Cement and Concrete Composites 74 (2016) 182–190

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Influence of basalt fibres on free and restrained plastic shrinkage

John Branston [a], Sreekanta Das [a, *], Sara Y. Kenno [b], Craig Taylor [b]

[a] University of Windsor, Windsor, Ontario, Canada
[b] MEDA Limited, Windsor, Ontario, Canada

A R T I C L E I N F O

Article history:
Received 1 October 2015
Received in revised form
15 July 2016
Accepted 1 October 2016
Available online 4 October 2016

Keywords:
Basalt fibre
Minibars
Basalt fibre reinforced concrete
Durability
Plastic shrinkage cracking

A B S T R A C T

Early-age cracking due to plastic shrinkage is often attributed to reducing the durability of concrete structures. The objective of this paper is to evaluate the potential use of chopped basalt fibres in preventing these cracks. Testing was undertaken to measure the magnitude of shrinkage strain that develops in unrestrained specimens, and the severity of cracking that occurs when shrinkage is restrained. Results indicate basalt fibres are effective in preventing cracks by reducing the magnitude of free shrinkage, and by restricting the growth of cracks if they do occur. The latter mechanism is more prominent when the w/c ratio is decreased.

1. Introduction

Chopped basalt fibre is a relatively new concrete reinforcing material, with excellent mechanical properties and an environmentally friendly manufacturing process. The majority of research into basalt fibre reinforced concrete has focused on its mechanical properties [1–3]. In these studies, the results do not suggest the fibres are particularly effective in enhancing the post-cracking response of the concrete, which is one of the most significant benefits of fibre reinforcement [4]. Previous research has also indicated basalt fibres without any protective coating suffer from a lack of long-term durability in the alkaline environment of concrete [5,6]. Until this problem is resolved, a useful application of the fibre in its current state of development could be in enhancing the durability of concrete by preventing early-age cracking due to plastic shrinkage. It seems probable the fibres could be effective in this regard before any potential degradation negates their benefit.

Plastic shrinkage refers to the volumetric contraction of cement-based materials that occurs during the first few hours after placement, while the material is in a plastic state. The contraction is driven by a combination of autogenous mechanisms and capillary pressure that develops in the pore structure near the surface when the rate of water evaporating from the concrete exceeds the rate at which it can be replaced by rising bleed water. When restrained, shrinkage will induce tensile stresses. If those stresses exceed the tensile strength of the concrete, it will crack. Restraint is generally present to at least some degree in practical applications by internal factors, such as rebar and aggregate, or by external factors, such as connections to walls and columns. Although initially shallow, plastic shrinkage cracks can grow to full-depth over time [7]. The cracks are not only unsightly, but they allow the penetration of deleterious substances and can lead to the rapid deterioration of structures; most notably the penetration of water and chlorides enabling the corrosion of embedded steel reinforcement. Shrinkage cracking is generally most prominent in structures with a large surface area to volume ratio, including: slabs-on-grade, tunnel linings, and repair overlays. One prominent example is the reduced serviceability of bridge decks due to early-age cracking. A number of reports published from various state departments of transportation (DOTs) in the United States of America suggest that shrinkage is a major contributing factor to early-age cracking [8–11]. In these reports, shrinkage refers to the strain that develops at both an early-age (plastic shrinkage), and over a longer duration after the concrete has hardened (drying shrinkage). However, according to the Transportation Research Board [12], the mechanisms that lead to plastic shrinkage cracks do not explain full depth cracks, and therefore, it is probable drying shrinkage can propagate plastic shrinkage cracks. Since cracks in concrete can propagate at a stress lower than that required to initiate them [13], the control of plastic shrinkage cracking should be a key design consideration in

* Corresponding author.
E-mail address: sdas@uwindsor.ca (S. Das).

http://dx.doi.org/10.1016/j.cemconcomp.2016.10.004
0958-9465/© 2016 Published by Elsevier Ltd.

regards to mitigating cracking at later ages, and in-turn, minimizing long-term maintenance costs.

It has been well established that the addition of short, randomly distributed fibres to concrete is an effective method in mitigating plastic shrinkage cracking. The fibres are effective in this regard for two reasons: first, they reduce the overall shrinkage strains and lower the possibility of tensile stresses exceeding tensile strength, and second, the fibres are able to restrict their development if they do occur [14]. According to Naaman et al. [15], the addition of any fibre with a diameter smaller than 40 μm, an aspect ratio above 200, in volume fractions of 0.2%–0.4%, should effectively eliminate plastic shrinkage cracking in concrete. Hence, it is unsurprising such a wide variety of fibres have been shown to be beneficial in this regard, including: steel, glass, various synthetic fibres (polypropylene, polyethylene, polyvinyl, and carbon), and various natural fibres (sisal, coconut, flax, and cellulose) [15–20]. However, the mechanisms by which different fibres reduce plastic shrinkage strain, and the resultant cracking, is not as thoroughly studied. This is an important consideration in order to understand the circumstances in which the use of a particular type of fibre is most effective.

Only one study, completed by the Florida Department of Transportation (FDOT), could be found in regards to the usefulness of basalt fibres on early-age cracking due to shrinkage. The study concluded that stiff fibres, including basalt, steel, and glass, should not be used for early-age crack control due to drying shrinkage, since it was evident their stiffness initiated cracking sooner, and the cracks were wider [21]. The conclusions were based on the results of the ASTM C1581 [22] test method, in which a steel ring is used as a restraint element. In that case, the poor performance of the stiff fibres may be due to the relatively lower ability of the fibres to bend and align with the circumference of the cracks that develop due to the circumferential shrinkage stress induced by the ring, in comparison with the other more flexible fibres used (e.g. polypropylene). The results in that study may not be a good representation of the effectiveness of basalt fibres in structures with more typical rectangular geometry, where there is greater probability of the fibres bridging cracks in a more favorable orientation. The test method has previously been criticized for producing an unrealistic stress field in regards to repair overlays [14].

