrete samples with various water mixtures (Table 1) were cast. There were no significant differences between average values obtained for the various combinations that were studied for compressive strength (Table 3). Hence, the presence of organic matter and various salts coming from wastewater did not present harm to the concrete samples. The same was reported by Al-Ghusain & Terro (2003) and Al-Jabri *et al.* (2011).

Al-Jabri *et al.* (2011) found results that indicate that the cube compressive strength values for mixtures with 25% and 100% wastewater substitution are slightly lower than the strength of the control mixture (100% tap water) at 7 and 28 days of curing. However, the mixture with 50% wastewater substitution yielded a strength value that is comparable to the control mixture. They also concluded that as the curing period increases the compressive strength of the

Table 2 | Quality of potable water and treated wastewater used in this research

Parameter	Potable water	Treated wastewater*	Brazilian regulation (NBR 15900-1 2009)	European regulation (EN 1008 2002)
pH	6.90 ± 0.09	7.44 ± 0.34	≥5	≥4
Total alkalinity (mg $CaCO_3L^{-1}$)		191.04 ± 5.50	≤2,422 (1)	≤2,422 (1)
Conductivity (uS)		243 ± 89		
Turbidity (uT)	0.45 ± 0.09	57 ± 5		
Nitrite-N (mgL^{-1})	<0.005	4.4 ± 2.1		
Nitrate-N (mgL^{-1})	1.27 ± 0.22	0.1 ± 0.1	≤112.9 (2)	≤112.9 (2)
NH_3-N (mgL^{-1})	1.03 ± 0.25	25.3 ± 1.3		
NTK-N (mgL^{-1})		32.2 ± 2.9		
Phosphorus (mgL^{-1})		3.4 ± 0.1	≤43.7 (3)	≤43.7 (3)
DO (at 23.7 °C) (mgL^{-1})		5.1		
COD (mgL^{-1})		70 ± 13		
Sulfate (mg SO_4^{2-} L^{-1})	7.14 ± 4.21	3.99	≤2,000	≤2,000
SST		27 ± 3		
Total solids (mgL^{-1})		0.395	≤50,000	
Fixed solids (mgL^{-1})		0.295		
Volatile solids (mgL^{-1})		0.100		

*Treated wastewater from UASB + trickling filter. (1) According to NBR 15900-1 (2009) and EN 1008 (2002), the alkali content in mixing water must not exceed 1,500 mg Na_2O L^{-1}, which is equivalent to 2,422 mg $CaCO_3$ L^{-1}. (2) According to NBR 15900-1 (2009) and EN 1008 (2002), the nitrate content in mixing water must not exceed 500 mg NO_3^- L^{-1}, which is equivalent to 112.9 mg NO_3^--N L^{-1}. (3) According to NBR 15900-1 (2009) and EN 1008 (2002), the phosphorus content in mixing water must not exceed 100 mg P_2O_5 L^{-1}, which is equivalent to 43.7 mg P L^{-1}.

Table 3 | Compressive strength and water absorption results for cylindrical concrete samples

Potable water:treated wastewater (%)	Compressive strength (MPa)	Water absorption (%)
100:0	45.40 ± 2.65a	2.99 ± 0.08a
50:50	46.56 ± 1.17a	2.94 ± 0.30a
25:75	44.24 ± 1.12a	3.03 ± 0.35a
0:100	43.61 ± 0.75a	3.01 ± 0.32a

Each average was obtained from six repetitions ($n = 6$). The different letters in each line indicate significant difference ($p < 0.05$).

concrete is also increased irrespective of the wastewater percentage used. This led to no significant difference in the concrete cube compressive strength for different mixes after 28 days of curing.

Results from Tay & Yip (1987) showed a general increase in early (3–28 day) compressive strength with increasing amounts of reclaimed wastewater used in the concrete mixes. For ages of 3 months and higher, compressive strengths of cubes made with 100% reclaimed wastewater, and those made with potable water, were similar. The use of reclaimed wastewater in concrete mixing did not seem to have an adverse effect on the concrete. The 28-day strength of cubes cured in reclaimed wastewater was 1.5% higher than those cured in potable water.

