

Effect of water-to-cement ratio and curing method on the strength, shrinkage and slump of the biosand filter concrete body

Nicole Chan, Candice Young-Rojanschi and Simon Li

ABSTRACT

The biosand filter is a household-level water treatment technology used globally in low-resource settings. As of December 2016, over 900,000 biosand filters had been implemented in 60 countries around the world. Local, decentralized production is one of the main advantages of this technology, but it also creates challenges, especially in regards to quality control. Using the current recommended proportions for the biosand filter concrete mix, slump was measured at water-to-cement ratios of 0.51, 0.64 and 0.76, with two replicates for each level. Twenty-eight-day strength was tested on four replicate cylinders, each at water-to-cement ratios of 0.51, 0.59, 0.67 and 0.76. Wet curing and dry curing were compared for 28-day strength and for their effect on shrinkage. Maximum strength occurred at water-to-cement ratios of 0.51–0.59, equivalent to 8–9.3 L water for a full-scale filter assuming saturated media, corresponding to a slump class of S1 (10–40 mm). Wet curing significantly improved strength of the concrete mix and reduced shrinkage. Quality control measures such as the slump test can significantly improve the quality within decentralized production of biosand filters, despite localized differences in production conditions.

Key words | biosand filter, concrete, decentralized production, quality control

Nicole Chan

University of Calgary,
2500 University Dr NW, Calgary,
AB T2N 1N4, Canada

Candice Young-Rojanschi

Centre for Affordable Water and Sanitation
Technology (CAWST),
Upper 424 Aviation Road NE, Calgary,
AB T2E 8H6, Canada

Simon Li (corresponding author)

Department of Mechanical Engineering,
University of Calgary,
2500 University Dr NW, Calgary,
AB T2N 1N4, Canada
E-mail: simoli@ucalgary.ca

INTRODUCTION

As of 2012, it was estimated that 1.9 billion people in the world relied on fecally contaminated water for drinking. Infectious diarrhoeal diseases attributed to inadequate water are estimated to cause 502,000 deaths a year, with the majority being children under age five (Prüss-Ustün *et al.* 2014). The biosand filter (BSF) is one of the most promising household-level water treatment technologies currently available. It is composed of a concrete or plastic body with prepared sand as a filter medium and two supporting gravel layers as an under-drain. The schmutzdecke, a biological layer that is responsible for the majority of bacterial removal, forms within the upper centimetres of the filter media over time.

In laboratory studies, BSFs have been shown to have mean removal rates of $>5 \log_{10}$ of *Giardia lamblia* cysts,

$3.8 \log_{10}$ *Cryptosporidium* sp. oocysts (Palmateer *et al.* 1999), $>1.6 \log_{10}$ of *E. coli* (Napotnik & Jellison 2014; Young-Rojanschi & Madramootoo 2014; Elliott *et al.* 2015) and $>0.5 \log_{10}$ of MS2 (Jenkins *et al.* 2011; Young-Rojanschi & Madramootoo 2014; Elliott *et al.* 2015). The BSF has been documented to reduce diarrhoeal disease by 61% and 54% in randomized controlled trials in the Dominican Republic and Kenya respectively (Aiken *et al.* 2011; Sisson *et al.* 2013). To date, over 900,000 BSFs have been distributed worldwide. One of the main advantages of BSFs is that they are locally produced. Local production means that expertise and technical support reside within a community.

One challenge with local and decentralized production of household water treatment products is ensuring consistent quality of the technology. Ngai *et al.* (2014) analysed 32 BSF project evaluations in 19 countries by different organizations between 2002 and 2012 in order to characterize the global adoption, use, and performance of the technology (Ngai *et al.* 2014). Although the results of the evaluations

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were positive overall, several key challenges were identified. Eight of the 32 studies reported issues with poor fabrication quality, including leaks and cracks.

Among various quality issues, this study focuses on the quality of the BSF's concrete cases. In fact, the quality of filter cases could be one limiting factor in the adoption of water-treatment technologies. For example, parametric variability in the production of ceramic pot filters has been observed to lead to reductions in filter quality and effectiveness. The lack of universal quality control standards has been identified as a key barrier to the effective scaling-up of ceramic pot filter production (Rayner *et al.* 2013). Similar issues with quality control have been observed with the BSF. In Nicaragua ($n = 237$), a study conducted on three and eight-year-old filters showed sustained usage rates of 7% and 30% respectively. In the three-year-old filters, the most common mode of failure was cracking of the concrete body, leading to water and sand leaking out of the filters. The cracking was likely a function of poor quality control during production (Vanderzwaag *et al.* 2009). In the eight-year-old filters, the modes of failure were cracks in the body and dislodgement of outlet pipes. In contrast, a study in Zimbabwe of filters two years after installation ($n = 37$) reported no leaks (Artwell *et al.* 2014).