The purpose of the experimental work reported in this paper is to evaluate the influence of three different types of basalt fibre on the plastic shrinkage of concrete. The basalt fibres used in this study are: bundle dispersion fibres (BD), filament dispersion fibres (FD) and minibars (MB). The influence of the fibres is quantified by the measurement of strain when the specimens are unrestrained (free shrinkage), and the measurement of crack severity in specimens that are restrained from shrinking with a rectangular restraint element. The primary importance of this study lies in the fact there is minimal literature addressing the usefulness of basalt fibres for early-age crack control in concrete. Secondly, the work provides some insight on test methods for measuring free and restrained plastic shrinkage, for which there seems to be a lack of any one generally accepted test method.

2. Experimental procedure

2.1. Environmental chamber

All testing was completed in an environmental chamber that operated at a temperature of 48 °C (±2 °C) and relative humidity of 15% (±3%). This was achieved by connecting a heater fan to a temperature and humidity controller capable of reading temperature accurate to ±1.5 °C and relative humidity to ±2%. These conditions resulted in an evaporation rate of approximately 0.75 kg/m^2/h. The environmental chamber is depicted in Fig. 1.

2.2. Free shrinkage testing

The test setup for the free (unrestrained) shrinkage testing was developed based on similar methods used by other researchers [23,24]. Concrete specimens were 500 mm in length and 80 mm by 80 mm in cross-section. The interior of the forms were lined with a thick polypropylene sheet (vapour barrier) that was lightly coated with Teflon spray. A Teflon plate was placed at one end of the form with a 9.5 mm diameter bolt threaded into it that extended 30 mm into the form. The Teflon plate was loose fitting so that it could move with minimal resistance. As shrinkage occurred, the plate was moved by the bond between the bolt and the concrete. The displacement of the plate was measured with a 5 mm linear variable differential transformer (LVDT) that was accurate to 5 μm. A 25 mm thick piece of foam was placed behind the Teflon plate so that movement due to thermal expansion was also possible. The forms were placed in the environmental chamber and data was collected for 4 h. Free shrinkage test results reported in this study are the mean values calculated based on three specimens per fibre dosage. The setup is illustrated in Fig. 2.

2.3. Restrained shrinkage testing

The test setup for restrained shrinkage testing closely followed

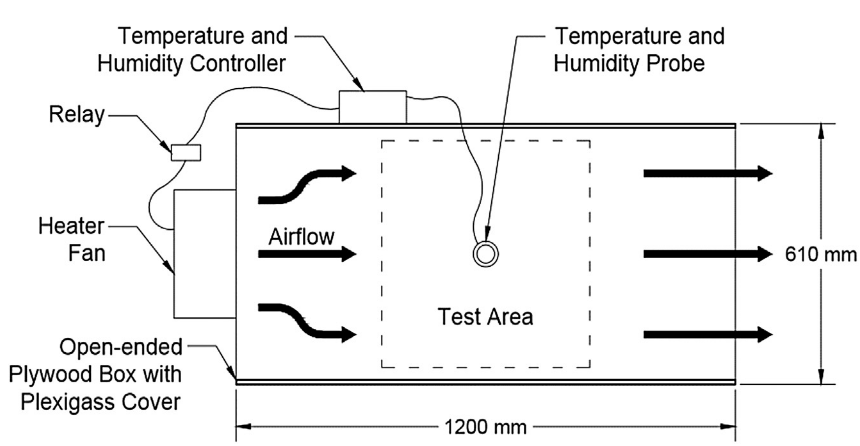


Fig. 1. Environmental chamber.

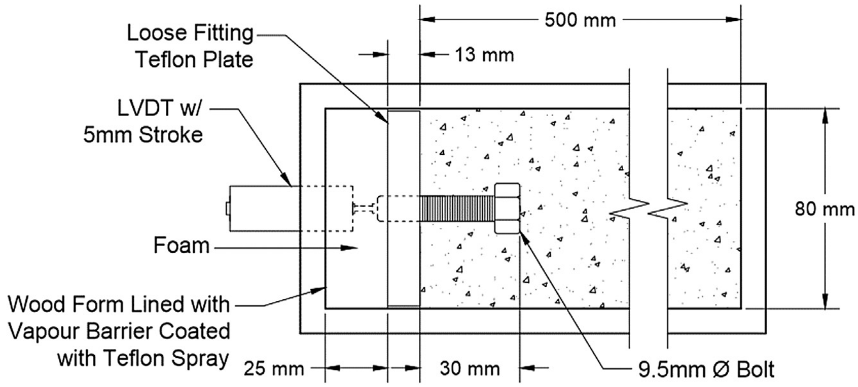


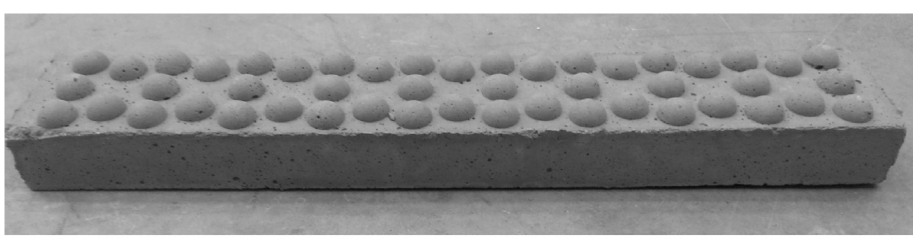
Fig. 2. Free plastic shrinkage test setup.

the method proposed by Banthia and Gupta [14], with two exceptions: the length of the restraint element (Fig. 3a) was increased from 300 mm to 500 mm to match that of the free shrinkage testing, and the thickness of the mortar overlay was reduced from 60 mm to 35 mm to represent a typical concrete cover for the application of the results directly to a rehabilitation project in the field. The restraint elements had an average 28 day compressive strength of approximately 60 MPa. The mortar overlay was placed over the restraint element and then the form was placed in the environmental chamber. The form was carefully removed after 1.5 h in order to increase the exposed surface area of the concrete, and in-turn, the severity of the cracking. Fig. 3b depicts the development of cracks after removing the specimen from the environmental chamber after a total of 4 h. The cracks were measured using a 240× magnification digital microscope. The total area of all cracks on the surface for each specimen was measured, and the largest crack width was recorded. Restrained shrinkage test results reported in this study are the mean values calculated based on three specimens per fibre dosage.

