Construction and Building Materials 164 (2018) 716–730

Contents lists available at ScienceDirect

Construction and Building Materials

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

Evaluation of resonance acoustic mixing technology using ultra high performance concrete

Aileen Vandenberg [a], Kay Wille [b,*]

[a] Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Unit 3037, Storrs, CT 06269-3037, United States
[b] Department of Civil and Environmental Engineering, University of Connecticut, United States

HIGHLIGHTS

- Mixing UHPC using Resonance Acoustic Mixing (RAM) Technology® was assessed.
- Comparisons of a RAM mixer and a table top paddle mixer were made.
- Workability and flowability properties differed between mixers.
- UHPC mixed with RAM demonstrated an increase in mechanical properties.

ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form 15 December 2017
Accepted 27 December 2017

Keywords:
Ultra-high performance concrete
Resonant acoustic mixing
Concrete mixers
Mechanical properties
Flow properties
Rheology
Cement

ABSTRACT

This study presents an investigation on the mixing efficiency of Resonance Acoustic Mixing (RAM) Technology® using ultra-high performance concrete (UHPC). In the first part, RAM is optimized through acceleration curve profiles, specific mixing energy, and workability spread flow tests. In the second part, RAM is compared with a regular table top paddle mixer with regards to its effects on workability and flow, as well as, compressive and flexural strength properties. For the UHPC used in this study results showed that: 1) RAM was a viable mixing technology for UHPC, and 2) RAM produced samples of reduced rheological properties, but increased mechanical properties compared to a table top paddle mixer.

1. Introduction

Research in cement hydration, pozzolanic reactivity, particle packing density, and cement-polymer interactions has led to the development of ultra-high performance concrete (UHPC) [1]. UHPC is generally defined as a concrete composite with a compressive strength exceeding 150 MPa (22 ksi), a low water-to-binder ratio ($w/b \approx 0.2$) and a high volume (30–50%) of filler and reactive micro-sized particles, such as cement, fly ash, quartz powder and silica fume [2]. Producing high quality UHPC is dependent on an efficient mixing procedure and the type of mixer used. Inadequate mixing may lead to undesirable macroscopic effects on the fresh and hardened state properties of the material [3]. However, a well-mixed mixture permits the concrete constituents to distribute uniformly in its system such that the cementitious materials can hydrate uniformly to create a hardened concrete homogeneous microstructure for better performance [4]. Intensive high-shear mixers have become the industry standard in producing well-mixed UHPC. It has been shown that they are reliable and efficient mixers that reduce mixing times, improve mixing energy distributions, and possess built-in power consumption monitoring [5–9].

Conversely, as the interest grows to produce UHPC as a multi-functional material, such as with the incorporation of carbon nano-tubes [10] or other types of nano-size particles [11–13], or in a more economical manner, such as the utilization of local materials, higher cement replacement, or poorer quality materials [14,15], the mixing efficiency becomes the essence of producing high quality UHPC. This will require more research into not only the mixing procedure, but also the type of mixer used, and hence better understanding of current mixing technologies.

To illustrate, the powder industry employs multiple mixing technologies such as tumbler mixers, gravity silo mixers,

* Corresponding author.
E-mail addresses: aileen.vandenberg@uconn.edu (A. Vandenberg), kay.wille@uconn.edu (K. Wille).

https://doi.org/10.1016/j.conbuildmat.2017.12.217
0950-0618/

pneumatic blenders, and agitation mixers [16]. Notwithstanding, the cement and concrete industry mainly relies on impeller agitation mixers where the main mixing mechanisms are shear and convection [17] via a blade or paddle tool. The reader is referred to [8,18] for a more in-depth review of current concrete mixing technologies.

Concerning cement and concrete, very little research exists utilizing other types of mixers [19–22] used a paint shaker mixer to mix cement paste and assess cement properties such as porosity, chemical shrinkage, and silica/limestone powder activation sites [23] employed power ultrasound-assisted mixing for concrete production and assessed spread and compressive strength properties. They found that the compressive strength increased, while the spread decreased depending on the strength of the ultrasound mixing. Nonetheless, to the authors' knowledge mixing cementitious materials with mixing technologies such as reciprocating movement agitator mixers or bubble acoustic streaming mixers have not been used. Reciprocating agitator mixers work by moving the mixing medium back and forth usually by a vibrating plate to obtain a uniform mixing distribution (Fig. 1a). The power consumed by the mixing is dependent on the frequency, amplitude, and diameter of the plate [24]. Bubble acoustic streaming mixers exploit the acoustic frequency resonance of air bubbles to create micro-mixing convection streaming zones around the mixing media particles (Fig. 1b) [25].

