Cement & Concrete Composites 57 (2015) 84–93

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

The role of hardwood pulp fibers in mitigation of early-age cracking

Passarin Jongvisuttisun [a], Kimberly E. Kurtis [b,*]

[a] Siam Research and Innovation Co., Ltd., SCG, 51 Moo 8, Tubkwang, Kaeng Khoi, Saraburi 18260, Thailand
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, Georgia 30332-0355, USA

A R T I C L E I N F O

Article history:
Received 30 April 2014
Received in revised form 11 December 2014
Accepted 15 December 2014
Available online 26 December 2014

Keywords:
Hardwood pulp
Restrained ring test
Early-age cracking

A B S T R A C T

The availability, relative consistency, and renewability of hardwood pulp fibers have prompted interest in their use in fiber–cement composites, in which they may be used for a variety of purposes. This study clarifies the ability of hardwood pulp to reinforce mortar, its capacity to provide internal curing, and its role as early-age crack-control reinforcement through a coordinated series of restrained shrinkage, free shrinkage, and mechanical testing on mortar samples. It finds that hardwood pulp improves the restrained shrinkage behavior of mortar at an early age. That is, 0.5% and 0.75% (by volume) hardwood pulp-reinforced mortars exhibited a lower rate of stress development and lengthened time-to-cracking by about 1.6 times and 2.3 times, respectively, compared to a companion crack-prone ordinary mortar. The initial crack width also decreased by 88% in 0.75% hardwood pulp-reinforced mortar samples, which suggested an application aimed at assisting self-healing in cement-based materials with an appropriate binder composition. Hardwood pulp successfully provided internal curing to crack-prone mortar and thus reduced autogenous shrinkage. This reduction in shrinkage, together with a combination of increased early tensile capacity, reduced stiffness, and improved post-cracking toughness were identified as the key contributions of hardwood pulp in the improved resistance of mortar to early-age cracking.

1. Introduction

In the past few decades, the use of natural fibers as reinforcement in construction applications has been increasing as a result of two primary driving forces: health and energy concerns. Initially, most of the efforts in this area focused on the safe replacement of asbestos in cement siding, while more recently the need for sustainability and energy efficiency in construction materials has intensified [1,2]. Based on the increased demand for energy and concerns about climate change, considerable research effort has been devoted to the application of natural fibers in construction because such fibers are more renewable, economical, and abundant than other reinforcing materials. Currently, natural fiber–cement composites can be found in many products such as extruded non-pressure pipes and non-structural building materials such as siding, cladding, and soffit panels [3].

Although many studies have demonstrated that natural plant-based fibers improve the performance of cementitious materials in many aspects including toughness and crack resistance, not all fibers can be used on a large commercial scale because of their availability and variability. Since the large-scale production of mortar and concrete requires a significant quantity of raw materials with exceptional quality, the availability of fibers is a general prerequisite for their successful use in mortar and concrete. Fibers from different sources or locations can contain various chemical components that could interact with cement during the hydration reaction. For example, hemicellulose and lignin can be hydrolyzed by alkali media and then converted into numerous carboxylic acids, which retard the cement hydration reaction [4–7]. Therefore, the control of hydration reaction of fiber-reinforced composites from different sources of fiber is complicated and thus the homogenization of the chemical constituents of fibers is another crucial requirement in a production process.

Using wood-derived fibers obtained from large-scale commercial pulping mills could solve the problems of both the availability and variability in the chemical composition of fibers rendering the use of pulp more practical for wider use in mortar and concrete than perhaps other bio-derived fibers. Since the capacity and quality of products in pulp mills are monitored to maintain consistency, variability in fibers derived from commercial pulping processes can be understood and controlled. Because of these advantages, many studies have examined the use of softwood pulps as reinforcements in cement paste, mortar, and concrete. However significantly less well-explored for these applications

* Corresponding author. Tel.: +1 (404) 385 0825; fax: +1 (404) 894 2278.
E-mail addresses: passarij@scg.co.th (P. Jongvisuttisun), kimberly.kurtis@ce.gatech.edu (K.E. Kurtis).

http://dx.doi.org/10.1016/j.cemconcomp.2014.12.008
0958-9465/

are hardwood pulps, largely because they are shorter (i.e., lengths of 1–1.7 mm) than softwood pulps (e.g., pine pulp lengths are typically 2.5–4 mm [8]), which may limit their potential to improve the tensile strength and deformation capacity of the composites [9].

The greater availability of hardwood fibers in some regions has prompted several recent studies, which have begun evaluating their use in fiber–cement composites. They have found that hardwood fiber [10,11] facilitates uniform volumetric dispersion of short fibers in the matrix, which is important because fiber dispersion and spacing between individual fibers play an important role in both the strength and the toughness of the composite [10,12]. Others have demonstrated that hardwood pulps can provide internal curing in cementitious composites [13]. Because of their physical and chemical structures, hardwood pulps are capable of taking up water as both free and weakly bound water. This water may then be released into the cement matrix during hydration, potentially contributing to the mitigation of autogenous shrinkage in cement paste and mortar. Therefore, while hardwood pulps may not significantly improve the mechanical properties of mortar and concrete as much as longer plant-based fibers, they may enhance some early-age properties with the potential to limit the cracking of cementitious composites at early ages. This is especially so in a system that has a high cement content, where tensile stress-to-strength ratios are typically higher at the period between 24 h and 48 h after setting, making such materials prone to cracking [14]. Therefore, due to their availability, consistency, dispersability, internal curing capability, and crack-arresting properties, hardwood fibers warrant further examination for use in cement-based construction materials.