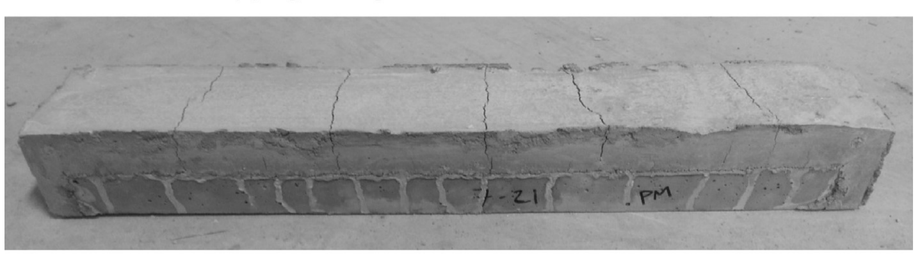
2.4. Materials and specimen preparation

All mixes were made with general use limestone (GUL) Portland cement conforming to CSA A3001 [25], and regular drinking water. Fine aggregate was local river sand with a fineness modulus of 2.7, and the coarse aggregate was well-graded with a maximum size of 19 mm. The cement had a Blaine fineness of 488 m^2/kg, and consisted of 9.5% limestone (94% $CaCO_3$ in limestone). The chemical composition of the cement can be found in Table 1.

The cement fineness and chemical composition have a direct influence on shrinkage, and are further discussed in section 3.2. Mortar was generally used in this study to increase the magnitude of shrinkage strain and in-turn, cracking severity, so that the influence of the fibre could be more readily measured. Table 2 shows



(a) High-strength concrete restraint element



(b) 35 mm thick mortar overlay after four hours in environmental chamber

Fig. 3. Restrained shrinkage testing.

Table 1
Portland cement type GUL chemical composition (%).

Loss on ignition	SiO_2	Fe_2O_3	Al_2O_3	CaO	Free CaO	MgO	SO_3	K_2O	Na_2O	TiO_2
4.8	18.2	2.76	4.5	62.3	1.5	3.1	3.47	0.45	0.22	0.21

Note: Chemical composition as provided by manufacturer.

Table 2
Mass proportions of concrete mixes used.

Designation	Cement	Water	Fine Aggregate	Coarse Aggregate	Super-plasticizer	Description
M1	1	0.5	2	0	0	Control mix
M2	1	0.35	2	0	varied	Low w/c ratio
M3	1	0.5	2	2	0	Add coarse aggregate
M4	1	0.5	1	0	0	Increased cracking
M5	1	0.35	1	0	varied	Low w/c ratio

the proportions (by mass) of each type of mix used in this work, along with a description indicating the purpose of the mix.

Cement to sand proportions of 1:2 (M1 and M2) and 1:1 (M4 and M5) were selected in an attempt to produce results comparable to other researchers using different fibres [17,20,24,26]. A w/c ratio of 0.5 was selected as a control to produce a mix with a high flow. For that reason, the mix would generally not be used in practical applications. However, it is useful for laboratory testing since it results in high shrinkage strain and promotes cracking, which makes the effect of the fibres easier to measure. The purpose of reducing the w/c ratio was for insight on the benefit of the fibres in a more realistic setting, where it is almost certain their effect on workability will need to be accounted for with the use of superplasticizer. Consequently, the effect of superplasticizer in this context should also be studied. Superplasticizer dosages in Table 2 listed as 'varied' refers to the increasing dosages required to produce an equivalent flow for increasing fibre dosages. It is well understood that fibres have an adverse effect on the flow (or workability) of concrete, and thus, greater quantities of superplasticizer were required as fibre dosages increased (further explained in section 3.1). Likewise, the effect of the fibres in a concrete mix with coarse aggregate (M3) is also considered as additional way of producing data more representative of actual application.

Three types of basalt fibre were evaluated: filament dispersion (FD), bundle dispersion (BD) and minibars (MB). Filament dispersion fibres disperse into individual filaments during mixing, whereas bundle dispersion fibres have a coating (sizing) that keeps the filaments together as a bundle. Minibars are an epoxy based polymer reinforced with basalt filaments; essentially a scaled down version of basalt fibre reinforced polymer rebar. These differences are depicted in Fig. 4.

The filament and bundle dispersion fibres consist of filaments 16 μm in diameter, and the minibars are constructed with filaments 17 μm in diameter. A summary of the fibre dosages used in this study is shown in Table 3. Designations are labelled according to fibre type, fibre length, and dosage. For example, the designation BD-25-0.1 indicates basalt bundle dispersion fibres of 25 mm length at a dosage of 0.1% by volume.

Cement and aggregate was mixed dry for 1 min. Next, fibres were slowly added by hand, and the dry mix continued until total mix time reached 3 min. Water (and plasticizer mixed in with the water as necessary) was then added and the mix continued for another 2 min. In all cases, the fibres dispersed without any noticeable balling or clumping. The flow of the mortar mixes was measured as per ASTM C1437 [27].

Table 3
Fibre dosages and test matrix.

Designation	Fibre type	Length (mm)	Dosage	
			Volume (%)	kg/m^3
PM	No fibre		0	0
BD-25-0.05	Bundle dispersion	25	0.05	1.3
BD-25-0.1			0.1	2.6
BD-25-0.3			0.3	7.8
FD-25-0.05	Filament dispersion	25	0.05	1.3
FD-25-0.1			0.1	2.6
FD-25-0.3			0.3	7.8
FD-12-0.05	Filament dispersion	12	0.05	1.3
FD-12-0.1			0.1	2.6
FD-12-0.3			0.3	7.8
MB-43-0.3	Minibar	43	0.5	6.2
MB-43-1.0			1.0	20

3. Results and discussion

3.1. Mortar flow

The effect of the 25 mm filament dispersion fibres on the flow of the control mix M1, and the reduced w/c ratio max M2, is shown in Table 4, since they had the greatest effect of all fibres tested. In this table, D_i is the initial diameter of the mortar, and D_f is the diameter of the mortar after dropping the plate 25 times within 15 s.