Al-Ghusain & Terro (2003) found that for ages of 3 months and higher, compressive strengths of cubes made with 100% reclaimed wastewater, and those made with potable water, were similar. The 28-day strength of cubes cured in reclaimed wastewater was also reported to be 1.5% higher than those cured in tap water. At early concrete ages of 3 and 7 days, the strength of concrete made with treated wastewater (TTWW) was higher than that of concrete made with treated water (TW).

Still according to these authors (Al-Ghusain & Terro 2003) tertiary treated wastewater, of the type produced from wastewater treatment plants in Kuwait, is suitable for mixing concrete. The fresh concrete properties, strength characteristics and steel reinforcement corrosion potential for concrete made with TTWW were all similar to those produced using tap water. Moreover, from a health perspective, TTWW is the most suitable type of treated wastewater for on-site use and for the construction workers to handle.

Regarding water absorption, there were no significant differences between average values obtained for the various combinations of water and wastewater (Table 3). Al-Jabri *et al.* (2011) found similar results, that is, all concrete mixtures with wastewater replacement showed similar water absorption rates to the control mixture.

Regarding the visual inspection, all concrete samples presented a homogeneous aspect, with slight color variations. They also did not present defects such as cracking.

Reactivity tests performed according to NBR 15577 (2018) indicated that the sand and gravel used are potentially innocuous materials for possible alkali–aggregate reactions in the concrete paver blocks.

Since results were satisfactory for cylindrical concrete samples, ICPB were produced with 100% treated wastewater, and control samples were produced with 100% potable water.

Table 4 | Compressive strength and water absorption results for interlocking concrete paver blocks

Potable water:treated wastewater (%)	Compressive strength (MPa)	Water absorption (%)
100:0	37.45 ± 5.97a	5.74 ± 0.44a
0:100	36.43 ± 2.64a	5.81 ± 0.86a

Each average was obtained from six repetitions ($n = 6$). The different letters in each line indicate significant difference ($p < 0.05$).

Just as happened for the cylindrical concrete samples, no significant differences were observed in compressive strength and water absorption for ICPB produced with treated wastewater and with potable water (Table 4). Both ICPB complied with Brazilian and European regulations that require strength resistance higher than 35 MPa and water absorption lower than 6%.

Regarding the visual inspections, both concrete floor samples presented a homogeneous aspect. The edges were smooth, with right angles and were free from burrs. No defects such as cracking, delamination or flaking were observed. Thereafter, the ICPB were installed in the parking lot from the School of Civil Engineering, Architecture and Urban Design from Unicamp (Figure 2).

Even after 6 months of use, no cracks or flaws in the appearance of the floors were identified. Other authors (Chen *et al.* 2013; Baeza-Brotons *et al.* 2014; Pérez-Carrión *et al.* 2014) used the sewage sludge ash and found that the bricks and floors produced met the requirements of European standards.

For example, Baeza-Brotons *et al.* (2014) produced paste, mortar and concrete samples replacing 5%, 10%, 15% and 20% of cement by sewage sludge ash. The addition of sewage sludge ash resulted in concretes with similar

Figure 2 | Interlocking concrete paver blocks (ICPB) produced with treated wastewater and potable water being tested in the parking lot.

densities and compressive strengths to the control sample, and significantly lower water absorption. Pérez-Carrión *et al.* (2014) also evaluated cement replacement by sewage sludge ash in precast concrete block production. They tested the blocks produced with 0%, 10% and 20% ash for compressive strength and obtained the best results for the samples containing 10% ash. Chen *et al.* (2013) aimed at obtaining the ideal ratio of cement and sewage sludge ash to produce a concrete that would satisfy both technical and environmental criteria. To add an environmental criterion to the evaluation, leaching tests were also performed, for sludge powder and for concrete produced with this sludge. Results showed that none of the contaminants were leached above the threshold limits for concrete samples.

This sludge ash has concentrations of salts much higher than those found in the present work. Therefore, it is demonstrated that the production of floors with effluent from the wastewater treatment plant that has been widely used in developing countries (UASB + trickling filter) can be a safe and sustainable alternative, which can contribute to the minimization of the water crisis in these places.

CONCLUSIONS

The comparison between results for interlocking concrete paver block samples produced with treated wastewater meeting standard discharge and with potable water showed that both were in accordance with Brazilian and European regulations for concrete pavement quality. Therefore, taking into account the necessity of new sanitation processes and techniques that minimize potable water consumption, concrete production with treated wastewater has proved to be a valuable alternative.

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