Cement & Concrete Composites 30 (2008) 929–937

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: cate/cemconcomp

Use of flax fibres to reduce plastic shrinkage cracking in concrete

Emma Boghossian [a], Leon D. Wegner [b,*]

[a] *AMEC Americas Limited, Vancouver, British Columbia, Canada*
[b] *Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A9*

a r t i c l e i n f o

Article history:
Received 12 July 2007
Received in revised form 2 September 2008
Accepted 4 September 2008
Available online 12 September 2008

:
Concrete
Fibre reinforcement
Shrinkage
Cracking

An experimental investigation was performed to measure the restrained and unrestrained plastic shrinkage properties of small mortar specimens containing short flax fibres (10–38 mm in length) in amounts ranging from 0.05% to 0.3% by volume. Based on the number of cracks, total crack area, and maximum crack widths produced within the first 24 h after casting and exposure to hot, dry, and windy conditions, flax fibres were found to be slightly more effective in controlling restrained plastic shrinkage cracking than commercially available polypropylene and glass fibres for the mortar mixture studied. At a flax fibre volume fraction of 0.3%, total crack areas were reduced by at least 99.5% relative to plain mortar specimens and maximum crack widths were reduced by at least 98.5% to less than 0.022 mm. Fibre length did not significantly influence cracking behaviour, nor did the presence of flax fibres significantly influence the free plastic shrinkage strains observed.

1. Introduction

It is well-established that during the first few hours after casting, while still in a plastic state, concrete is prone to shrink if the rate at which water evaporates from the surface exceeds the rate at which it is replaced by bleed water from below. When such shrinkage is restrained, for example by an underlying rough granular base in the case of a slab on grade, the concrete will generally crack to relieve the tensile stresses that develop. Such plastic shrinkage cracking may lead to a reduction in the durability of the concrete element.

Ideally, proper curing and finishing practices can eliminate plastic shrinkage cracking. However, such practices are often not reliably followed. Alternatively, the addition of relatively small amounts (i.e. typically less than 0.5% by volume) of short fibres to concrete has been found to significantly reduce, if not completely eliminate, restrained plastic shrinkage cracking [1–4]. The mechanisms by which the fibres achieve a reduction in cracking reportedly include their ability to reduce free plastic shrinkage strains and to increase the early age tensile strength of the concrete [1].

Polymeric fibres such as fibrillated polypropylene or nylon are the most common types of fibres used for this application due to their cost-effectiveness [2]. However, a small number of published studies have shown that fibres derived from natural sources can provide similar benefits. For example, Toledo Filho and Sanjuan [5] found that the addition of 25 mm long sisal fibres at 0.2% by volume reduced free plastic shrinkage strains, and also reduced crack widths in restrained ring-type specimens of cement mortars. Soroushian and Ravanbakhsh [6] have also reported that cellulose fibres at 0.06% volume fraction reduced plastic shrinkage crack area by 78% relative to plain conventional concrete using a slab specimen incorporating stress risers. The use of other natural fibres in concrete, such as those derived from banana and coconut plants [7,8] or from palm leaves [9] has also been reported, but often at relatively high contents (i.e. greater than 1% by volume) and not specifically to control plastic shrinkage cracking.

Natural fibres are an abundant, low-cost, and generally underutilized resource. Often, they are produced as waste by-products of industrial or agricultural processes. In many countries, for example, flax is grown primarily for its oilseed, and the straw is discarded or burned as a waste material. However, the fibre within the straw is one of the most durable and strong natural fibres, making it an ideal candidate for an effective fibre reinforcement in concrete. According to the Food and Agriculture Organization of the United Nations [10] (2005 statistics), oilseed flax (as opposed to fibre flax, which is grown specifically for its fibre and used primarily in the textile industry) is produced in 46 countries on 2.5 million hectares. While 85% of the production occurs in North America and Asia, significant amounts are also grown in both Europe and Africa, making oilseed flax a readily-available source of fibres almost worldwide.

Very little has been reported in the literature on the use of flax fibres in concrete. In one study, high proportions (2–12% by mass) of 2.7 mm long flax fibres were considered as a replacement for asbestos fibres in fibre–cement composites and were found to significantly increase the flexural strength and fracture toughness of

* Corresponding author. Tel.: ; fax: .
E-mail address: leon.wegner@usask.ca (L.D. Wegner).

0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2008.09.003

Cement & Concrete Composites 30 (2008) 929–937

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: cate/cemconcomp

Use of flax fibres to reduce plastic shrinkage cracking in concrete

Emma Boghossian [a], Leon D. Wegner [b,*]

[a] AMEC Americas Limited, Vancouver, British Columbia, Canada
[b] Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A9

ARTICLE INFO

Article history:
Received 12 July 2007
Received in revised form 2 September 2008
Accepted 4 September 2008
Available online 12 September 2008

:
Concrete
Fibre reinforcement
Shrinkage
Cracking

An experimental investigation was performed to measure the restrained and unrestrained plastic shrinkage properties of small mortar specimens containing short flax fibres (10–38 mm in length) in amounts ranging from 0.05% to 0.3% by volume. Based on the number of cracks, total crack area, and maximum crack widths produced within the first 24 h after casting and exposure to hot, dry, and windy conditions, flax fibres were found to be slightly more effective in controlling restrained plastic shrinkage cracking than commercially available polypropylene and glass fibres for the mortar mixture studied. At a flax fibre volume fraction of 0.3%, total crack areas were reduced by at least 99.5% relative to plain mortar specimens and maximum crack widths were reduced by at least 98.5% to less than 0.022 mm. Fibre length did not significantly influence cracking behaviour, nor did the presence of flax fibres significantly influence the free plastic shrinkage strains observed.

1. Introduction

It is well-established that during the first few hours after casting, while still in a plastic state, concrete is prone to shrink if the rate at which water evaporates from the surface exceeds the rate at which it is replaced by bleed water from below. When such shrinkage is restrained, for example by an underlying rough granular base in the case of a slab on grade, the concrete will generally crack to relieve the tensile stresses that develop. Such plastic shrinkage cracking may lead to a reduction in the durability of the concrete element.

Ideally, proper curing and finishing practices can eliminate plastic shrinkage cracking. However, such practices are often not reliably followed. Alternatively, the addition of relatively small amounts (i.e. typically less than 0.5% by volume) of short fibres to concrete has been found to significantly reduce, if not completely eliminate, restrained plastic shrinkage cracking [1–4]. The mechanisms by which the fibres achieve a reduction in cracking reportedly include their ability to reduce free plastic shrinkage strains and to increase the early age tensile strength of the concrete [1].

Polymeric fibres such as fibrillated polypropylene or nylon are the most common types of fibres used for this application due to their cost-effectiveness [2]. However, a small number of published studies have shown that fibres derived from natural sources can provide similar benefits. For example, Toledo Filho and Sanjuan [5] found that the addition of 25 mm long sisal fibres at 0.2% by volume reduced free plastic shrinkage strains, and also reduced crack widths in restrained ring-type specimens of cement mortars. Soroushian and Ravanbakhsh [6] have also reported that cellulose fibres at 0.06% volume fraction reduced plastic shrinkage crack area by 78% relative to plain conventional concrete using a slab specimen incorporating stress risers. The use of other natural fibres in concrete, such as those derived from banana and coconut plants [7,8] or from palm leaves [9] has also been reported, but often at relatively high contents (i.e. greater than 1% by volume) and not specifically to control plastic shrinkage cracking.

Natural fibres are an abundant, low-cost, and generally underutilized resource. Often, they are produced as waste by-products of industrial or agricultural processes. In many countries, for example, flax is grown primarily for its oilseed, and the straw is discarded or burned as a waste material. However, the fibre within the straw is one of the most durable and strong natural fibres, making it an ideal candidate for an effective fibre reinforcement in concrete. According to the Food and Agriculture Organization of the United Nations [10] (2005 statistics), oilseed flax (as opposed to fibre flax, which is grown specifically for its fibre and used primarily in the textile industry) is produced in 46 countries on 2.5 million hectares. While 85% of the production occurs in North America and Asia, significant amounts are also grown in both Europe and Africa, making oilseed flax a readily-available source of fibres almost worldwide.

Very little has been reported in the literature on the use of flax fibres in concrete. In one study, high proportions (2–12% by mass) of 2.7 mm long flax fibres were considered as a replacement for asbestos fibres in fibre–cement composites and were found to significantly increase the flexural strength and fracture toughness of

* Corresponding author. Tel.: ; fax: .
E-mail address: leon.wegner@usask.ca (L.D. Wegner).

0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2008.09.003

cement mortars at the higher fibre amounts [11]. In another study, the addition of flax fibres at a relatively high volume fraction of 5% was reported to improve the compressive strength and flexural toughness of mortar specimens [12]. The consideration of flax fibres at low volume fractions for controlling plastic shrinkage cracking has apparently not been reported in the literature.