Results for other types of fibre followed the same trend, and thus, are not shown in this table. However, it should be noted that the order from greatest to least in terms of their effect on the flow was: FD-25, FD-12, BD-25, and MB-43. In cases where the mortar spilled off the plate before being dropped 25 times, the flow could not be accurately calculated. The effect of the fibres is evident by the decreasing value of D_i with increasing fibre dosages in M1. The number of drops required to cause the mortar to spill increased from 17 without fibre, to 22 when a fibre dosage of 0.05% was used.

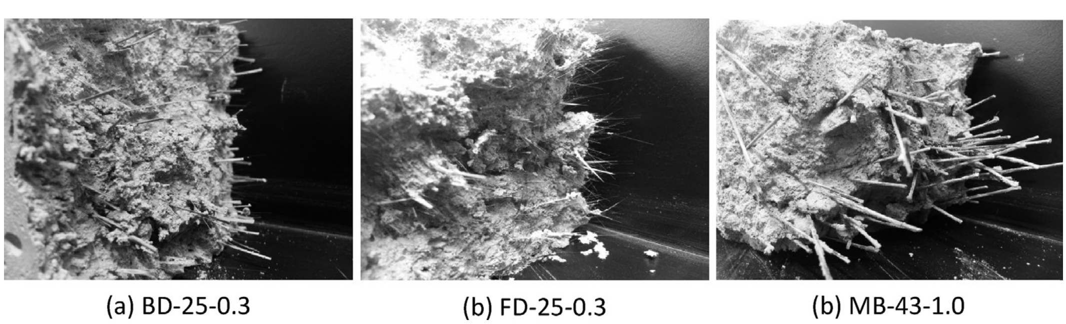


Fig. 4. Difference in dispersion of fibres used in this study.

Table 4
Flow of mortar.

Mix designation	FD-25 dosage (%)	Super-plasticizer (mL)	D_i (mm)	D_f (mm)	Flow (%)
M1	0	0	100	230*	≥130
	0.05	0	90	230*	≥156
	0.1	0	85	230	171
	0.3	0	70	195	179
M2	0	40	75	200	167
	0.05	45	75	200	167
	0.1	60	70	200	186
	0.3	110	70	195	179

Note: * indicates mortar spilled off the plate before 25 drops.

At fibre dosages of 0.1% and 0.3% it did not spill. In the case of M2, superplasticizer was added to each mix in an attempt to produce an equivalent flow for all fibre dosages. To achieve this, greater dosages of superplasticizer were required as fibre dosage increased. The underlying idea being that the most efficient use of materials would be using the smallest amount of superplasticizer to achieve a minimum flow, or workability. In this case, that was a flow of approximately 170%.

3.2. Free plastic shrinkage

Preliminary testing showed that rapid increases in free shrinkage strain occurred after approximately 120 min, and then stopped after approximately 180 min. Shrinkage strains measured after 24 h in several specimens were deemed insignificant in comparison with those occurring in the first few hours, regardless of fibre dosage. Significance in this case is based on the fact that continuing the test for 24 h would not offer further meaningful insight into the discussion or conclusions resulting from this testing. Thus, free shrinkage testing was stopped after 240 min (4 h) for all specimens. Fig. 5 shows the mean values of strain measured over time for M1 specimens reinforced with BD-12, FD-25, and FD-12 fibre at a dosage of 0.1% by volume.

In general, the behaviour depicted in Fig. 5 shows good agreement with the behaviour found by other researchers using similar test methods [17,20,23,24,26]. It should be noted that the strain is not only the result of water loss, but also autogenous mechanisms. During the first few hours of curing, autogenous shrinkage is fully attributed to chemical shrinkage [28]. Chemical shrinkage is based on the difference in volume of cement minerals before and after hydration. The mineral with the greatest reduction in volume, and therefore effect on chemical shrinkage, is C_3A, followed by C_4AF, C_3S, and C_2S [28,29]. The quantity of these minerals in the cement used in this study could be approximated with the use of the Bogue calculation, based on the chemical composition provided in Table 1. Such an analysis may be of interest if studying the effect of fibres in low w/c ratio mixes where autogenous shrinkage mechanisms are more prominent. Moreover, the relatively high fineness of the cement used in this study will increase the rate of chemical shrinkage, but not the magnitude [28,29]. It could be of interest to examine the effect of cement fineness on water demand, with the intent of optimizing workability (e.g. minimizing superplasticizer). Notwithstanding the mechanisms causing shrinkage, further discussion will focus on the relative influence of the basalt fibres. The mean shrinkage strains after 4 h are depicted in Fig. 6 for all fibre dosages used in the control mix M1. The error bars represent one standard deviation on either side of the mean.

Based on their work with steel fibres, Mangat and Azari [26] suggested that the reduction in shrinkage strain is the result of a frictional force between the fibre-cement interface that restrains the movement of the cement as it slides past the fibres. Experimental results shown in Fig. 6 would strongly agree with this explanation. The increase in contact surface area between fibres and cement when using filament dispersion fibres, as opposed to bundle dispersion fibres or minibars, should theoretically increase frictional resistance, and thus, provides a probable explanation for the results in Fig. 6. Building on this logic, it is not clear as to why the 12 mm filament dispersion fibres had less effect than the 25 mm filament dispersion fibres; though the differences may simply be the result of variation in the data. Reduction in free shrinkage also correlates with the effect on the flow. That is, the effect of each type of fibre ordered from greatest to least is the same for reductions to both flow and free shrinkage.

It was found that the 25 mm filament dispersion fibres produced the greatest reduction on free shrinkage (Fig. 6). Hence, these fibres were used in a low w/c ratio mortar mix (M2), and a concrete mix (M3), to determine if they were still effective in reducing free shrinkage in a more realistic mix. A plot comparing the development of shrinkage strains in M2 and M3, as well as the influence of FD-25-0.3 in both mixes, is shown in Fig. 7. Additionally, the mean shrinkage strains after 4 h are depicted in Fig. 8. The error bars represent one standard deviation on either side of the mean.