This present work will compare the performance of hardwood pulp on early-age cracking mitigation in ordinary types of mortar to that in mortar containing a common internal curing agent, a superabsorbent polymer (SAP). Both the ability of hardwood pulp to provide mechanical reinforcement and its capacity to provide internal curing are evaluated through a series of restrained shrinkage tests, early–age mechanical tests, and microstructural characterization. The overall goal is to better understand the roles of internal curing and reinforcement as they relate to shrinkage crack mitigation through the use of hardwood pulp fiber.

2. Material and methods

2.1. Materials

A highly renewable hardwood fiber, unbleached soda pulp fiber (USF), was obtained from a commercial soda-pulp mill located in Southeast Asia. The pulp was never dried, so it retained its original structure. The kappa number of the pulp was 14.6, giving a total residual lignin content of 2.23%. The average length of the fiber was approximately 0.69 ± 0.02 mm. The as-received moisture content of the USF was 245%, determined according to ASTM D4442-07 (procedure a) [15]. The superabsorbent polymer (SAP) used for comparison was a cross-linked acrylamide/acrylic acid copolymer, the most predominant type of SAP used for internal curing [16]. The SAP was in powder form and added to dry cement prior to mixing.

Mortar samples were prepared using commercially available ASTM Type I/II portland cement (Lafarge, North America), natural siliceous sand (Atlanta, Georgia, USA), and tap water. The oxide analysis of the cement was performed by X-ray fluorescence (XRF, Bruker AXS S8 Tiger) spectrometry. The oxide composition of the cement was (as percentage by mass) 19.73% SiO_2, 4.82% Al_2O_3, 3.16% Fe_2O_3, 62.41% CaO, 3.64% MgO, 2.99% SO_3, 0.08% Na_2O, 0.48% K_2O, and 2.2% loss on ignition (LOI). The crystalline phases of cement, as identified by quantitative X-ray diffraction analysis (QXRD, Bruker AXS D4 Endeavor) with the Rietveld method using TOPAS software, was (as percentage by mass) 52.6% alite, 20.7% belite, 3.7% aluminate, 11% ferrite, 0.1% lime, 2.3% portlandite, 2.6% periclase, 0.6% arcanite, 0.4% aphthitalite, 0.9% gypsum, 2.4% bassanite, and 2.7% calcite. The particle size distribution of the sand, shown in Fig. 1, was adjusted to meet ASTM C897-05 requirements [17]. The oven-dry specific gravity of the sand was 2.62 and its fineness modulus was 2.68.

Mortars were prepared at a water-to-cement mass ratio (w/c) of 0.40 and a sand-to-cement volume ratio (s/c) of 1.5. All mixture design proportions tested in this study are shown in Table 1. Maintaining a consistent w/c, particularly for mortars that contain either of the internal curing agents—USF and SAP—requires that the amount of internal curing water available to the paste be accounted for during mixture proportioning. Therefore, the amounts of "entrained water" (e.g., water available for internal curing [18]), which depend on the amounts of USF and SAP in the mortar as well as the intrinsic properties of these agents and the cement used [16,19,20], were quantified using a consistent method [21], with the mixing water masses adjusted accordingly. The absorption capacity of USF was determined to be 1, while that of SAP was 10. The absorption capacity of SAP was close to that previously reported [22], in which the absorption capacity was determined through measurement of chemical shrinkage. Since a high efficiency polycarboxylate-based superplasticizer, ADVA455 (WR Grace), was added to enhance the workability of the fiber-containing mortar, the same amount was also added in each of the companion samples (3 μL per gram of cement). With pulp fibers, limits on workability do influence the maximum internal curing water which can be provided.

2.2. Restrained shrinkage

To evaluate the effect of USF hardwood pulp on early-age cracking, this work employed the restrained ring test (ASTM C1581-09 [23]). Strain development in the steel ring was monitored by attaching two electrical resistance strain gauges, 180° apart, to the inner surface of the steel ring at mid-height. The strain gauges were connected to a quarter-bridge strain gauge module attached to a data acquisition system. The strain data were recorded every 3 min. The amounts of fiber used in restrained shrinkage studies were 0.5% and 0.75% by volume of the original mixture. The role

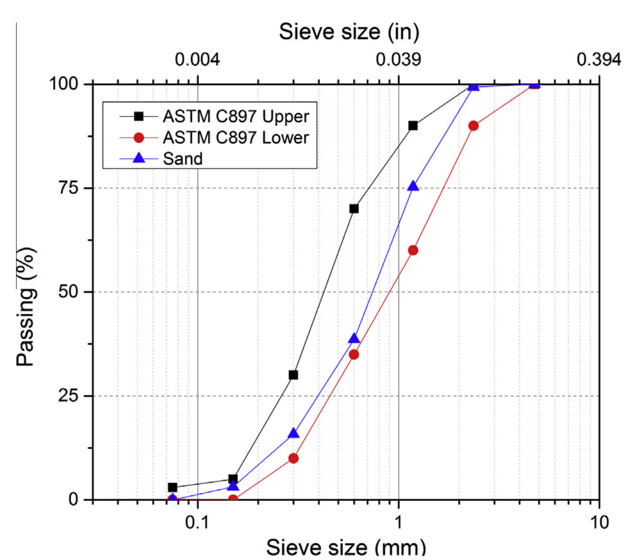

Fig. 1. Particle size distribution of the sand used in this study.