The focus of this research is to mix UHPC by employing a novel type of mixing technology that combines the principles of reciprocating movement agitation and acoustic streaming micro-mixing zones called Resonant Acoustic® Mixing (RAM) technology. RAM is an innovative type of mixing technology that works on vertical reciprocating movement of springs to apply a short amplitude and high frequency (~60 Hz) acoustic pressure wave that induces mixing [26]. Micro-mixing zones and bulk movements of the material are created without the contact of any mixing elements [27]. As an in-container reciprocating movement agitator, RAM has already shown potential in the pharmaceutical [28] and food [29] industries, and thus, could have potential in the cement and concrete industry as well.

In this study, the authors monitored the mixing efficiency of RAM for producing high quality UHPC through acceleration consumption curves, specific mixing energy, and spread flow properties. Then, a designated UPHC mix was selected to assess its fresh state properties and mechanical properties compared to a table top paddle mixer. The aim of this paper is twofold – 1) to test the suitability of RAM for mixing UHPC, and 2) to investigate how RAM mixing compares to a commonly used mixer in the cement and concrete industry.

2. Materials and mixing methods

2.1. Properties of materials

Type I white cement conforming to ASTM C150 [30] was used in all the mixtures. A commercially available high-range water reducer conforming to ASTM C494 [31] Type A & F polycarboxylate (PCE) superplasticizer (SP), with specific gravity of 1.06 and solid content of 29%, was used at 1% by weight of cement (bwoc). White silica fume (SF) and quartz powder (QP) were used as secondary cementitious and filler materials, respectively. Aggregates consisted of fine grade quartz sand (QS) with a medium particle size of d_{50} ~0.18 mm and a maximum size of d_{max} ~0.30 mm. Table 1 provides the mineral and physical composition of the materials used in this study.

2.2. Mix compositions

The mixing proportions were based off the recommendations provided in [2] and are presented in Table 2. The powder proportions remained the same, while the water-to-cement (w/c) ratio was varied between 0.25 and 0.21. The U21 series was utilized for the comparative study with the table top mixer.

2.3. RAM overview

The principal behind Resonant Acoustic Mixing (RAM) (Butte, MT) is illustrated in Fig. 2. The mixing system consists of a three-mass system, spring assembly, and loaded mixing vessel. A motor that subjects the mixing media to a reciprocating agitation movement controls the spring assembly. The system attains resonance when the stored forces in the spring and the inertia forces from the mass equal each other. The resonance of the mechanical

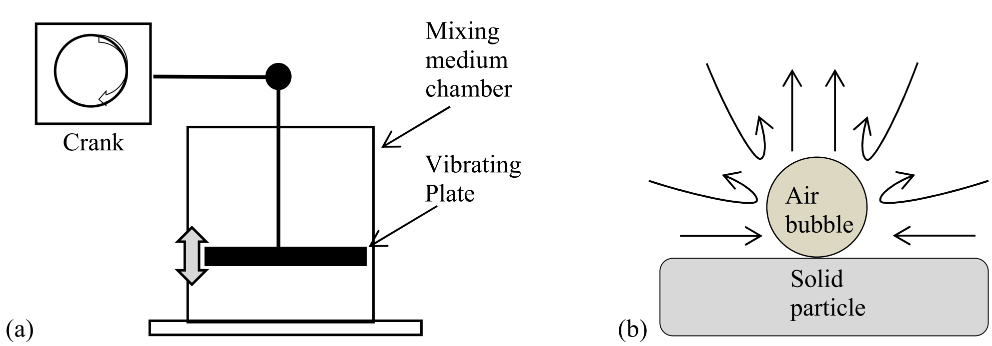

Fig. 1. Two examples of mixing technologies used in other industries: a) reciprocating agitation mixer in which the vibrating plate is moved by a mechanical crank according to [23], and b) acoustic bubble microstreaming in which an air bubble resonates when subjected to a sound field of a matching resonate frequency according to [24].

Table 1
Physical and mineralogical properties of UHPC constituents.

Constituent	Nomenclature	C_3S	C_2S	$C_3S + C_2S$	C_3A	C_4AF	SiO_2	Specific Surface Area/ Mean Particle size
White Cement Type I	C	74%	13%	87%	5%	1%		395 m^2/kg
White Silica Fume	SF						>96%	d_{50} ~0.15 µm
White Quartz Powder	QP						>99%	d_{50} ~1.7 µm
Quartz Sand, fine	QS1							d_{50} ~0.18 mm