In the absence of any fibre, it can be seen from Figs. 7 and 8 that nearly equivalent reductions to the free shrinkage strain from M1 (approximately 2400 micro-strain – Fig. 6) could be achieved by either reducing the water content (M2), or by adding coarse aggregate (M3). In the case of M2, a fibre dosage of 0.3% did not significantly reduce the free shrinkage strain (Figs. 7 and 8a). On the other hand, when that same fibre dosage was used in M3, a significant decrease was found (Figs. 7 and 8b). This difference is most likely due to the addition of superplasticizer to the M2 mixes, which was not present in M3 mixes. It would stand to reason that

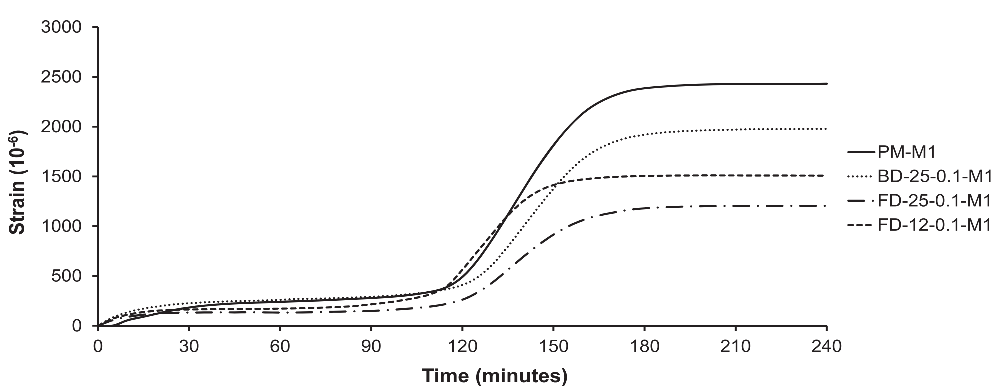


Fig. 5. Mean curves for development of strain over time.

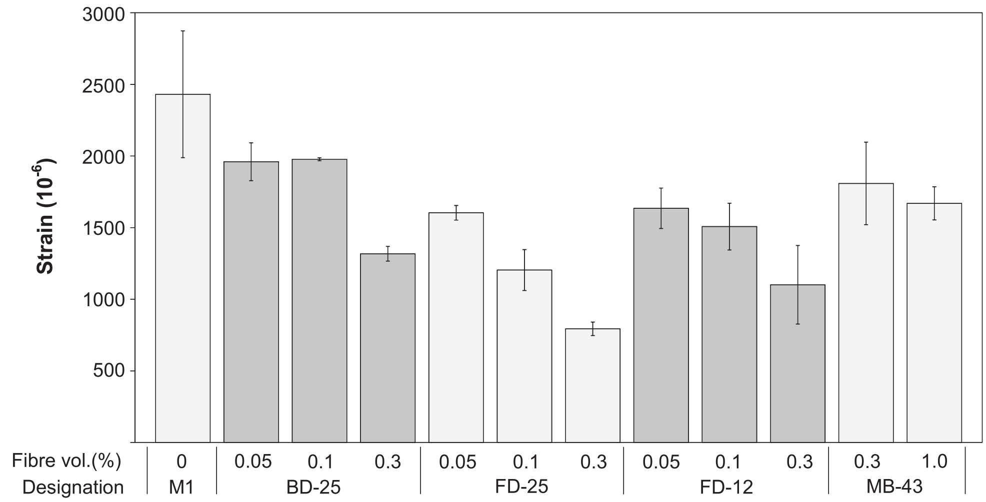


Fig. 6. Mean strain values measured after 4 h in control mix (M1).

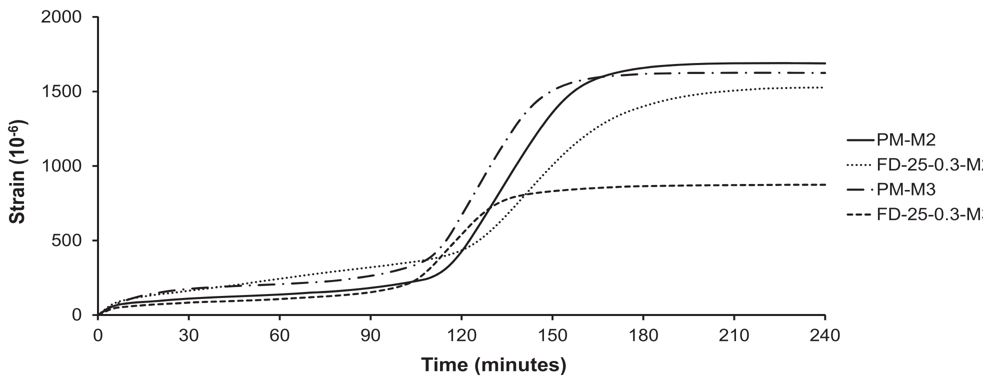


Fig. 7. Comparison between reduced w/c ratio mix (M2) and concrete mix (M3).

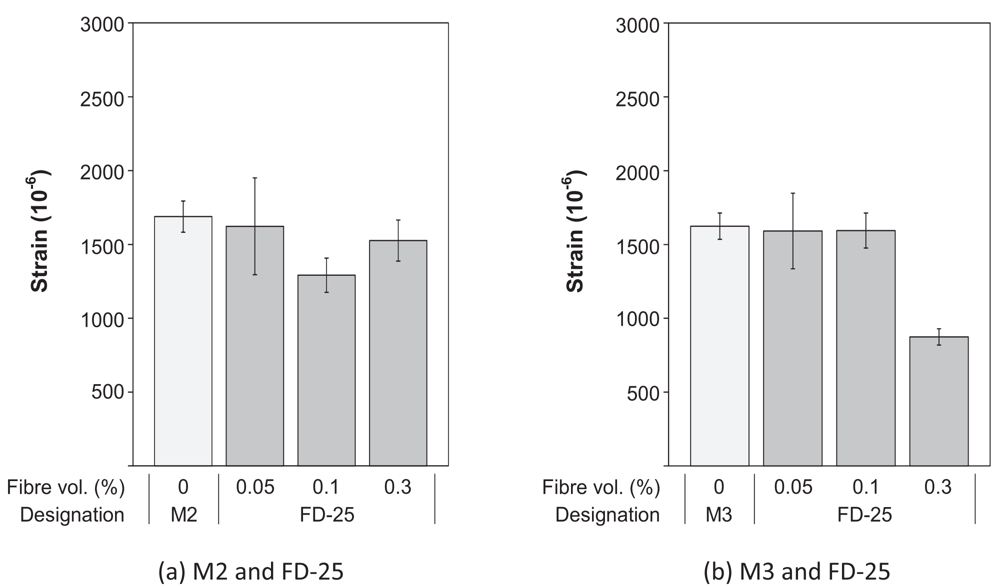


Fig. 8. Mean strain values measured after 4 h.