The primary objective of the study described in this paper was to measure the restrained plastic shrinkage properties of mortars reinforced with short flax fibres at low volume fractions in order to evaluate their effectiveness in reducing plastic shrinkage cracking. The performance of flax fibres was compared to that of other commercially available synthetic fibres at equal lengths and volume fractions. Unrestrained plastic shrinkage was also measured to determine the degree to which a reduction in free shrinkage associated with fibre addition contributed to a reduction in restrained plastic shrinkage cracking.

2. Experimental program

2.1. Overview

The experimental program was designed to measure both the restrained and unrestrained plastic shrinkage behaviour of fibre reinforced and plain mortar specimens. Mortar was used rather than concrete in order to increase the cracking experienced during restrained tests so as to enhance the ability to compare the performance of flax fibres with that of other fibre types. Restrained plastic shrinkage tests consisted of casting overlays of fibre reinforced mortars over roughened concrete substrate bases, and subjecting the fresh specimens to hot, dry, and windy conditions in an environmental chamber. The test methods employed were based on procedures developed at the University of British Columbia [13,14]. The number, width, and length of surface cracks were measured at regular intervals until crack growth had stabilized. The effects of different fibre types, lengths, and dosages were evaluated.

Unrestrained plastic shrinkage tests consisted of casting specimens of similar plan dimensions to those used for the restrained plastic shrinkage tests, but without the roughened substrate bases. This allowed specimens to contract freely rather than crack, and provided a measure of the influence of fibre addition on the propensity of the mortars to shrink. Specimens were subjected to identical hot, dry, and windy conditions, and free shrinkage strains were measured until they had stabilized.

2.2. Materials and specimen preparation

Fibres derived from flax straw were obtained from SANELINK Corporation (Pointe-Claire, Quebec, Canada) in discrete lengths of 10, 19, and 38 mm. For comparison, 18 and 40 mm long alkali resistant (AR) glass fibres (Cem-FIL HC 62/2, Saint-Gobain Vetrotex, Spain), 19 and 38 mm fibrillated polypropylene fibres (FORTA ECONONET™, FORTA Corporation, Grove City, PA) and 19 mm monofilament polypropylene fibres (FORTA MIGHTY-MONO™) were also investigated. Fibre volume fractions ranged from 0% to 0.3% for each type of fibre, as detailed below. A photograph of the four types of fibres at the 18 or 19 mm lengths is shown in Fig. 1.

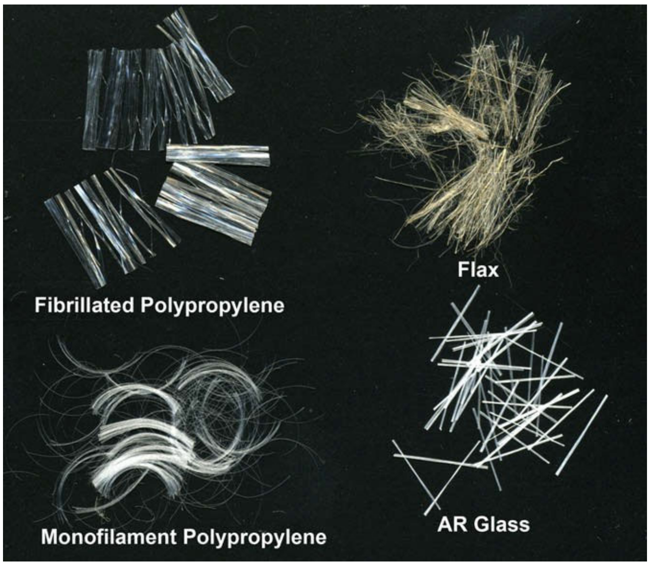

Fig. 1. Photograph of the four types of fibres used at the 18 or 19 mm lengths.

Some of the physical and mechanical properties of the fibres, as derived from manufacturers' literature, materials handbooks, and other literature, are listed in Table 1. One important difference between the flax and synthetic fibres is the propensity of flax fibres to absorb water. In addition, flax fibres may be susceptible to certain degradation mechanisms when exposed to a highly alkaline environment [8,15]. However, the presence, extent, and influence of this potential degradation in a cement paste environment have not yet been determined. It should be noted, though, that since the target application is for the control of plastic shrinkage cracking, the fibres will have performed their function long before they begin to degrade. It is also important to note that the structure of a flax fibre is complex, consisting of fibres and fibre bundles at several different scales [16,17]. The range of flax fibre diameters listed in the table encompasses the most prevalent fibre sizes observed by microscopic examination, and corresponds to the normal size range for elementary fibres, which are single plant cells. However, a nontrivial percentage of fibre bundles with diameters of 200 lm or more were present. These correspond to so-called technical fibres, which comprise bundles of 10–40 elementary fibres bound together by a pectin interface. Some smaller fibres were also observed. No attempt was made to sort the as-received flax fibres or to perform a detailed analysis of fibre sizes.

Both the mix design and the geometrical configuration of the substrate bases were based on work conducted at the University of British Columbia [13]. The bases were prepared 28 days prior to casting the overlays so that sufficient strength would be achieved prior to conducting the restrained plastic shrinkage tests. Mix proportions for the substrate bases, which included Type I Portland cement with 8% interground silica fume, are shown in Table 2. The fine aggregate was clean river sand, and the coarse aggregate had a maximum size of 10 mm. Dimensions of the substrates were 95   325 mm in plan and 40 mm thick.

In order to maintain a well controlled and consistent surface roughness (i.e. uniform restraint conditions for the overlays), bases were cast in PVC moulds with a regular pattern of hemispherical depressions, 20 mm in diameter, machined into the bottom surface. The resulting bases thus had a regular pattern of hemispherical bumps protruding 10 mm above the surface, as shown in Fig. 2. Two 16 mm diameter steel reinforcing bars were cast longitudinally into each base in order to enhance its stiffness. Bases were demoulded 24 h after casting and immersed in lime-saturated water at 25 C for at least 28 days. One day before placing the overlays, bases were removed from the water and dried overnight in air at approximately 22 C.

Overlay mortar specimens with a total of 24 different combinations of fibre type, length, and volume fraction were prepared and tested. The mix proportions for the overlays are also shown in Table 2 and, except for fibre types, are similar to those reported by cement mortars at the higher fibre amounts [11]. In another study, the addition of flax fibres at a relatively high volume fraction of 5% was reported to improve the compressive strength and flexural toughness of mortar specimens [12]. The consideration of flax fibres at low volume fractions for controlling plastic shrinkage cracking has apparently not been reported in the literature.

The primary objective of the study described in this paper was to measure the restrained plastic shrinkage properties of mortars reinforced with short flax fibres at low volume fractions in order to evaluate their effectiveness in reducing plastic shrinkage cracking. The performance of flax fibres was compared to that of other commercially available synthetic fibres at equal lengths and volume fractions. Unrestrained plastic shrinkage was also measured to determine the degree to which a reduction in free shrinkage associated with fibre addition contributed to a reduction in restrained plastic shrinkage cracking.

2. Experimental program

2.1. Overview

The experimental program was designed to measure both the restrained and unrestrained plastic shrinkage behaviour of fibre reinforced and plain mortar specimens. Mortar was used rather than concrete in order to increase the cracking experienced during restrained tests so as to enhance the ability to compare the performance of flax fibres with that of other fibre types. Restrained plastic shrinkage tests consisted of casting overlays of fibre reinforced mortars over roughened concrete substrate bases, and subjecting the fresh specimens to hot, dry, and windy conditions in an environmental chamber. The test methods employed were based on procedures developed at the University of British Columbia [13,14]. The number, width, and length of surface cracks were measured at regular intervals until crack growth had stabilized. The effects of different fibre types, lengths, and dosages were evaluated.

Unrestrained plastic shrinkage tests consisted of casting specimens of similar plan dimensions to those used for the restrained plastic shrinkage tests, but without the roughened substrate bases. This allowed specimens to contract freely rather than crack, and provided a measure of the influence of fibre addition on the propensity of the mortars to shrink. Specimens were subjected to identical hot, dry, and windy conditions, and free shrinkage strains were measured until they had stabilized.

2.2. Materials and specimen preparation

Fibres derived from flax straw were obtained from SANELINK Corporation (Pointe-Claire, Quebec, Canada) in discrete lengths of 10, 19, and 38 mm. For comparison, 18 and 40 mm long alkali resistant (AR) glass fibres (Cem-FIL® HC 62/2, Saint-Gobain Vetrotex, Spain), 19 and 38 mm fibrillated polypropylene fibres (FORTA® ECONONET™, FORTA Corporation, Grove City, PA) and 19 mm monofilament polypropylene fibres (FORTA® MIGHTY-MONO™) were also investigated. Fibre volume fractions ranged from 0% to 0.3% for each type of fibre, as detailed below. A photograph of the four types of fibres at the 18 or 19 mm lengths is shown in Fig. 1.