In this study, two production factors (i.e., water-to-cement [w/c] ratio and curing method) are investigated in view of three properties of the concrete (i.e., strength, shrinkage, and slump). One area of high variability in BSF body construction is with the w/c ratio of the concrete mix. Producers have been observed to generally add more water than is currently recommended in the BSF construction manual (CAWST 2012). Excess water can reduce the strength of concrete, leading to a higher probability of cracking (Sivakumar 2013). The accurate amount of water can differ, depending on the saturation condition of the aggregate and the relative humidity of the production site. For example, implementers in Zambia compared to implementers in Nepal may have the same proportion mix, but because of the type of aggregate used and atmospheric relative humidity, the ideal amount of water to add would be different.

Shrinkage in concrete can also lead to crack formation. In early-age shrinking (<24 hours), low w/c ratios and low relative humidity can increase the risk of cracking (Holt & Leivo 2004). Early-age shrinkage can result in cracks that propagate at later ages, increasing the probability of crack formation. Specifically, tension stresses develop under conditions of restrained shrinkage (Hover 2005). In the case of the BSF, the mold provides external restraints that increase cracking potential.

One test with the potential to standardize concrete quality is the slump test. The slump test is a measure of concrete consistency, and is the most widely used field test for concrete producers. However, there is a lack of information regarding what the optimal w/c ratio is for the BSF concrete mix, taking into account the trade-off between workability and strength, and what the corresponding slump would be. Therefore, it was desired to determine the effect of various production parameters, mainly water content and curing methods, on the quality of concrete, as defined by strength and shrinkage. Within these ideal production parameters, an ideal slump value could be determined to recommend to implementers in the field, which could help mitigate the current locational differences that make it difficult to recommend an ideal volume of water to add.

In the literature, the relationship between the w/c ratio and the strength of concrete is well established (Gambhir & Jamwal 2014). The strength of concrete is directly proportional to porosity within the concrete. The porosity is a function of the w/c ratio (Popovics & Ujhelyi 2008). In one study, mortars were constructed with ordinary Portland cement with w/c ratios of 0.45 to 0.60. This increase in w/c resulted in a 150% increase in porosity, a 139% increase in water loss and a 75.6% decrease in compressive strength (Kim *et al.* 2014). Increasing the w/c ratio has also been associated with increased plastic shrinkage crack length, though the crack width did not increase (Sivakumar 2013), and a decrease in concrete fracture toughness due to increasing porosity. In this context, the added value of this study is to investigate the concrete properties based on the concrete mix recommended by CAWST.

In sum, the objective of this study was to explore whether the current CAWST recommendations for the water content are optimal for maximizing strength and minimizing shrinkage within the concrete mix. This study also tested the effect of curing methods on strength and shrinkage. The strength and shrinkage results will aid in the development of recommendations for the result of the slump test, which implementers can use for quality control within their operations.

METHODS

Preparation of concrete samples

Concrete cylinders 102 mm in diameter and 203 mm in length were constructed with different w/c ratios. Cylinders were constructed as per the American Society for Testing and Materials (ASTM) standards. The mix consisted of (by volume):

- 2 parts sand (<0.7 mm),

- 1 part small gravel (1 mm–6 mm),
- 1 part large gravel (6 mm–12 mm), and
- 1 part Lafarge, type GU cement.

There was a slight deviation from the standard CAWST BSF mix in that, for logistical reasons, the sand had a maximum grain size of 0.7 mm instead of the recommended 1 mm (CAWST 2012). Raw material was sourced from a local landscaping centre and sieved using 12 mm, 6 mm and 0.7 mm sieves. Each size fraction was thoroughly mixed.

Absorption was measured in accordance with ASTM C 70 and C 127. A sample was drawn from each size fraction and the mass measured. The samples were oven-dried at 110 °C and the mass re-measured. Finally, the samples were soaked in water overnight and brought to saturated-surface condition, at which point a third mass measurement was taken. The absorption of water by the aggregate was calculated from the mass measurements, and was equivalent to a water volume ratio of 0.02.

Concrete was cast according to ASTM C 192. Water was added incrementally and the concrete thoroughly hand-mixed. The w/c ratio investigated in this study ranged from 0.51–0.76, which would be equivalent to the addition of 8–12 L of water in a concrete batch for a full-scale filter box. The concrete was then poured into 102 mm × 203 mm standard concrete molds. For cylinders used for the investigation of the effect of water content on strength, the concrete was hand compacted with a tamping rod and rubber mallet. Otherwise, cylinders were vibrated using a vibration table. The cylinders were demolded after approximately 24 hours, cured in either ambient air conditions or in the moist room depending on the experimental treatment group, and tested at 28 days after casting.