both the flow and shrinkage of the mortar are strongly influenced by the frictional effects of the fibres. Consequently, adding superplasticizer to the mix so that it is workable seems to negate the benefit of reducing shrinkage strain. Superplasticizer is a key component in concrete mixes with a low w/c ratio (e.g. high-strength concrete). Thus, the addition of fibres in these types of mixes will only be useful if they are effective in bridging shrinkage cracks to restrict their growth.

The FDOT [21] found that the addition of fibres (including basalt) at low dosages (<0.5%) generally did not have a significant effect on the workability of concrete; though it should be noted that marginal decreases in the workability were found with stiffer fibres. Boghossian and Wegner [17] studied the effect of flax, polypropylene, and glass fibres on free shrinkage and found that glass fibres, having a higher elastic modulus than the other fibres, were the only type of fibres to consistently reduce the free shrinkage strain. This may suggest that the use of relatively high-modulus fibres like basalt comes with a trade-off: they are more effective in decreasing the free shrinkage strain, but probably have a more adverse effect on workability than low-modulus fibres (e.g. polypropylene). Wongtanakitcharoen and Naaman [24] expressed the idea that assuming everything else being the same, fibres with a higher elastic modulus should produce greater frictional resistance, and therefore, lead to a greater reduction in free shrinkage strain. However, in their study with carbon, polypropylene, and PVA fibres, the results did not support that idea. That is likely due to the fact that the condition of 'everything else being the same' was not met, since the range of elastic modulus considered was the result of using different materials. Results presented in this paper would suggest it could be possible to predict the reduction fibres have on free shrinkage strain by measuring their effect on the flow, for which related literature suggests the fibre elastic modulus is likely to be a major influencing factor. Although this could perhaps be of interest for future research, the ability of the fibres to prevent shrinkage cracking is most important.

3.3. Restrained shrinkage testing

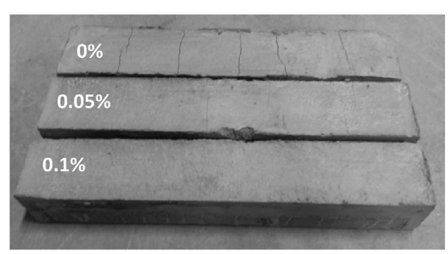
Preliminary testing showed that at the lowest dosage (0.05% by volume), 25 mm filament dispersion fibres completely eliminated shrinkage cracking in the control mix M1. Thus, the amount of fine aggregate was reduced for mix M4, which in-turn increased the unit volume of cement and water. Since plastic shrinkage is largely influenced by the pore pressure of evaporating water, this resulted in greater shrinkage strain and more cracking. In-turn, the effect of the different fibres could be more easily distinguished. Fig. 9 shows the typical appearance of fibre reinforced specimens with varying fibre dosages versus an unreinforced specimen after 4 h. Additionally, the influence of the fibres on the total crack area and largest crack width are shown in Figs. 10 and 11, respectively.

Again, the 25 mm filament dispersion fibres had the greatest effect. In this case, they produced the greatest reduction of the crack area and the crack width. The results from the free shrinkage testing correlated well with both measured parameters: total crack area and largest crack width. In other words, the magnitude of shrinkage strain was very indicative of the crack severity. However, it is clear that the benefit of the fibres is not just because of their ability to reduce free shrinkage strain. The fibres are effective, at least partly, due to their ability to bridge cracks and restrict growth, as shown in Fig. 12.

Further evidence of their ability to restrict crack growth is provided in Fig. 13, in which it can be found that the 25 mm filament dispersion fibres are also effective in reducing the crack area in the low w/c ratio mix M5. Free shrinkage testing revealed that the fibres did not have a significant effect on the reduction in strain when superplasticizer was used to produce an equivalent flow to that of the unreinforced control specimen. Therefore, their effectiveness in this case must be attributed to their ability to restrict the growth of cracks.

The performance of 12 mm filament dispersion fibres was very similar to that of the 25 mm filament dispersion fibres. It is likely the greater bond strength, due to their increased length, makes them more effective in restricting crack growth. Banthia and Gupta [16] reported similar findings in their study on polypropylene fibres. In the case of bundle dispersion fibres and minibars, the fibres were not observed bridging the cracks. This makes sense, since

(a) BD-25



(b) FD-25

Fig. 9. Crack reduction with increasing fibre dosage in M4.

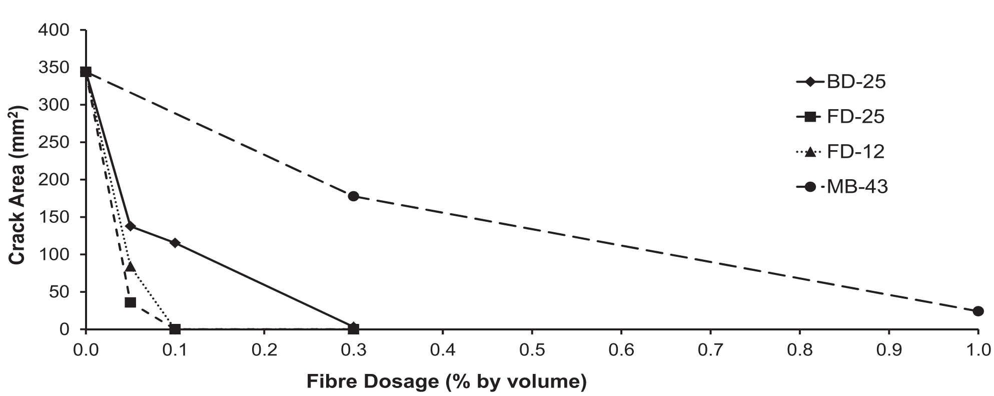


Fig. 10. Effect of fibres on total crack area on specimen surface in M4.

