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Effect of hemp fibers on fire resistance of concrete

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HIGHLIGHTS

- The use of hemp fibers for improving fire resistance of concrete has been studied.
- The concrete specimens were heated to 400 °C and cooled.
- Fibers did not significantly influence the residual properties concrete.
- Visual observations showed that the hemp fibers were partially disintegrated.
- The incompletely disintegrated hemp fibers could reduce crack propagation.

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ABSTRACT

This study investigated the use of hemp fibers for improving the fire resistance of concrete. The characterization of the fibers was carried out through SEM, TGA/DSC, FTIR and crystallinity index. A reference concrete mixture, polypropylene fibers mixture, and four mixtures with different chemically treated hemp fibers were prepared. The concrete specimens were heated to 400 °C and cooled. Their compressive strength, static modulus of elasticity, residual weight, and residual ultrasonic pulse velocity were then determined and compared. The addition of fibers did not significantly influence the fire resistance of the concrete in terms of the residual properties. Visual observations from scanning electron microscope and microimages of the concrete mixtures showed that the hemp fibers were partially disintegrated within the concrete after being heated; thus, the incompletely disintegrated hemp fibers could reduce crack propagation at high temperatures thus improving the fire resistance of concrete.

1. Introduction

Fiber-reinforced concrete (FRC) is a composite concrete material comprising a hydraulic cement matrix reinforced with discontinuous discrete fibers. The modern development of fiber reinforced concrete dates back to the 1960s [1]. The most typical fibers used today in cementitious composites as fiber reinforcement are steel, synthetic, or glass fibers [2,3]. These fibers are short and randomly distributed in the concrete. With the addition of fiber reinforcement, the transition of the concrete's behavior from brittle to quasi-ductile or even ductile behavior with increased toughness and energy absorption capacity could be achieved [4,5]. It has been reported [3,4,6,7] that with the incorporation of fiber reinforcement (steel, synthetic, or glass fibers) in cementitious materials, the cracking due to plastic shrinkage and drying shrinkage in the material as well as its permeability could be significantly reduced, the impact and abrasion resistance increased, and the tensile strain capacity of the material substantially improved. However, the production of fibers results in high pollution and carbon dioxide emissions [8]. Therefore, governmental laws are compelling both the academic and industrial sectors to develop a new method of generating energy-efficient fiber-reinforced cementitious building materials that allow for enhanced environmental sustainability. As contribution to a new generation of FRCs, extensive research is in progress for finding alternative fibers for use in concrete [5,9,10]. Several researches are now focused on the use of natural fibers as reinforcement. A unique aspect of natural fibers is the low amount of energy required to

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extract these fibers from its source [2]. Three types of natural fibers are suitable for concrete reinforcement: animal-based, mineral-derived, and plant-based fibers. The suitable animal fibers include silk, wool, and hair fiber. Mineral-derived fibers include wollastonite, and palygorskite. Finally, the suitable plant-based fibers include cotton, hemp, jute, flax, ramie, sisal, bagasse, and specialty fibers processed from wood [11]. The application of nylon and bamboo fibers in concrete has been studied in [11], and it was found that only the bamboo reinforcement led to an improvement in the concrete compressive strain energy. Other than the constructive role of fibers in concrete, i.e., the fibers are expected to partially or completely replace conventional reinforcement for certain uses, the role of some types of fibers is to increase the resistance of concrete to fire or to prevent cracking [12]. For example, it is recorded in [12] that steel fibers limit cracking during thermal treatment and control the spread of these cracks during mechanical loading. According to [13], polymeric fibers improve the fire resistance of concrete. Furthermore, cement paste that has a low water–cement ratio has a dense and fairly impervious microstructure that prevents the moisture vapor from escaping in a high temperature environment. This can lead to high internal pressures and spalling. Polypropylene fibers can be effectively used to enhance the connectivity of a dense cement matrix at high temperatures. This improvement in connectivity occurs owing to the destruction of the polypropylene fibers. They melt, evaporate, and form channels that enable the vapor pressure inside the specimen to diminish. According to [14], polypropylene fibers melt at 170 °C, thus creating a porosity that limits the pore pressure owing to the evaporation of the pore water that occurs during heat exposure [15]. Consequently, the cracking of the concrete is reduced during exposure to heat [16].

Among the natural fibers studied in the extant literature, the most common are hemp fibers [17–19]. Hemp is one of the oldest plant that has been used in a variety of applications and is thus one of the most recognizable plants in the world. Industrial hemp is used in the construction, textile, food, automobile, biofuel, and several other industries. In the construction industry, it has found application in the form of lime-hemp plaster, insulating "quilts," polymeric hemp-based composites and hemp concrete.