Some of the physical and mechanical properties of the fibres, as derived from manufacturers' literature, materials handbooks, and other literature, are listed in Table 1. One important difference between the flax and synthetic fibres is the propensity of flax fibres to absorb water. In addition, flax fibres may be susceptible to certain degradation mechanisms when exposed to a highly alkaline environment [8,15]. However, the presence, extent, and influence of

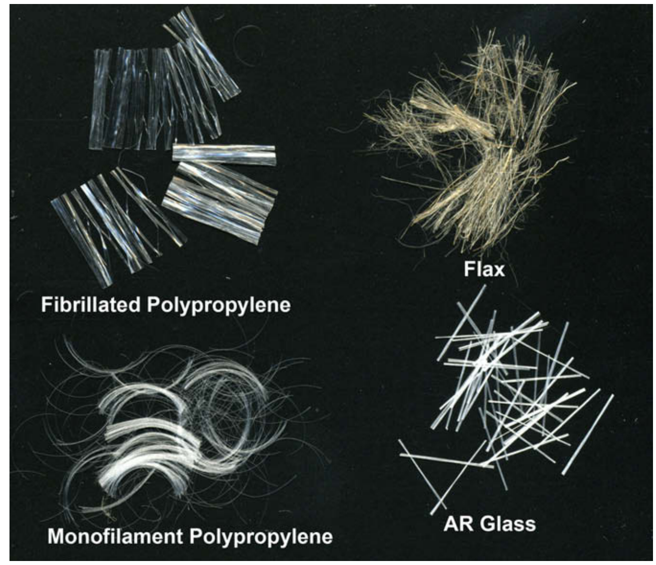

Fig. 1. Photograph of the four types of fibres used at the 18 or 19 mm lengths.

this potential degradation in a cement paste environment have not yet been determined. It should be noted, though, that since the target application is for the control of plastic shrinkage cracking, the fibres will have performed their function long before they begin to degrade. It is also important to note that the structure of a flax fibre is complex, consisting of fibres and fibre bundles at several different scales [16,17]. The range of flax fibre diameters listed in the table encompasses the most prevalent fibre sizes observed by microscopic examination, and corresponds to the normal size range for elementary fibres, which are single plant cells. However, a nontrivial percentage of fibre bundles with diameters of 200 μm or more were present. These correspond to so-called technical fibres, which comprise bundles of 10–40 elementary fibres bound together by a pectin interface. Some smaller fibres were also observed. No attempt was made to sort the as-received flax fibres or to perform a detailed analysis of fibre sizes.

Both the mix design and the geometrical configuration of the substrate bases were based on work conducted at the University of British Columbia [13]. The bases were prepared 28 days prior to casting the overlays so that sufficient strength would be achieved prior to conducting the restrained plastic shrinkage tests. Mix proportions for the substrate bases, which included Type I Portland cement with 8% interground silica fume, are shown in Table 2. The fine aggregate was clean river sand, and the coarse aggregate had a maximum size of 10 mm. Dimensions of the substrates were 95 × 325 mm in plan and 40 mm thick.

In order to maintain a well controlled and consistent surface roughness (i.e. uniform restraint conditions for the overlays), bases were cast in PVC moulds with a regular pattern of hemispherical depressions, 20 mm in diameter, machined into the bottom surface. The resulting bases thus had a regular pattern of hemispherical bumps protruding 10 mm above the surface, as shown in Fig. 2. Two 16 mm diameter steel reinforcing bars were cast longitudinally into each base in order to enhance its stiffness. Bases were demoulded 24 h after casting and immersed in lime-saturated water at 25 °C for at least 28 days. One day before placing the overlays, bases were removed from the water and dried overnight in air at approximately 22 °C.

Overlay mortar specimens with a total of 24 different combinations of fibre type, length, and volume fraction were prepared and tested. The mix proportions for the overlays are also shown in Table 2 and, except for fibre types, are similar to those reported by

Table 1
Properties of fibres

Fibre type	Length (mm)	Diameter (μm)	Relative density	Tensile strength (MPa)	Elastic modulus (GPa)	Strain at failure (%)	Water absorption (%)
Flax	10 19 38	10–60	1.52 [18]	840 [18]–1500 [16]	50 [16]–100 [18]	1.8 [18]	95
Monofilament polypropylene	19	52	0.91[a]	620–758[a]	4–5 [19]	N/A	0
Fibrillated polypropylene	19 38	N/A	0.91[a]	620–758[a]	4–5 [19]	8–10 [19]	0
Glass	18 40	200[b]	2.68[a]	1700[a]	72[a]	4.5[a]	0

[a] As reported by manufacturer.
[b] Glass fibres had a flattened cross section. Number given is diameter for equivalent surface area.

Banthia and Yan [14]. A relatively rich mix incorporating Type I Portland cement with 8% interground silica fume was used to increase the propensity for cracking. The influence of the binder system was not investigated as part of this work, as the primary focus was on the performance of the flax fibres relative to other fibre types, and so a single mortar mix was used for all specimens. Coarse aggregates were omitted to eliminate their reinforcing influence on the mortar and promote the development of cracks so as to facilitate the comparison of cracking between specimens. The influence of flax fibres at three lengths (10, 19 and 38 mm) and three volume fractions (0.05%, 0.10%, and 0.30%) was evaluated and compared to the other three fibre types at similar dosages. A minimum of four and a maximum of six specimens of each combination of variables were tested, resulting in a total of 140 specimens, including plain control specimens. These were tested in 20 batches of seven specimens, each batch consisting of overlays incorporating one fibre type and length with two specimens at each volume fraction, plus one plain control specimen. Batches were prepared by first dry mixing the interground cement and sand for 2–3 min and then adding the water and mixing for another 2 min. Plain specimens were then cast. Enough fibres to produce a volume fraction of 0.05% by volume were added and these specimens were cast. This was followed by two subsequent fibre addition and casting steps to produce specimens with fibre volume fractions of 0.1% and 0.3%. This procedure allowed specimens with the full range of fibre volume fractions to be cast with the same batch of mortar, minimizing differences in mortar properties.

Table 2
Mix proportions (by mass) for mortar overlays and substrate bases

Ingredient	Overlay mortars	Substrate bases
Cement (8% silica fume)	1.00	1.00
Water	0.46	0.28
Sand	0.95	1.36
Coarse aggregate	–	1.36
Superplasticizer	–	3 mL/kg
Fibres	Varied	–

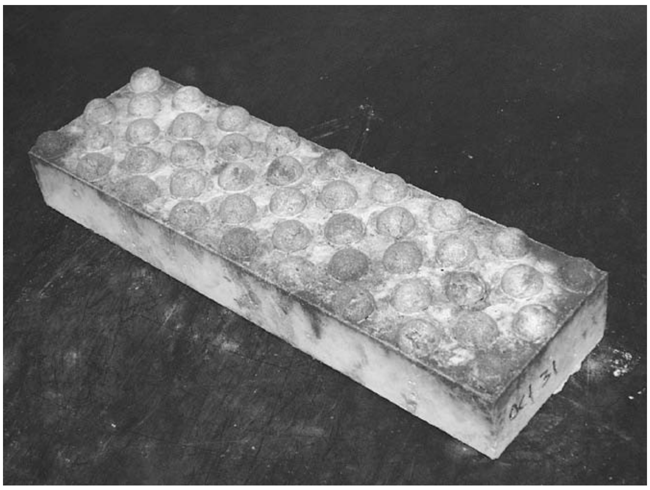

Fig. 2. Photograph of a substrate base, showing the regular pattern of hemispherical protrusions.

Overlay mortars 60 mm thick were cast over the substrate bases, which had been centered in the bottom of PVC moulds 100 mm 375 mm in plan and 100 mm deep. Specimens were vibrated on a vibrating table for approximately 1 min and surfaces were lightly troweled to produce a relatively smooth surface on which crack sizes could be accurately measured. Specimens were then immediately transferred into the environmental chamber (described below) for testing. Approximately 10 min later, moulds were removed using quick release levers, taking care not to disturb the fresh mortar.

2.3. Environmental chamber and test procedures

A schematic drawing of the environmental chamber used for the study is shown in Fig. 3. The 3 3 m chamber was constructed of wood framing and OSB sheathing and was insulated and sealed from the surrounding laboratory environment. It housed two specially constructed wind tunnels, each of which could accommodate four specimens. A removable Plexiglas lid in each wind tunnel permitted easy positioning of the specimens and allowed access to them during testing. Air from the surrounding laboratory was drawn into the chamber through an opening in the wall, and was forced to pass through three 4800 W heaters before entering the wind tunnels. The outlets of the wind tunnels passed through the chamber wall and were connected directly to the exhaust ventilation system for the building in which the laboratory was housed. The exhaust fan, mounted on the roof of the building, was capable of drawing approximately 42 m^3/min and provided the primary source of air draw for the system. A box fan was provided at the inlet to the chamber to assist in the movement of air.