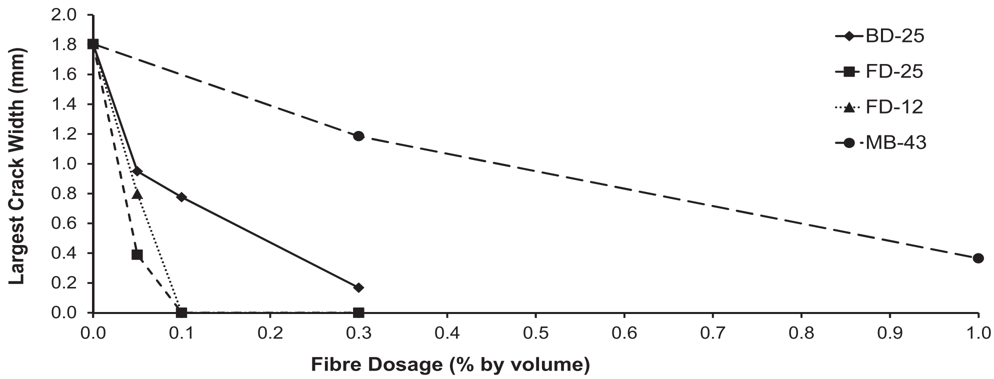
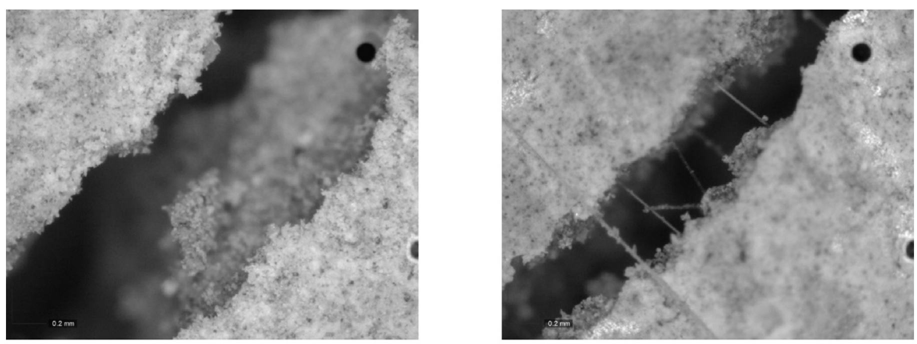


Fig. 11. Effect of fibres on crack width on specimen surface in M4.



(a) M4 (b) FD-25-0.05

Fig. 12. Crack development without fibre (a) and with fibre (b).

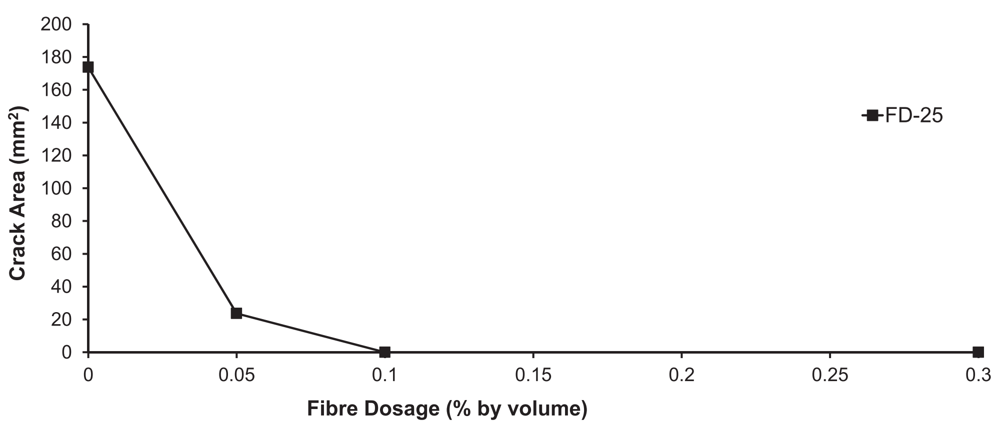


Fig. 13. Effect of FD-25 on crack area in low w/c ratio mix M5.

cracks are more likely to develop where fibres are not present. The filament dispersion fibres cover a much greater area, and therefore, there is a higher probability they will bridge a developing crack.

Restrained shrinkage testing was not undertaken with the concrete mix M3, since the size of the aggregate used relative to the thickness of the overlay was prohibitive. However, it would be reasonable to assume that basalt fibres would have a similar benefit in concrete mixes and this could be of interest to future research. The results of the restrained shrinkage testing in this paper would seem to disagree entirely with those of the FDOT [21], which not only found basalt fibres were ineffective, but detrimental. In that case, crack measurements were taken after 12 and 28 days of curing, and so the results are not directly comparable. However, agreement of results would only be possible in the unlikely case that cracks in fibre reinforced specimens in this work began growing at a faster rate than the unreinforced specimens in the three weeks following testing.

4. Conclusions

The results presented in this paper suggest basalt fibres are effective in mitigating the detrimental effects of plastic shrinkage by reducing the magnitude of the shrinkage strain, and by restricting the growth of cracks if they do occur. As the w/c ratio decreases, it is the latter mechanism that becomes more prominent. However, related literature suggests that high-modulus fibres like basalt have a more severe impact to workability than low-modulus fibres. Therefore, the application of basalt fibres for early-age crack control is likely best suited for general-use concrete, where the w/c ratio is often high enough that the fibres will not require additional measures (and cost) to restore workability. Moreover, they will be more efficient in this scenario due to the ability to simultaneously reduce the shrinkage strain and restrict crack growth. An example of such a mix can be found in a previous study, in which it was shown the addition of basalt filament dispersion fibres did not have a significant effect on the workability of regular-strength concrete (30–35 MPa compressive strength) with a w/c ratio of 0.5 until a dosage of approximately 0.46% by volume [2].