Each replicate in this study was prepared from a new batch of concrete, not from multiple cylinders of the same batch.

Investigation of water-to-cement ratio on compressive strength

The effect of water content on strength was investigated at the w/c ratios of 0.51, 0.59, 0.67 and 0.76. Each level had four replicates, each from a new batch, leading to 16 concrete batches. The order of batching was randomized to avoid bias that could be introduced by operator fatigue. Curing was conducted at 21 ± 1 °C and 29% relative humidity (RH). After 28 days of curing, the cylinders were destructively tested using an Amsler compression testing machine (Alfred J. Amsler & Co., Switzerland) according to ASTM C 39.

Investigation of slump

Slump was investigated at w/c ratios of 0.51, 0.64 and 0.76. Each level had two replicates. Slump was measured using a standard slump cone as per ASTM C 143 standards. Prior to casting, a sample was extracted from each batch of concrete, and a slump cone filled in incremental thirds. After each third, the concrete was tamped 25 times using a steel rod. Upon filling the cone, the concrete was struck off using the rod. The mold was lifted gently from the concrete and the difference between the highest point of the concrete and the height of the mold was recorded as the slump.

Investigation of curing method on compressive strength

The effect of curing method on strength was investigated at two levels, dry curing (13.9% RH) and wet curing (100% RH), for the w/c ratios of 0.64 and 0.76. Wet curing occurred in a moist room and dry curing occurred in ambient conditions. The average temperature was 21 ± 1 °C. Each level had two replicates for a total of eight cylinders. The observed measurement uncertainty was ±2% RH. However, at low and high relative humidities the uncertainty of the sensors can increase to ±5%. After 28 days of curing, the cylinders were destructively tested using an Amsler compression testing machine according to ASTM C 39.

Investigation of shrinkage

The effect of water content on shrinkage was investigated at w/c ratios of 0.51, 0.64 and 0.76. The effect of curing on shrinkage was also investigated for these w/c ratios at two levels: dry curing (13.9% RH) and wet curing (100% RH). Each experimental group had two replicates for a total of 12 cylinders. The length of the concrete cylinder after demolding was measured one day and 28 days after casting using demountable mechanical strain gauges (DEMECs). The percentage of shrinkage was calculated based on the difference in length from these two time points. Temperature was kept constant within 2 °C during the experiment.

Statistical analyses

The research experiment sought to determine a model for slump based on the w/c ratio. An ideal slump value was determined for maximizing strength and minimizing shrinkage by examining the effects of the w/c ratio on strength and shrinkage. Significance and size of factor effects were estimated using restricted maximum likelihood (REML) and

ANOVA general linear modelling (GLM), where $\alpha = 0.05$. Outliers in the dataset were removed to preserve the integrity of the analysis. Values of p less than 0.05 were deemed statistically significant. Models were fitted after being analysed using Design-Expert[®]. Model appropriateness was assessed using Levene's test for the equality of variances and examining normal probability plots. Model assumptions were not found to be violated.

RESULTS AND DISCUSSION

Effect of water content

Compressive strength

The mean compressive strength values for the final experiment are shown in Figure 1. The w/c ratio was a statistically significant variable impacting strength ($p < 0.0001$).

There was not a significant difference in strength between w/c = 0.51 and 0.59 and w/c = 0.67 and 0.76. However, the strengths at w/c = 0.51 and 0.59 were significantly different from the strengths at w/c = 0.67 and 0.76. There was a 28% drop in strength from w/c = 0.59 to w/c = 0.67.

According to Abram's Law, the compressive strength of concrete exhibits an inverse relationship with the w/c ratio, in the form:

$$\text{Strength} = A/B^w \quad (1)$$

where A and B are constants and w corresponds to the w/c ratio (Domone & Illston 2010).

As the w/c ratio increases, the strength decreases. Complete hydration of cement generally only requires a w/c ratio of 0.42. Beyond this value, extra water increases the workability of concrete for compaction but is not necessary for hydration. Free water that does not react occupies pore space in the concrete microstructure. When the water evaporates, air voids remain in the microstructure. These air voids reduce the strength of concrete. Even 1% of air by volume can reduce concrete strength by 6% (Domone & Illston 2010). The results observed in this study, of decreasing strength with increasing water content, align with the current body of knowledge regarding concrete strength.

