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Use of flax fibres to reduce plastic shrinkage cracking in concrete

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ABSTRACT

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

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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 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.

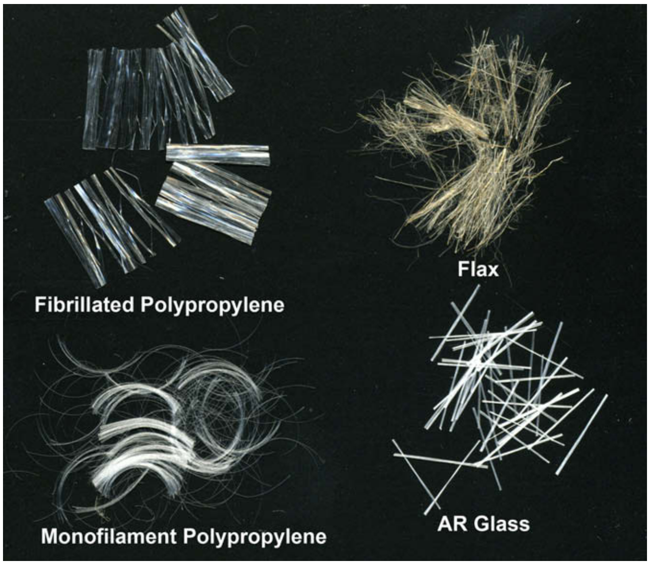

Fig. 1. Photograph of the four types of fibres used at the 18 or 19 mm lengths.

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