Temperature and relative humidity were continuously monitored using a relative humidity sensor connected to a PC based data acquisition system. Temperature was measured with an accuracy of ±0.6 C and relative humidity with an accuracy of ±2%. Steady state conditions of 45 ± 2 C and less than 3% relative humidity were achieved using this system. The wind speed in both wind tunnels across the surfaces of specimens was measured to be

Table 1
Properties of fibres

Fibre type	Length (mm)	Diameter (μm)	Relative density	Tensile strength (MPa)	Elastic modulus (GPa)	Strain at failure (%)	Water absorption (%)
Flax	10 19 38	10–60	1.52 [18]	840 [18]–1500 [16]	50 [16]–100 [18]	1.8 [18]	95
Monofilament polypropylene	19	52	0.91[a]	620–758[a]	4–5 [19]	N/A	0
Fibrillated polypropylene	19 38	N/A	0.91[a]	620–758[a]	4–5 [19]	8–10 [19]	0
Glass	18 40	200[b]	2.68[a]	1700[a]	72[a]	4.5[a]	0

[a] As reported by manufacturer.
[b] Glass fibres had a flattened cross section. Number given is diameter for equivalent surface area.

Banthia and Yan [14]. A relatively rich mix incorporating Type I Portland cement with 8% interground silica fume was used to increase the propensity for cracking. The influence of the binder system was not investigated as part of this work, as the primary focus was on the performance of the flax fibres relative to other fibre types, and so a single mortar mix was used for all specimens. Coarse aggregates were omitted to eliminate their reinforcing influence on the mortar and promote the development of cracks so as to facilitate the comparison of cracking between specimens.

The influence of flax fibres at three lengths (10, 19 and 38 mm) and three volume fractions (0.05%, 0.10%, and 0.30%) was evaluated and compared to the other three fibre types at similar dosages. A minimum of four and a maximum of six specimens of each combination of variables were tested, resulting in a total of 140 specimens, including plain control specimens. These were tested in 20 batches of seven specimens, each batch consisting of overlays incorporating one fibre type and length with two specimens at each volume fraction, plus one plain control specimen. Batches were prepared by first dry mixing the interground cement and sand for 2–3 min and then adding the water and mixing for another 2 min. Plain specimens were then cast. Enough fibres to produce a volume fraction of 0.05% by volume were added and these specimens were cast. This was followed by two subsequent fibre addition and casting steps to produce specimens with fibre volume fractions of 0.1% and 0.3%. This procedure allowed specimens with the full range of fibre volume fractions to be cast with the same batch of mortar, minimizing differences in mortar properties.

Table 2
Mix proportions (by mass) for mortar overlays and substrate bases

Ingredient	Overlay mortars	Substrate bases
Cement (8% silica fume)	1.00	1.00
Water	0.46	0.28
Sand	0.95	1.36
Coarse aggregate	–	1.36
Superplasticizer	–	3 mL/kg
Fibres	Varied	–

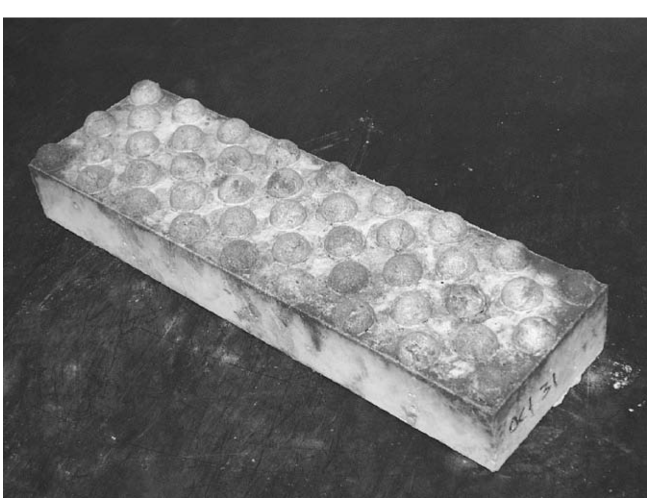

Fig. 2. Photograph of a substrate base, showing the regular pattern of hemispherical protrusions.

Overlay mortars 60 mm thick were cast over the substrate bases, which had been centered in the bottom of PVC moulds 100 mm × 375 mm in plan and 100 mm deep. Specimens were vibrated on a vibrating table for approximately 1 min and surfaces were lightly troweled to produce a relatively smooth surface on which crack sizes could be accurately measured. Specimens were then immediately transferred into the environmental chamber (described below) for testing. Approximately 10 min later, moulds were removed using quick release levers, taking care not to disturb the fresh mortar.

2.3. Environmental chamber and test procedures

A schematic drawing of the environmental chamber used for the study is shown in Fig. 3. The 3 × 3 m chamber was constructed of wood framing and OSB sheathing and was insulated and sealed from the surrounding laboratory environment. It housed two specially constructed wind tunnels, each of which could accommodate four specimens. A removable Plexiglas lid in each wind tunnel permitted easy positioning of the specimens and allowed access to them during testing. Air from the surrounding laboratory was drawn into the chamber through an opening in the wall, and was forced to pass through three 4800 W heaters before entering the wind tunnels. The outlets of the wind tunnels passed through the chamber wall and were connected directly to the exhaust ventilation system for the building in which the laboratory was housed. The exhaust fan, mounted on the roof of the building, was capable of drawing approximately 42 m^3/min and provided the primary source of air draw for the system. A box fan was provided at the inlet to the chamber to assist in the movement of air.

Temperature and relative humidity were continuously monitored using a relative humidity sensor connected to a PC based data acquisition system. Temperature was measured with an accuracy of ±0.6 °C and relative humidity with an accuracy of ±2%. Steady state conditions of 45 ± 2 °C and less than 3% relative humidity were achieved using this system. The wind speed in both wind tunnels across the surfaces of specimens was measured to be

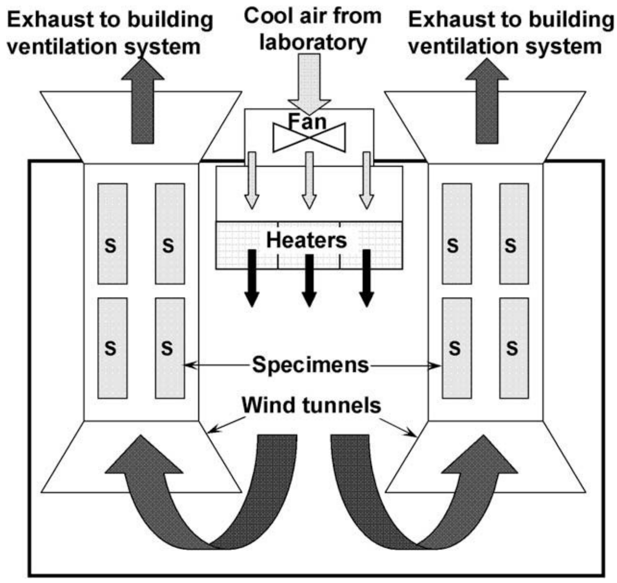

Fig. 3. Schematic plan view of the environmental chamber test setup.

approximately 3.7 km/h using a hand-held anemometer. These conditions produced an evaporation rate of approximately 1.0 kg/m²/h from the free surface of a tray of water.

Specimens remained in the chamber for approximately 24 h, after which the length and width of cracks were measured. Crack lengths were measured to the nearest 1 mm with the aid of string, which was capable of following crack paths. Crack widths were measured to the nearest 0.01 mm at three different points along the length of each crack with the aid of a hand-held 50 micro-scope. The smallest crack that was capable of being detected was 0.005 mm in width. Crack widths smaller than 0.01 mm were assumed to be 0.005 mm for calculation of crack areas. Maximum crack width, total crack area (calculated as the sum of the products of length and average width of all cracks), and number of cracks were recorded for each specimen.

2.4. Unrestrained plastic shrinkage tests

Unrestrained plastic shrinkage tests differed from the restrained shrinkage tests in that substrate bases were not used. Instead, mortar specimens were cast in the 100 375 100 mm deep moulds, which were lined with oiled polyethylene sheets to minimize restraint. Fresh specimens were placed in the wind tunnels under conditions identical to those described above, and moulds were removed 10 min later. After demoulding, small indented brass plates were positioned on the top surface of specimens, spaced approximately 200 mm apart longitudinally. The distance between plate indentations was measured to the nearest 0.01 mm using a digital caliper at regular intervals for 4–6 h. A final measurement was made 24 h after casting. Four specimens of each combination of fibre type, length, and volume fraction were tested, in addition to 16 plain control specimens, for a total of 112 specimens. Batching procedures were identical to those used for the restrained shrinkage tests.

3. Experimental results and discussion

3.1. Unrestrained plastic shrinkage

Fig. 4 shows the development of free shrinkage strains over a 24 h time period for representative specimens containing a 0.1% volume fraction of flax fibres. As shown, shrinkage strains typically stabilized within the first 4 h after casting. A similar stabilization time was observed for all specimens regardless of fibre type, length, or volume fraction. All results presented hereafter correspond to measurements made 24 h after casting, long after the condition of specimens had stabilized.

