Dry Forced Packing of Blends for Ultra High Performance Concrete: Effect on Physical-Mechanical Properties of the Composition and Concrete Made from it

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Keywords: high performance concrete, silica fume, microstructure, physical properties

INTRODUCTION

The close packing of raw materials is generally recognized as the first of the basic principles for design of Ultra High Performance Concrete (UHPC). There are numerous mathematical models for optimizing granular packing [1]. In these models particle packing density is primarily based on “ideal” powders, meaning that individual particles are loose and not interconnected into agglomerations. According to this concept, upon mixing silica fume with larger inorganic binders, the ultrafine microsilica particles are uniformly arranged in the voids between coarser cement particles, together creating a densely packed matrix. However, in actual practice, silica fume particles have a tendency to aggregate. The smaller the particle size, the more aggregation. Particle aggregation prevents uniform distribution of the silica fume particles, and the density, as well as other properties of the concrete matrix are jeopardized in various ways, including but not limited to higher porosity and permeability, and lower strength and durability. Many solutions have been identified to overcome the problem of silica fume particle aggregation, including introduction of silica fume after chemical pre-treatment [2], or as a colloidal suspension often in combination with sonication or combinations thereof [3]. Breaking down silica fume with cement in the process of cement milling has been proven successful and has become standard practice; however cement milling is generally performed in a factory utilizing a process of clinker milling which produces large batches for commercial use. One disadvantage of incorporating silica fume into the process of cement manufacturing is a lack of production flexibility. Specifically, it is impractical to produce relatively small and diverse batches of blended hydraulic cement according to requirements of dissimilar customers. Another drawback is that a limited amount of silica fume can be added into cement in the process of its manufacturing. Silica fume is normally added at a range between 3 and 10% by weight, and almost certainly under the maximum 15% defined by many national standards, and particularly by National Standard of Canada CAN/CSA-A3000-13. This quantity of silica fume is generally below its optimum amount (up to 25% in many UHPC compositions and higher in some) required for making blended cement compositions with maximum packing density. Besides, the milling cannot be used for optimum packing of multi-component mixtures, containing materials in addition to silica fume, for example other supplementary cementitious material like fly ash, slag, etc., or non-cementitious fillers like quartz powder, sand, etc. Another reason milling cannot be used for optimum packing of multi-component cementitious mixtures is that it is considered impossible to calculate the optimum ratio of the components based on their original sizes because of comminution of different components to varying and unpredictable degrees in the process of milling.

This study discusses a method for forced packing of dry multi-component mixtures, and studies the effect of such forced packing on physicochemical properties of the composition, microstructure, homogeneity, and mechanical properties of UHPC produced using standard blended mixtures, and dry forced packed mixtures. Initially, all of the dry materials (Table 1) were combined in an Eirich R09T 200 L intensive mixer (abbreviated IM) with a counter-current rotating pan and high speed rotor tool with a fixed pan scraper blade for a period of 1 minute at rotor speed of 380 rpm.

Table 1. Mix design

Material	**kg/m^3**	**kg/m^3***
Portland cement, Holcim Mississauga GU, spg 3.11	1030	946
Silica fume, Norchem densified SF, spg 2.20	258	236
Fine aggregate, Sand Fairmount Santrol LS-80, spg 2.64	640	588
Superplasticizer, BASF MasterGlenium 3400, spg 1.10	46.5	43.4
Water, City of Toronto, spg 1.00	238	296