Some of the problems associated with untreated natural fiber-reinforced composites include poor interfacial adhesion between the cellulose fiber and the matrix, limited thermal stability of the composites and poor fiber separation and dispersion within the composites [20]. These disadvantages of natural fibers can be overcome by fiber treatment. Anhydride modification, organosilane treatment and various coupling agent have been used to improve interfacial bonding, although alkali treatment has been found to be most feasible. Alkali treatment of fibers has also been seen to increase the crystallinity of cellulose which can lead to increase in fiber strength [21]. Commonly used alkaline solutions for fiber treating are NaOH and Na_2SO_3 [20–22].

The objective of this research is to determine how different hemp fiber treatments influence their properties at ambient temperature, whether hemp fibers can be used to improve the fire resistance of concrete and how they behave when exposed to high temperatures as compared to polypropylene fibers.

2. Experimental program

2.1. Material characterization

2.1.1. Aggregate properties

All the concrete mixtures examined in this study were prepared with dolomite aggregate (fractions corresponding to 0–4 mm, 4–8 mm, and 8–16 mm) of which the particle-size distribution was determined according to EN 933-1 [23] as shown in Fig. 1.

The density of the crushed dolomite aggregate was 2750 kg/m^3 and was tested according to EN 1097-6 [24]. The aggregate fractions that were used for preparing the concrete were first saturated and then surface-dried. This was achieved in an artificial manner by dipping aggregates into a water tank for 24 h, removing them, and then wiping the excess water from their surfaces. The chemical and physical properties of dolomite aggregate are listed in Table 1. The chemical analysis of dolomite powder was performed based on EN 196-2 [25].

2.1.2. Cement properties

The cement used was Portland cement, CEM II/A-M(S-V) 42.5 N, as per EN 197-1 [26]. The chemical and physical properties of the cement are listed in Table 2. The chemical analysis of the cement was performed based on EN 196-2 [25]. The density and Blaine surface/fineness were measured according to EN 196-6 [27].

2.1.3. Properties of fibers

2.1.3.1. Surface treatment. The hemp fibers, bought in the market, were about 1 m long in their original form. Prior to the treatment, the fibers were manually cut to the length of 18 mm. The effect of surface treatment on the properties of the natural fibers was investigated using alkaline solutions of various concentrations. The chemicals used in this study were sodium hydroxide (2.5% and 5% NaOH) and sodium sulphite (2% Na_2SO_3). After weighting and washing the fibers a few times with demineralized water (DW), the fibers were submerged and heated (sterilized) in distilled water (DW) for 1 h at 100 °C. After sterilization, the fibers were again washed several times, pressed, and dried for 12 h at 70 °C. The samples were distributed into four batches after this washing procedure. One batch of fibers was mixed with 2 L of 2.5% NaOH for 1 h at 95 °C, and a second batch was submerged in 2 L of 5% NaOH for 1 h at 95 °C. After this alkaline treatment, the fibers were rinsed with DW to eliminate any residual NaOH solution, dried in an oven at 70 °C for 24 h, and weighed after cooling. The remaining two fiber batches were treated in the same way but with different solutions: 1.6 L 2.5% NaOH and 0.4 L of 2% Na_2SO_3, and 1.6 L of 5% NaOH and 0.4 L of 2% Na_2SO_3, respectively.

In case of polypropylene fibers, fibrillated polypropylene fibers of renowned company with the length of 18 mm were used.

2.1.3.2. Characterization of fibers.

2.1.3.2.1. Mechanical properties of fibers. The mechanical properties of all the fiber types were determined through testing according to EN 14889-2 [28], the results of which are presented in Table 3 in terms of average value and standard deviations for each property.

2.1.3.2.2. Scanning electron microscopy (SEM). The morphology of the fibers prior to and after the alkaline treatment was investigated using a scanning electron microscope (SEM) (JEOL JSM 7000F, working voltage 10.0 kV) at Ruđer Bošković Institute in Zagreb. The samples were not coated either with graphite or gold but were placed on a graphite tape.

Fig. 2a–g show the scanning electron micrographs of polypropylene and of untreated, sterilized, and alkali-treated hemp fibers. While the polypropylene fibers were found to be smooth and uniform, the untreated hemp fibers were covered with a membrane that was eliminated to some extent by sterilization along with the impurities that were eliminated. It was apparent that the alkaline treatment eliminated this fiber membrane. As the NaOH concentration increased, nearly the entire membrane of the biopolymers (lignin, cellulose, and hemicellulose) was removed from the surface of the fiber and the diameter of the fiber increased slightly (Table 3) [22]. The strength measurement data presented in Table 3 clearly show a significant increase in the fiber tensile strength with the alkaline treatment as compared to untreated fibers. However, it appears that a higher alkaline concentration