Unrestrained (free) plastic shrinkage strains for each of the 24 combinations of fibre type, length, and volume fraction are plotted in Fig. 5. The error bars shown in Fig. 5 correspond to one standard deviation on either side of the mean. Specimens which exhibited shrinkage strains that differed significantly from those of the plain control specimens at the 95% level of confidence are indicated by an asterisk in Fig. 5.

Plain mortar specimens contracted an average of 1.61% in the first 24 h, and exhibited a relatively high variability with a coefficient of variation (COV) of 21%. The addition of flax fibres at all lengths and volume fractions did not have a significant effect on free plastic shrinkage. Other fibre types appear to show a slight reduction in free shrinkage with fibre addition, particularly at higher volume fractions. However, the only fibre type that consistently reduced the plastic shrinkage strains was the glass fibres; in this case, reductions of 20–30% were observed. Based on these re-

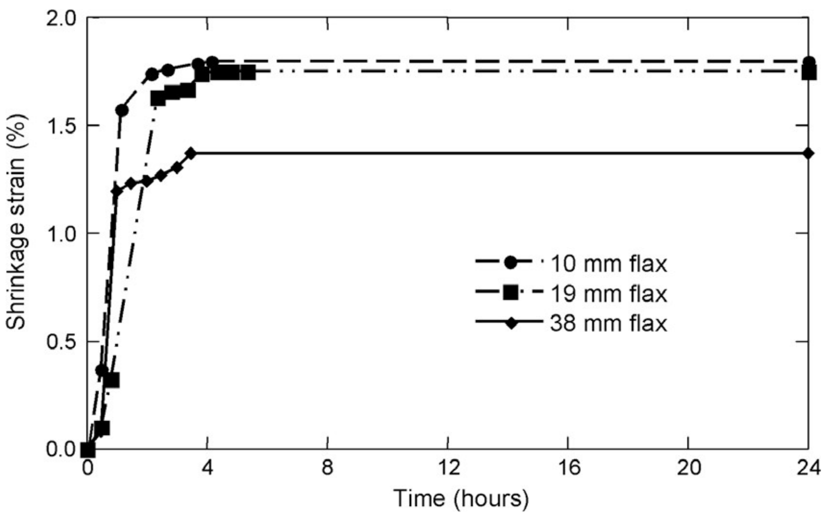

Fig. 4. Development of free shrinkage over time for specimens containing 0.1% volume fraction of flax fibres.

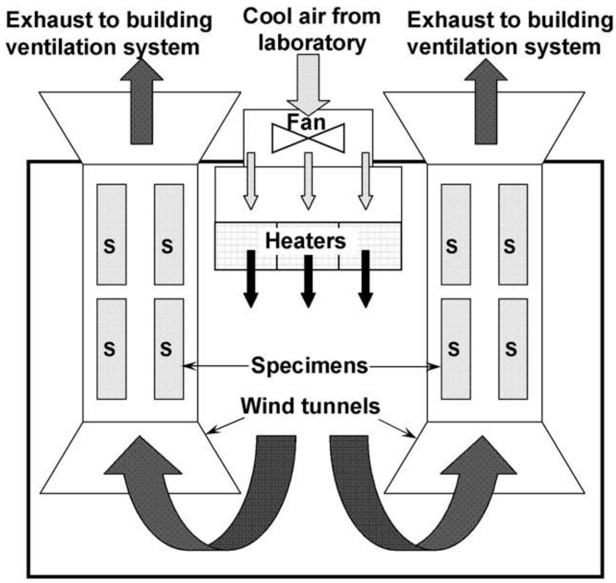

Fig. 3. Schematic plan view of the environmental chamber test setup.

approximately 3.7 km/h using a hand-held anemometer. These conditions produced an evaporation rate of approximately 1.0 kg/m^2/h from the free surface of a tray of water.

Specimens remained in the chamber for approximately 24 h, after which the length and width of cracks were measured. Crack lengths were measured to the nearest 1 mm with the aid of string, which was capable of following crack paths. Crack widths were measured to the nearest 0.01 mm at three different points along the length of each crack with the aid of a hand-held 50× microscope. The smallest crack that was capable of being detected was 0.005 mm in width. Crack widths smaller than 0.01 mm were assumed to be 0.005 mm for calculation of crack areas. Maximum crack width, total crack area (calculated as the sum of the products of length and average width of all cracks), and number of cracks were recorded for each specimen.

2.4. Unrestrained plastic shrinkage tests

Unrestrained plastic shrinkage tests differed from the restrained shrinkage tests in that substrate bases were not used. Instead, mortar specimens were cast in the 100 × 375 × 100 mm deep moulds, which were lined with oiled polyethylene sheets to minimize restraint. Fresh specimens were placed in the wind tunnels under conditions identical to those described above, and moulds were removed 10 min later. After demoulding, small indented brass plates were positioned on the top surface of specimens, spaced approximately 200 mm apart longitudinally. The distance between plate indentations was measured to the nearest 0.01 mm using a digital caliper at regular intervals for 4–6 h. A final measurement was made 24 h after casting. Four specimens of each combination of fibre type, length, and volume fraction were tested, in addition to 16 plain control specimens, for a total of 112 specimens. Batching procedures were identical to those used for the restrained shrinkage tests.

3. Experimental results and discussion

3.1. Unrestrained plastic shrinkage

Fig. 4 shows the development of free shrinkage strains over a 24 h time period for representative specimens containing a 0.1% volume fraction of flax fibres. As shown, shrinkage strains typically stabilized within the first 4 h after casting. A similar stabilization time was observed for all specimens regardless of fibre type, length, or volume fraction. All results presented hereafter correspond to measurements made 24 h after casting, long after the condition of specimens had stabilized.

Unrestrained (free) plastic shrinkage strains for each of the 24 combinations of fibre type, length, and volume fraction are plotted in Fig. 5. The error bars shown in Fig. 5 correspond to one standard deviation on either side of the mean. Specimens which exhibited shrinkage strains that differed significantly from those of the plain control specimens at the 95% level of confidence are indicated by an asterisk in Fig. 5.

Plain mortar specimens contracted an average of 1.61% in the first 24 h, and exhibited a relatively high variability with a coefficient of variation (COV) of 21%. The addition of flax fibres at all lengths and volume fractions did not have a significant effect on free plastic shrinkage. Other fibre types appear to show a slight reduction in free shrinkage with fibre addition, particularly at higher volume fractions. However, the only fibre type that consistently reduced the plastic shrinkage strains was the glass fibres; in this case, reductions of 20–30% were observed. Based on these re-

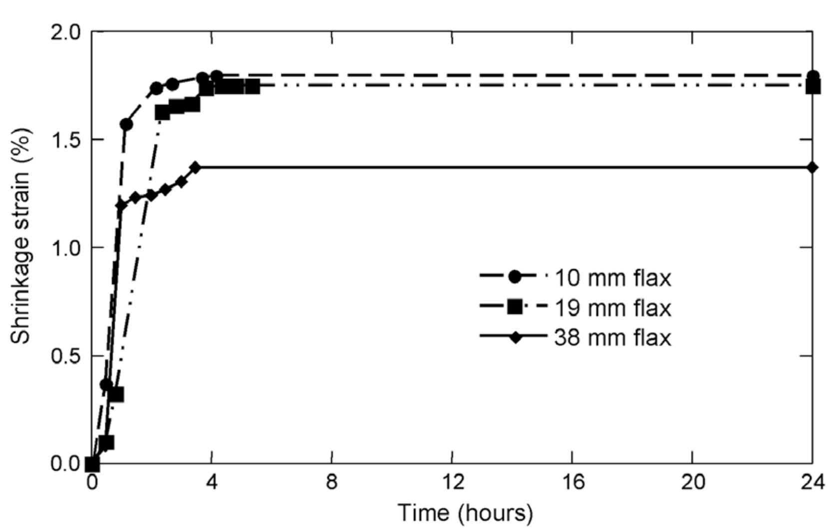

Fig. 4. Development of free shrinkage over time for specimens containing 0.1% volume fraction of flax fibres.