Aggregate segregation, where denser aggregate settles to the bottom of the cylinder, was observed for the mixes at w/c = 0.76, as shown in Figure 2. Segregation occurred to a lesser degree in the cylinders with a w/c ratio of 0.67, which can be observed in Figure 3. There was no obvious segregation at the lower w/c ratios.

Aggregate segregation is an indicator of bleeding. Bleeding occurs when mix water is forced to the surface of the concrete due to the settling of aggregate and cement. Excess bleeding results in a variable w/c ratio throughout the structure, causing as much as a 20–30% difference between the top and bottom zones and a total loss of up to 30% in the recorded strength of the overall structure (Giaccio & Giovambattista 1986). Movement of bleed water can also create a capillary network of pores that reduce the integrity of concrete within those zones. A sharp decrease in strength was also observed in Apebo *et al.* (2013) studies investigating the effects of using crushed gravel over burnt bricks for coarse aggregate. Varying the mix ratios will alter the shape of the

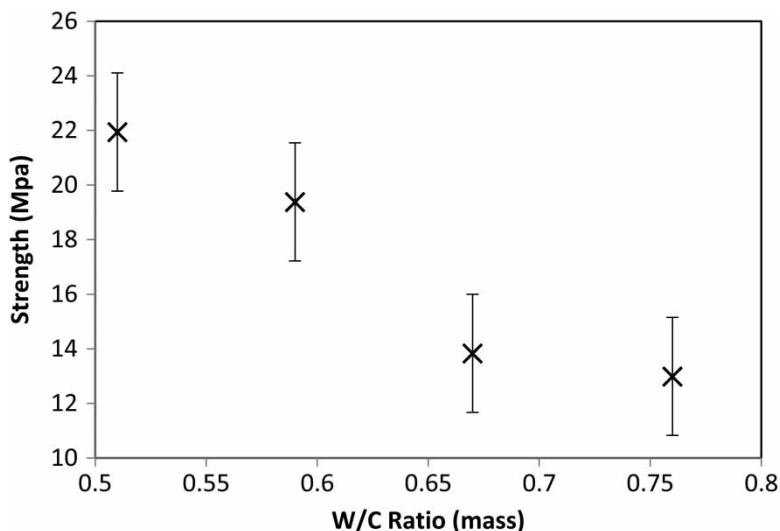


Figure 1 | Strength as a function of the w/c ratio with 95% confidence intervals.



Figure 2 | Top and bottom of cylinders with w/c ratio 0.76.



Figure 3 | Top and bottom of cylinders with w/c ratio 0.67.

curve of strength as a function of w/c ratio, altering the maximum strengths attained and the degree of strength loss due to additional water (Apebo et al. 2013). Aggregate segregation due to bleeding was most likely responsible for the significant drop in strength after w/c = 0.59 in this study.

Slump

The slump values as a function of w/c ratio are shown in Table 1.

The fitted model is as follows:

$$\text{Slump} = 695 - 2782 * w + 2821 w^2 \quad (2)$$

Table 1 | Slump as a function of water content

Slump (± 5 mm)	Water-to-cement ratio		0.67
	0.51	0.59	
Replicate 1	10	80	210
Replicate 2	10	60	210

Using Design-Expert[®], the w/c ratio ($p = 0.0003$) had a statistically significant effect on the slump. The R^2 value of the model is 0.995, indicating an excellent fit.

The British Standards Institution has five classifications for slump (The Concrete Society 2016):

- S1: 10–40 mm
- S2: 50–90 mm
- S3: 100–150 mm
- S4: 160–210 mm
- S5: >220 mm

At a w/c ratio of 0.51, the average slump was 10 mm, which is in the consistence class S1. This mix had a low workability. At a w/c ratio of 0.64, the average slump was 70 mm. This mix had a medium workability with a consistence class of S2. There was sufficient workability in this mix. At a w/c ratio of 0.76, the average slump was 210 mm in a consistence class of S4. This mix had a very high workability and was at the detection limit for the slump test.

According to Equation (2), a w/c = 0.59 would correspond to a slump of 42 mm. The slump is closest to an S1 class, which is from 10–40 mm slump. Generally, for mechanical compaction, a slump of 0–25 mm is considered very dry. As such, a slump of greater than 25 mm would be required for the practical purposes of workability.

The results in this study align with a similar study conducted by Deaconu & Gupta (2015). They investigated the effect of water on the CAWST concrete mix and measured the slump at those data points. The strength of their concrete was 73 MPa with a slump of 10 mm for w/c = 0.51. Although the magnitude of their strength was higher than the current study, their slump values were similar (Deaconu & Gupta 2015). Deaconu & Gupta (2015) did not use replicates within their study. They also did not account for the absorption of water by aggregate. The results within this study compare appropriately with other studies, indicating that the results are of sufficient quality. According to ASTM C 39, strength is not an intrinsic property of concrete. Aggregate proportions, aggregate type, the mixing process, and ambient conditions all affect strength.