The filament dispersion fibres were most beneficial, likely due to two reasons: an increased surface area resulting in greater frictional restraint, and a greater probability of bridging cracks because of the increased number of uniformly spaced filaments. Moreover, filament dispersion fibres 25 mm in length were more effective than fibres 12 mm in length, although the difference was minor and may be a result of the inherent variability in both test methods applied. Using the filament dispersion fibres, shrinkage cracks were completely eliminated at a dosage of 0.1% by volume in all cases in this study. However, in practical applications, shrinkage cracking could likely be eliminated at even lower fibre dosages, since the environmental conditions and mix proportions used in this study were designed to exaggerate the effects of shrinkage. From a manufacturing point of view, the fibre dosage required to eliminate cracking could likely be decreased further by reducing the diameter of the filaments. This would increase the number of individual filaments and the surface area of the fibres, with respect to the quantity of material.

Although this study has concluded that bundle dispersion fibres and minibars are not optimal for controlling plastic shrinkage cracking, they were still clearly effective, albeit to a lesser extent than the filament dispersion fibres. Therefore, it may be of interest to pursue future research into the use of these fibres as secondary reinforcement with the intent of minor enhancements to both mechanical behaviour and reductions to plastic shrinkage strains and early-age cracking.

Acknowledgements

The authors appreciate the financial assistance received from OCE, NSERC, Connect Canada, and MEDA Limited. The authors also appreciate the technical assistance and donation of materials from MEDA Limited.

References

[1] C. High, H.M. Seliem, A. El-Safty, S.H. Rizkalla, Use of basalt fibers for concrete structures, Constr. Build. Mater. 96 (2015) 37–46.
[2] P. Iyer, S. Kenno, S. Das, Mechanical properties of fiber-reinforced concrete made with basalt filament fibers, J. Mater. Civ. Eng. (2015) 04015015.
[3] C. Jiang, K. Fan, F. Wu, D. Chen, Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete, Mater. Des. 58 (2014) 187–193.
[4] ACI Committee 544, 544.1R-96: Report on Fiber Reinforced Concrete (Reapproved 2009), Technical Documents, 1996.
[5] J.J. Lee, J. Song, H. Kim, Chemical stability of basalt fiber in alkaline solution, Fibers Polym. 15 (11) (2014) 2329–2334.
[6] F. Rabinovich, V. Zueva, L. Makeeva, Stability of basalt fibers in a medium of hydrating cement, Glass Ceram. 58 (11–12) (2001) 431–434.
[7] ACI Committee 224, 224.1R-07: Causes, Evaluation, and Repair of Cracks in Concrete Structures, Technical Documents, 2007.
[8] H.M. Aktan, G. Fu, W. Dekelbab, U. Attanayaka, Investigate Causes & Develop Methods to Minimize Early-age Deck Cracking on Michigan Bridge Decks, 2003.
[9] K. Folliard, C. Smith, G. Sellers, M. Brown, J. Breen, Evaluation of Alternative Materials to Control Drying-shrinkage Cracking in Concrete Bridge Decks, 2003.
[10] M.S. Linford, L.D. Reaveley, A Study of the I-15 Reconstruction Project to Investigate Variables Affecting Bridge Deck Cracking, 2004.
[11] M.A. Saadeghvaziri, R. Hadidi, Cause and Control of Transverse Cracking in Concrete Bridge Decks, 2002.
[12] Transportation Research Board, Control of Cracking in Concrete, Policy Analysis, 2006.
[13] ACI Committee 446, 446.1R-91: Fracture Mechanics of Concrete: Concepts, Models, and Determination of Material Properties (Reapproved 1999), Technical Documents, 1991.
[14] N. Banthia, R. Gupta, Test method for evaluation of plastic shrinkage cracking in fiber-reinforced cementitious materials, Exp. Tech. 31 (6) (2007) 44–48.
[15] A.E. Naaman, T. Wongtanakitcharoen, G. Hauser, Influence of different fibers on plastic shrinkage cracking of concrete, ACI Mater. J. 102 (1) (2005).
[16] N. Banthia, R. Gupta, Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete, Cem. Concr. Res. 36 (7) (2006) 1263–1267.
[17] E. Boghossian, L.D. Wegner, Use of flax fibres to reduce plastic shrinkage cracking in concrete, Cem. Concr. Compos. 30 (10) (2008) 929–937.
[18] H. Shah, J. Weiss, Quantifying shrinkage cracking in fiber reinforced concrete using the ring test, Mater. Struct. 39 (9) (2006) 887–899.
[19] P. Soroushian, S. Ravanbakhsh, Control of plastic shrinkage cracking with specialty cellulose fibers, ACI Mater. J. 95 (4) (1998).
[20] R.D. Toledo Filho, K. Ghavami, M.A. Sanjuán, G.L. England, Free, restrained and drying shrinkage of cement mortar composites reinforced with vegetable fibres, Cem. Concr. Compos. 27 (5) (2005) 537–546.
[21] N. Suksawang, A. Mirmiran, D. Yohannes, Use of Fiber Reinforced Concrete for Concrete Pavement Slab Replacement, 2014.
[22] ASTM C1581, Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage, ASTM International, West Conshohocken, PA, 2009.
[23] D. Myers, T.H.-K. Kang, C. Ramseyer, Early-age properties of polymer fibre-reinforced concrete, ACI Mater. J. 2 (1) (2008) 9–14.
[24] T. Wongtanakitcharoen, A.E. Naaman, Unrestrained early age shrinkage of concrete with polypropylene, PVA, and carbon fibers, Mater. Struct. 40 (3) (2007) 289–300.
[25] CSA, Cementitious Materials Used in Concrete. Mississauga, Ontario, 2013.
[26] P. Mangat, M. Azari, Plastic shrinkage of steel fibre reinforced concrete, Mater. Struct. 23 (3) (1990) 186–195.
[27] ASTM C1437, Standard Test Method for Flow of Hydraulic Cement Mortar, ASTM International, West Conshohocken, PA, 2013.
[28] E.E. Holt, Early Age Autogenous Shrinkage of Concrete, PhD thesis, 2001.
[29] W. Kurdowski, Cement and Concrete Chemistry, Springer, Dordrecht, 2014.