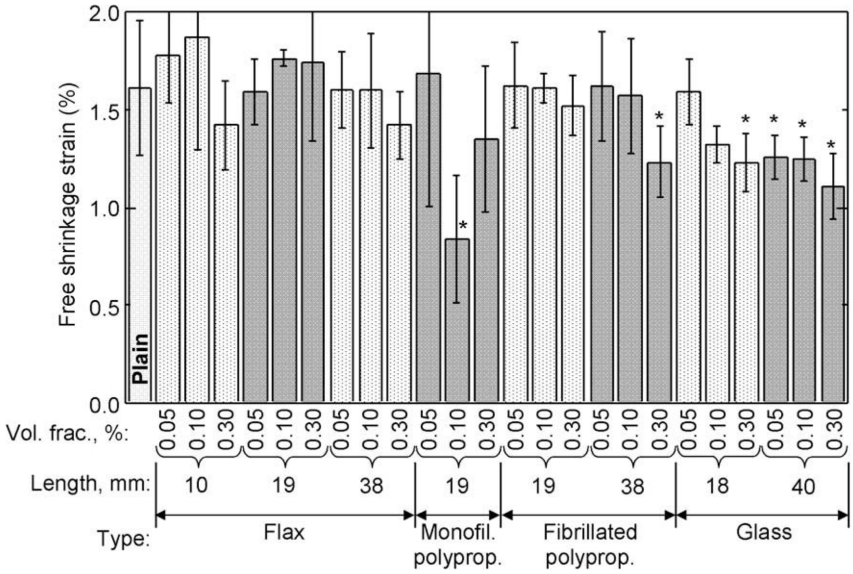

Fig. 5. Measured unrestrained plastic shrinkage strains. Asterisks indicate data points that differed significantly from plain control specimens at the 95% level of confidence.

sults, for fibre types other than glass, any reduction in restrained plastic shrinkage cracking that might be observed with fibre addition, as presented below, cannot be the result of a reduction in the propensity for fibre reinforced specimens to shrink, but must rather be attributed to other mechanisms, namely the increased early age tensile capacity of mortars containing fibres and the ability of the fibres to restrict the growth of cracks that do form.

3.2. Restrained plastic shrinkage cracking

Measured crack properties for restrained plastic shrinkage tests for each of the 24 combinations of fibre type, length, and volume fraction are given in Table 3. A relatively high variability in the number and size of cracks was experienced for these tests, as manifested by the high values for coefficient of variation in many cases.

Table 3
Summary of restrained plastic shrinkage test results

Fibre type	Fibre length (mm)	Volume fraction (%)	No.[a]	No. of cracks	Maximum crack width (mm)	Total crack area (mm^2)
Plain	–	–	20	10.4 [35.2][b]	1.823 [33.9]	212 [24.8]
Flax	10	0.05	4	14.0 [5.8]	0.608 [90.0]	56.0 [113]
		0.10	4	11.5 [8.7]	0.160 [101]	9.27 [113]
		0.30	4	7.5 [25.5]	0.010[c] [0.0]	0.14 [22.1]
	19	0.05	4	12.5 [19.0]	0.380 [22.7]	30.9 [24.0]
		0.10	4	9.3 [31.1]	0.173 [25.2]	6.44 [49.2]
		0.30	4	6.0 [13.6]	0.015 [38.5]	0.79 [146]
	38	0.05	6	11.0 [12.9]	0.847 [56.3]	62.1 [44.8]
		0.10	6	9.2 [12.8]	0.098 [39.3]	3.81 [68.6]
		0.30	6	7.3 [33.0]	0.022 [49.8][d]	0.38 [82.5][d]
Monofil. polyprop.	19	0.05	4	10.8 [15.9]	1.193 [12.4]	105 [9.9]
		0.10	4	10.3 [26.9]	0.313 [25.0]	11.1 [33.8]
		0.30	4	10.0 [14.1]	0.025 [69.3]	0.28 [20.1]
Fibrillated polyprop.	19	0.05	4	18.0 [22.7]	0.988 [47.8]	76.3 [64.6]
		0.10	4	16.3 [18.4]	0.185 [80.1]	9.51 [108]
		0.30	4	11.5 [11.2]	0.015 [38.5]	0.29 [26.0]
	38	0.05	6	19.3 [23.7]	0.802 [35.1]	49.9 [44.3]
		0.10	6	15.7 [10.4]	0.170 [44.0]	8.40 [64.5]
		0.30	6	14.5 [16.2]	0.014 [35.0]	0.43 [37.2]
AR glass	18	0.05	6	16.7 [6.2]	0.733 [11.7]	56.2 [27.2]
		0.10	6	13.5 [16.1]	0.011 [9.8][d]	0.32 [24.6][d]
		0.30	6	13.7 [34.5]	0.011 [10.1][d]	0.27 [20.2][d]
	40	0.05	6	22.5 [10.8]	0.525 [49.7]	59.7 [54.0]
		0.10	6	11.8 [19.6]	0.027 [23.1][d]	0.81 [46.6][d]
		0.30	6	12.0 [29.3]	0.020 [31.4]	0.48 [36.9]

[a] Refers to the number of specimens.
[b] The value in brackets is the coefficient of variation in %.
[c] Values listed in bold correspond to the minimum values achieved at a given volume fraction among fibres of different length.
[d] Indicates that an outlier was omitted.

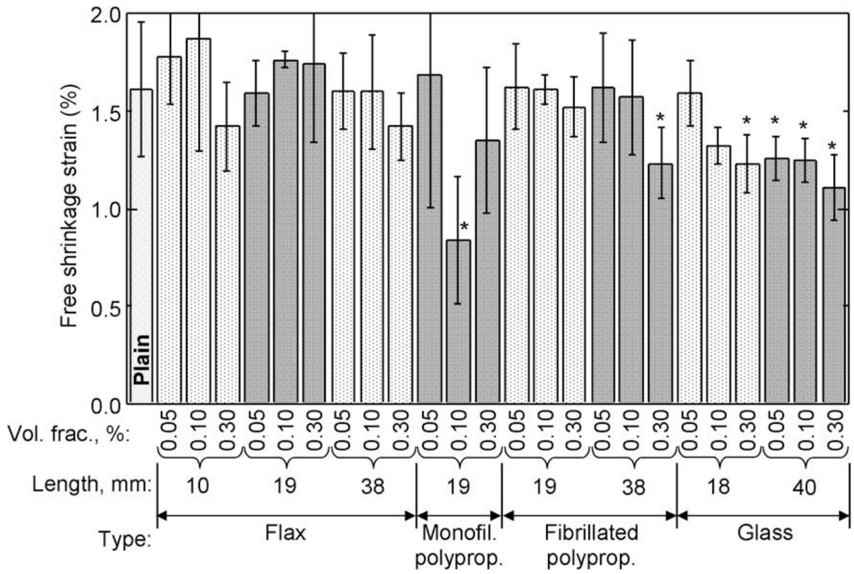

Fig. 5. Measured unrestrained plastic shrinkage strains. Asterisks indicate data points that differed significantly from plain control specimens at the 95% level of confidence.

sults, for fibre types other than glass, any reduction in restrained plastic shrinkage cracking that might be observed with fibre addition, as presented below, cannot be the result of a reduction in the propensity for fibre reinforced specimens to shrink, but must rather be attributed to other mechanisms, namely the increased early age tensile capacity of mortars containing fibres and the ability of the fibres to restrict the growth of cracks that do form.

3.2. Restrained plastic shrinkage cracking

Measured crack properties for restrained plastic shrinkage tests for each of the 24 combinations of fibre type, length, and volume fraction are given in Table 3. A relatively high variability in the number and size of cracks was experienced for these tests, as manifested by the high values for coefficient of variation in many cases.

Table 3
Summary of restrained plastic shrinkage test results

Fibre type	Fibre length (mm)	Volume fraction (%)	No.[a]	No. of cracks	Maximum crack width (mm)	Total crack area (mm^2)
Plain	–	–	20	10.4 [35.2][b]	1.823 [33.9]	212 [24.8]
Flax	10	0.05	4	14.0 [5.8]	0.608 [90.0]	56.0 [113]
		0.10	4	11.5 [8.7]	0.160 [101]	9.27 [113]
		0.30	4	7.5 [25.5]	**0.010**[c] [0.0]	**0.14** [22.1]
	19	0.05	4	12.5 [19.0]	**0.380** [22.7]	**30.9** [24.0]
		0.10	4	9.3 [31.1]	0.173 [25.2]	6.44 [49.2]
		0.30	4	6.0 [13.6]	0.015 [38.5]	0.79 [146]
	38	0.05	6	11.0 [12.9]	0.847 [56.3]	62.1 [44.8]
		0.10	6	9.2 [12.8]	**0.098** [39.3]	**3.81** [68.6]
		0.30	6	7.3 [33.0]	0.022 [49.8][d]	0.38 [82.5][d]
Monofil. polyprop.	19	0.05	4	10.8 [15.9]	**1.193** [12.4]	**105** [9.9]
		0.10	4	10.3 [26.9]	**0.313** [25.0]	**11.1** [33.8]
		0.30	4	10.0 [14.1]	**0.025** [69.3]	**0.28** [20.1]
Fibrillated polyprop.	19	0.05	4	18.0 [22.7]	0.988 [47.8]	76.3 [64.6]
		0.10	4	16.3 [18.4]	0.185 [80.1]	9.51 [108]
		0.30	4	11.5 [11.2]	0.015 [38.5]	**0.29** [26.0]
	38	0.05	6	19.3 [23.7]	**0.802** [35.1]	**49.9** [44.3]
		0.10	6	15.7 [10.4]	**0.170** [44.0]	**8.40** [64.5]
		0.30	6	14.5 [16.2]	**0.014** [35.0]	0.43 [37.2]
AR glass	18	0.05	6	16.7 [6.2]	0.733 [11.7]	**56.2** [27.2]
		0.10	6	13.5 [16.1]	**0.011** [9.8][d]	**0.32** [24.6][d]
		0.30	6	13.7 [34.5]	**0.011** [10.1][d]	**0.27** [20.2][d]
	40	0.05	6	22.5 [10.8]	**0.525** [49.7]	59.7 [54.0]
		0.10	6	11.8 [19.6]	0.027 [23.1][d]	0.81 [46.6][d]
		0.30	6	12.0 [29.3]	0.020 [31.4]	0.48 [36.9]

[a] Refers to the number of specimens.
[b] The value in brackets is the coefficient of variation in %.
[c] Values listed in bold correspond to the minimum values achieved at a given volume fraction among fibres of different length.
[d] Indicates that an outlier was omitted.