Effect of curing method

Compressive strength

On average, over the two water content groups, wet curing produced 27% stronger concrete than dry curing

($p < 0.0001$). The difference between the curing methods is due to the difference in relative humidity. Water is essential for the hydration reaction. Relative humidity controls the vapour-liquid equilibrium within the concrete. As the cement hydrates, water is consumed and the water vapour-liquid equilibrium shifts. In 100% relative humidity, water that reacts with cement is replenished by absorbing water from the atmosphere. At low relative humidity, water is unable to be replenished from the atmosphere and is lost through evaporation (Kosmatka *et al.* 2002). Evaporation can reduce the amount of water available for reaction, thus preventing the concrete from reaching maximal strength. Hydration forms the compounds that are instrumental to concrete strength (Kosmatka *et al.* 2002). Wet curing minimizes the effects of evaporation, and provides sufficient water for hydration. Kosmatka *et al.* (2002) found that maximum strength gain was proportional to the number of days where the concrete was initially moist cured.

Effect on shrinkage

The w/c ratio did not have a significant effect on shrinkage ($p = 0.60$). However, the effect of curing method was significant. At 28 days, shrinkage under wet curing was $- > 0.01 \pm 0.01\%$ ($0.01 \text{ mm/m} \pm 0.01 \text{ mm/m}$), indicating a very slight expansion. Concrete may swell in 100% relative humidity as water vapour from the ambient atmosphere enters the concrete. The swelling is caused by pore pressure but the expansion is very small and generally considered insignificant.

Shrinkage under dry curing was a $0.05\% \pm 0.01\%$ increase in strain ($0.5 \text{ mm/m} \pm 0.01 \text{ mm/m}$) over 28 days, using a 95% confidence interval. Typical shrinkage amounts in the literature are from 0.52 mm/m – 1.04 mm/m (Hover 2005). A crack can form when concrete is stretched beyond 0.08 mm/m or compressed beyond 2.5 mm/m . In a restrained shrinkage situation, shrinkage will cause cracks depending on internal and/or external restraints. For the biosand filter, the mold acts as an external restraint. Different rates of evaporation can lead to non-uniform shrinkage within concrete, creating a differential stress distribution under restrained conditions. The magnitude and direction of compressive and tensile forces is affected by the shrinkage gradient across the concrete body and location of external forces caused by restraints. Depending on the local strength resistance to stress forces, cracks can initiate when external forces overcome internal strength. This study did not directly examine crack initiation under restrained shrinkage; however, minimizing shrinkage should help reduce the formation of stress points within

the concrete body restrained by the mold, thus lowering the probability of crack initiation.

Maintaining a high relative humidity will prevent the surface from drying out, providing the necessary moisture needed to reach maximum strength and minimize shrinkage. However, fog rooms are not available for large-scale production of biosand filters and it is impractical to submerge the filter boxes in a water bath during curing.

To approximate wet curing conditions, the BSF manual advises producers to fill the filter box with water and cover the exterior of the filter box with a damp plastic sheet during curing (CAWST 2012). Following this simple recommendation could reduce the probability of leaks and cracks, as well improving the strength of the produced filters.

CONCLUSIONS

The main goal of this study was to develop recommendations for the slump test as a quality control test, by examining the effect of the water-to-cement ratio and the curing method on strength and shrinkage within the standard CAWST concrete biosand filter mix.

- The water-to-cement ratio with a maximum strength for this mix was 0.51–0.59, equivalent to 8–9.3 L water/filter per full-scale filter, assuming saturated sand and aggregate. More water would be required in drier conditions where aggregate is not saturated.
- The ideal slump range for this mix, after accounting for strength and workability, would be 25–40 mm, corresponding to the higher end of the British Standards Institution's slump category S1. This slump range could be used to indicate that the ideal water-to-cement ratio range had been achieved, regardless of humidity or aggregate saturation, which affects the actual amount of water that needs to be added.
- Wet curing increased strength and decreased shrinkage. Implementers should follow current recommendation of curing the filter under a damp sheet.

Further development of these recommendations is necessary in the field with full-size biosand filters to confirm the laboratory results and adjust to the practicalities of construction in resource-constrained environments.

Implementing the slump test to clarify the ideal amount of water to add to the concrete mix will aid implementers in producing consistently high-strength filters, resulting in the production of high-quality filters for the families that biosand filter implementers serve.

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