This variability is not unexpected, as cracking is a highly random and variable process. Occasionally, a single specimen exhibited a significantly higher maximum crack width and total crack area than other similar specimens. Because results were highly sensitive to experimental procedures (e.g. mould removal), values that differed significantly from the mean at a level of significance of 1% were considered outliers and were discarded. Data affected by this procedure are indicated by a footnote in the table.

It is instructive to first consider the behaviour of the plain mortar specimens. These specimens developed an average of just over 10 cracks, most of which were oriented roughly perpendicular to the long dimension of the specimen. The total projected area of the cracks (212 mm^2) represented approximately 0.6% of the top surface area of a specimen. Normally, one of the cracks extended the full 100 mm specimen width and grew to a relatively wide size (1.82 mm on average). This single crack typically accounted for almost 80% of the total crack area on the surface and its width represented approximately one-third of the free shrinkage that would have occurred if the specimens had been unrestrained, as measured by the unrestrained shrinkage tests.

Total crack area, expressed as a percentage of that observed on plain control specimens, and maximum observed crack widths for all groups of specimens are plotted in Figs. 6 and 7, respectively. In these figures, error bars represent one standard deviation on either side of the mean. Figs. 6 and 7 clearly indicate that the addition of fibres of all types, lengths and volume fractions resulted in significant reductions in both total crack area and maximum crack width relative to plain control specimens. Despite the large variability, the observed reductions and many of the differences between different groups of specimens are statistically significant.

The influence of fibre volume fraction on cracking behaviour is unmistakable. In all cases, total crack area and maximum crack

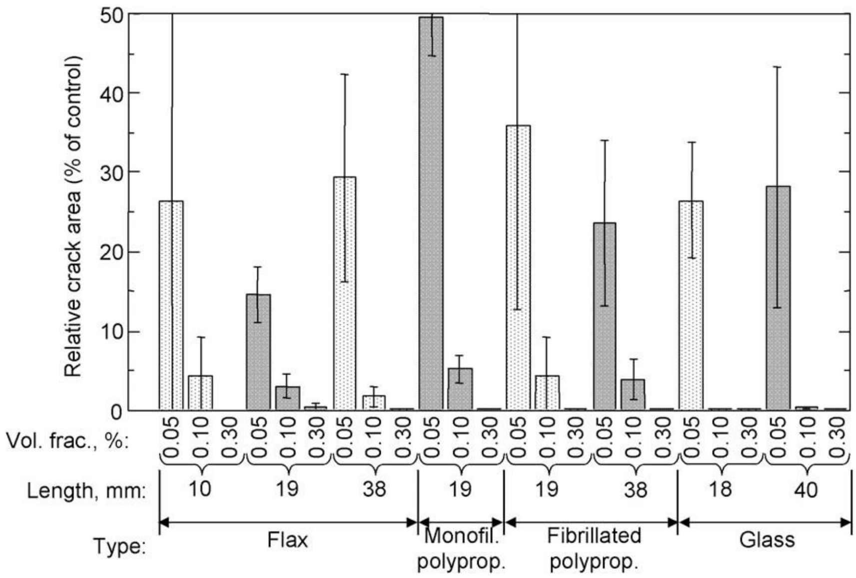

Fig. 6. Total crack area relative to plain control specimens for all restrained plastic shrinkage specimens.

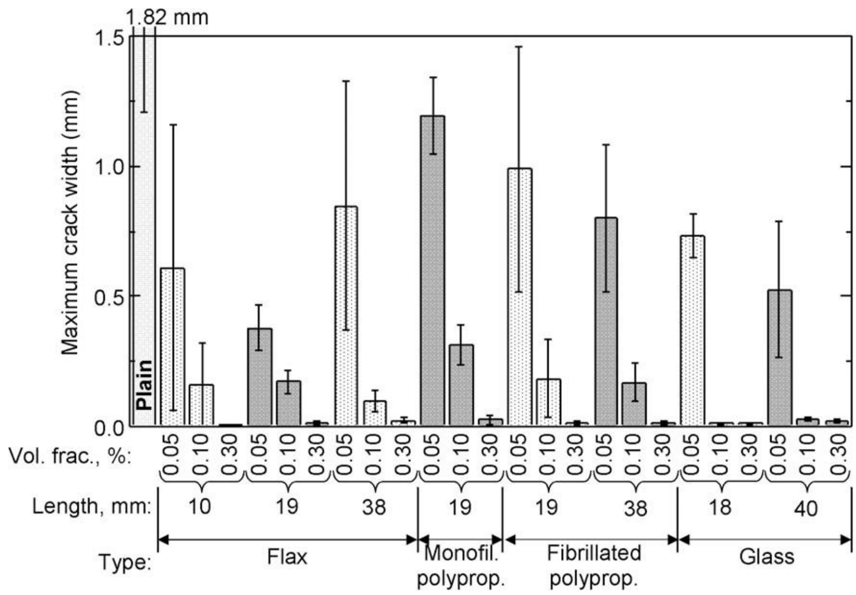

Fig. 7. Maximum crack widths for all restrained plastic shrinkage specimens.

This variability is not unexpected, as cracking is a highly random and variable process. Occasionally, a single specimen exhibited a significantly higher maximum crack width and total crack area than other similar specimens. Because results were highly sensitive to experimental procedures (e.g. mould removal), values that differed significantly from the mean at a level of significance of 1% were considered outliers and were discarded. Data affected by this procedure are indicated by a footnote in the table.

It is instructive to first consider the behaviour of the plain mortar specimens. These specimens developed an average of just over 10 cracks, most of which were oriented roughly perpendicular to the long dimension of the specimen. The total projected area of the cracks (212 mm^2) represented approximately 0.6% of the top surface area of a specimen. Normally, one of the cracks extended the full 100 mm specimen width and grew to a relatively wide size (1.82 mm on average). This single crack typically accounted for almost 80% of the total crack area on the surface and its width represented approximately one-third of the free shrinkage that would have occurred if the specimens had been unrestrained, as measured by the unrestrained shrinkage tests.

Total crack area, expressed as a percentage of that observed on plain control specimens, and maximum observed crack widths for all groups of specimens are plotted in Figs. 6 and 7, respectively. In these figures, error bars represent one standard deviation on either side of the mean. Figs. 6 and 7 clearly indicate that the addition of fibres of all types, lengths and volume fractions resulted in significant reductions in both total crack area and maximum crack width relative to plain control specimens. Despite the large variability, the observed reductions and many of the differences between different groups of specimens are statistically significant.

The influence of fibre volume fraction on cracking behaviour is unmistakable. In all cases, total crack area and maximum crack

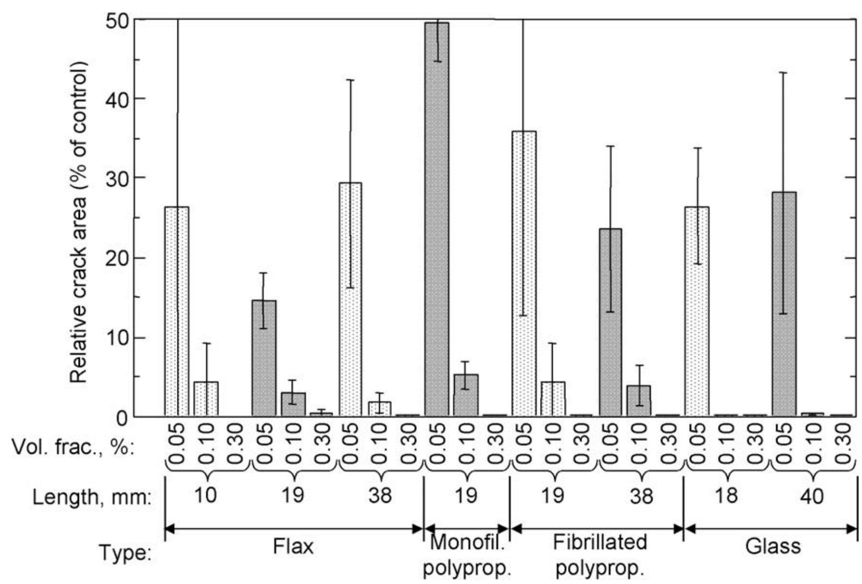

Fig. 6. Total crack area relative to plain control specimens for all restrained plastic shrinkage specimens.

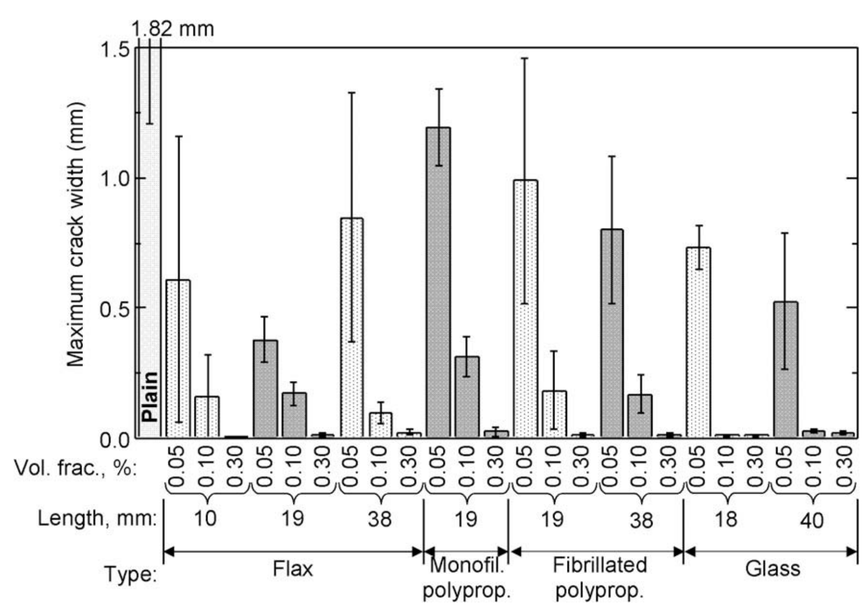

Fig. 7. Maximum crack widths for all restrained plastic shrinkage specimens.

width consistently decreased with increasing volume fraction. This trend was most striking as the volume fraction increased from 0.05% to 0.1%, over which interval all fibre types and lengths pro- duced very significant reductions. While the reduction in total crack area relative to plain mortar specimens varied from 51% to 87% (being typically in the 70–80% range) for specimens with 0.05% volume fractions, all specimens with 0.1% volume fractions exhibited reductions in total crack area of 95% or more. Glass fibres performed particularly well at the 0.1% volume fraction, reducing total crack areas by at least 99.5%, which is comparable to the per- formance of other fibre types at a volume fraction of 0.3%. At the 0.3% volume fraction, fibres of all types and lengths were extre- mely effective, reducing total crack areas by more than 99.5% in all cases.

Similar relationships were observed for maximum crack widths. Addition of fibres at a volume fraction of 0.05% produced reduc- tions in maximum crack widths relative to plain mortar specimens in the range of 35–80% in all cases. At a 0.1% volume fraction, reductions ranged from 83% to 99%, and at 0.3% maximum crack widths decreased by at least 98.5% to less than 0.025 mm in all cases. Again, the performance of glass fibres at a volume fraction of 0.1% is particularly noteworthy when compared to other fibre types at a similar volume fraction. In addition to the ability of fi- bres to increase the tensile strain capacity in the plastic state, the effectiveness of glass fibres may also be partly due to their ability to reduce the propensity for free plastic shrinkage, which was not observed for other fibre types.

No consistent trend in cracking behaviour with change in fibre length can be observed in the data. Although improved behaviour with increasing fibre length at a given volume fraction was ob- served in a large number of cases, a significant number of cases demonstrating the reverse trend were also observed. Most notably, both total crack area and maximum crack width increased signifi- cantly when the length of glass fibres at both 0.1% and 0.3% volume fractions increased from 18 to 40 mm. This may be indicative of an optimum fibre length closer to 18 mm for glass fibres, but this can- not be confirmed based on the data presented here. It suggests that a larger number of closely spaced 18 mm long glass fibres are more effective than half the number of 40 mm long fibres less densely packed. For most fibre types, an increase in fibre volume fraction had a much more significant influence than did an increase in fibre length.

The performance of flax fibres in particular was comparable to that of most other fibre types investigated. At a volume fraction of 0.1%, flax fibres at all lengths reduced the total crack area rela- tive to plain specimens by more than 95%, and reduced maximum crack widths by at least 90% to less than 0.18 mm. This is very sim- ilar to the performance of fibrillated polypropylene fibres at this volume fraction. Glass fibres performed significantly better, while monofilament polypropylene fibres did not perform as well. At a volume fraction of 0.3%, flax fibres produced reductions of greater than 99.5% for total crack area and 98.5% for maximum crack width, with maximum crack widths limited to less than 0.022 mm for all fibre lengths. At this volume fraction, all fibre types performed very similarly.

The performance of flax fibres relative to other fibre types may be better understood by considering Figs. 8 and 9, in which total crack areas and maximum crack widths, respectively, are plotted for the fibre length that produced the best results for a given fibre type and volume fraction. For example, at a volume fraction of 0.05%, the 19 mm long flax fibres produced the smallest total crack area as compared with other lengths of flax fibres, while at a vol- ume fraction of 0.1%, the 38 mm long flax fibres resulted in the smallest total crack area. These plots allow a comparison of the performance of different fibre types assuming that a near optimal fibre length has been used at each volume fraction for a particular

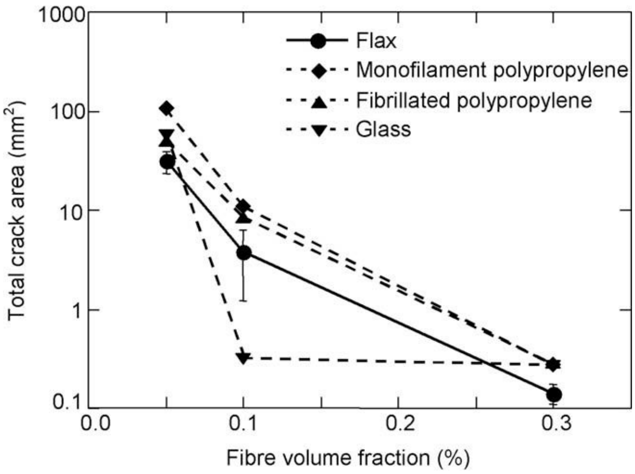

Fig. 8. Comparison of total crack areas for specimens with the best fibre lengths.

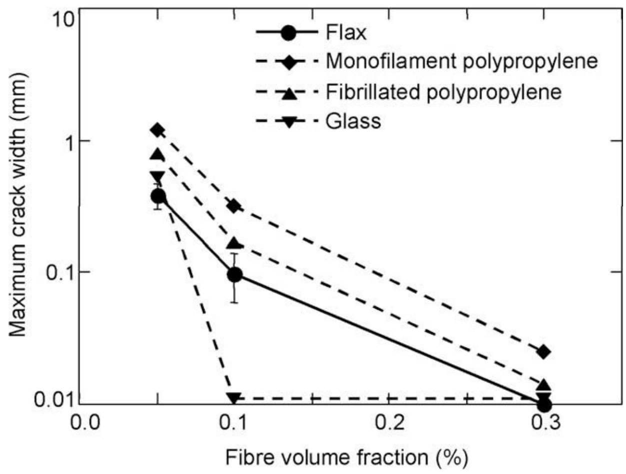

Fig. 9. Comparison of maximum crack widths for specimens with the best fibre lengths.

type. It should be noted that the best length typically varied with volume fraction. A logarithmic scale is used to facilitate plotting values spanning several orders of magnitude, and error bars are only plotted for flax fibre specimens to preserve clarity.

Both figures show that flax fibres generally performed the best among the fibre types investigated in terms of their ability to re- duce the total crack area and restrict the size of the largest cracks that formed. The only exception to this pattern occurred at a vol- ume fraction of 0.1%, at which glass fibres produced reductions in these parameters that were an order of magnitude better than flax fibres, which were the next best.

Some additional insight into the behaviour of the fibres may be gained by examining the number of cracks appearing on specimen surfaces, as listed in Table 3 and plotted in Fig. 10. In this figure, data points marked with an asterisk indicate that the average num- ber of cracks observed for a given set of specimens differed signif- icantly from those of the plain control specimens at the 95% level of confidence. The introduction of flax fibres at the lowest volume fraction produced a slight increase in the number of cracks relative to the plain mortar specimens, although this increase was only sta- tistically significant for the 10 mm long fibres. As the volume frac- tion of flax fibres increased to 0.30%, the number of cracks decreased to fewer than in the plain specimens. In contrast, the monofilament polypropylene fibres had virtually no influence on the number of cracks observed. On the other hand, addition of