**Adjustment for mixture made in drum mixer due to water addition during mixing.*

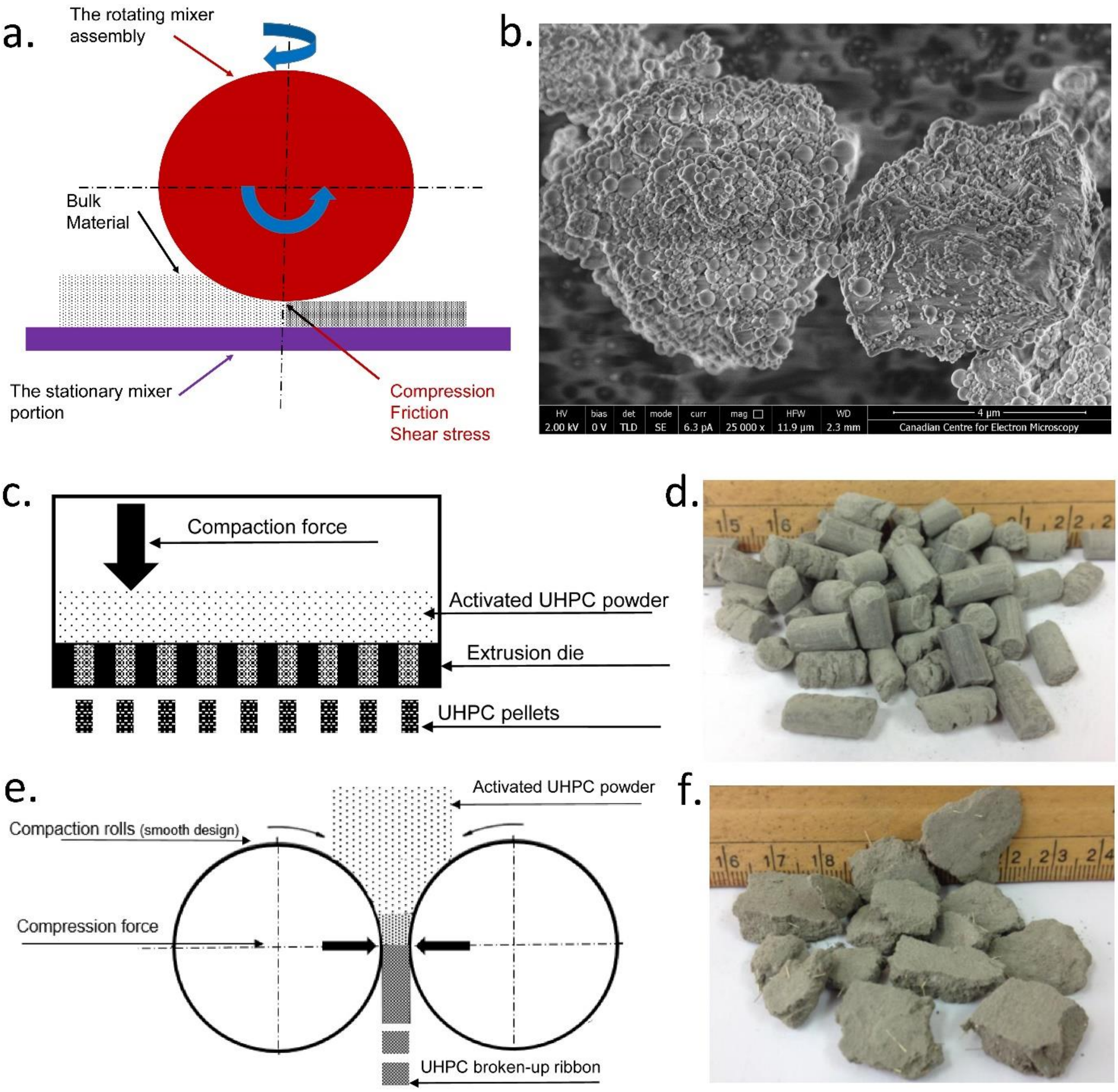

Figure 1. Dry force packing functional principle (a), scanning electron microscope image of silica fume coated cement grain after dry force packing (b), pelletization by extrusion (c) and produced pellets (d), roller compaction (e) and produced ribbon with steel fibre addition (f).

The dry-blended materials were discharged and stored in sealed pails for subsequent UHPC production in the IM, plaster/mortar (PM), drum (DR), and ordinary flat pan (FP) mixers. A portion of the dry-blended materials was further subjected to forced packing using a mortar and pestle based high intimacy mixer (Figure 1a). The dry force packed material exhibited an even distribution of silica fume particles coating the cement grains (Fig. 1b). To facilitate handling of the activated dry force packed material, pelletization (Figs. 1c, 1d) and briquetting (Figs. 1e, 1f) are additional options, that can also accomodate the introduction of fibres.

To produce UHPC, liquid admixtures were combined with the mix water, and added to the dry blended ingredients with the various mixers operated and mixed for a period of three minutes, followed by a two-minute resting period, followed by another two minutes of mixing. The same process was repeated with the dry force packed material, but only with the ordinary flat pan mixer. The mixture produced in the drum mixer was initially unworkable, so additional water was added during the final two minutes of mixing. UHPC was cast in 100 mm dia. × 200 mm cylinders, and moist cured prior to strength testing and preparation in thin section for microstructural image analysis of silica fume agglomeration content, size, and frequency.

RESULTS

The UHPC produced with the dry force packed material exhibited superior strength, and no silica fume agglomerations were observed (Table 2). Fig. 2 shows example transmitted plane polarized light micrographs from the thin sections.

Table 2. Compressive strength and silica fume agglomeration statistics.

		agglomeration statistics				**compressive strength**	
	Mixer ID	vol. %	avg. intercept (μm)	specific surface (mm^{-1})	frequency (aggl./cm)	7 d	28 d
Dry blended materials	IM	3.2	167	19.6	1.6	79.9 ±0.8	93.1 ±2.2
	PL	5.3	99	49.8	4.0	66.9 ±1.4	93.1 ±1.1
	DR	7.8	115	42.7	8.3	59.1 ±1.1	92.7 ±1.2
	FP	3.2	101	49.8	4.0	65.4 ±1.2	98.0 ±0.8
Dry force packed materials	FP	no agglomerations observed				129.5	152.5

CONCLUSIONS

SEM analysis of the dry force packed mixture showed coating of the larger cement particles by smaller silica fume particles, providing thereby the maximum packing density. The forced packing resulted in physicochemical activation that provided the possibility for pelletization and briquetting. Petrographic microscope analysis demonstrated that dry blended material mixtures resulted in silica fume agglomerations, and only the mixture produced with dry forced packed materials achieved full dispersal of the silica fume. Compressive strength of the UHPC produced with the dry force packed material was the highest of all other UHPCs, which may be attributed to highest uniformity of the cementitious matrix.

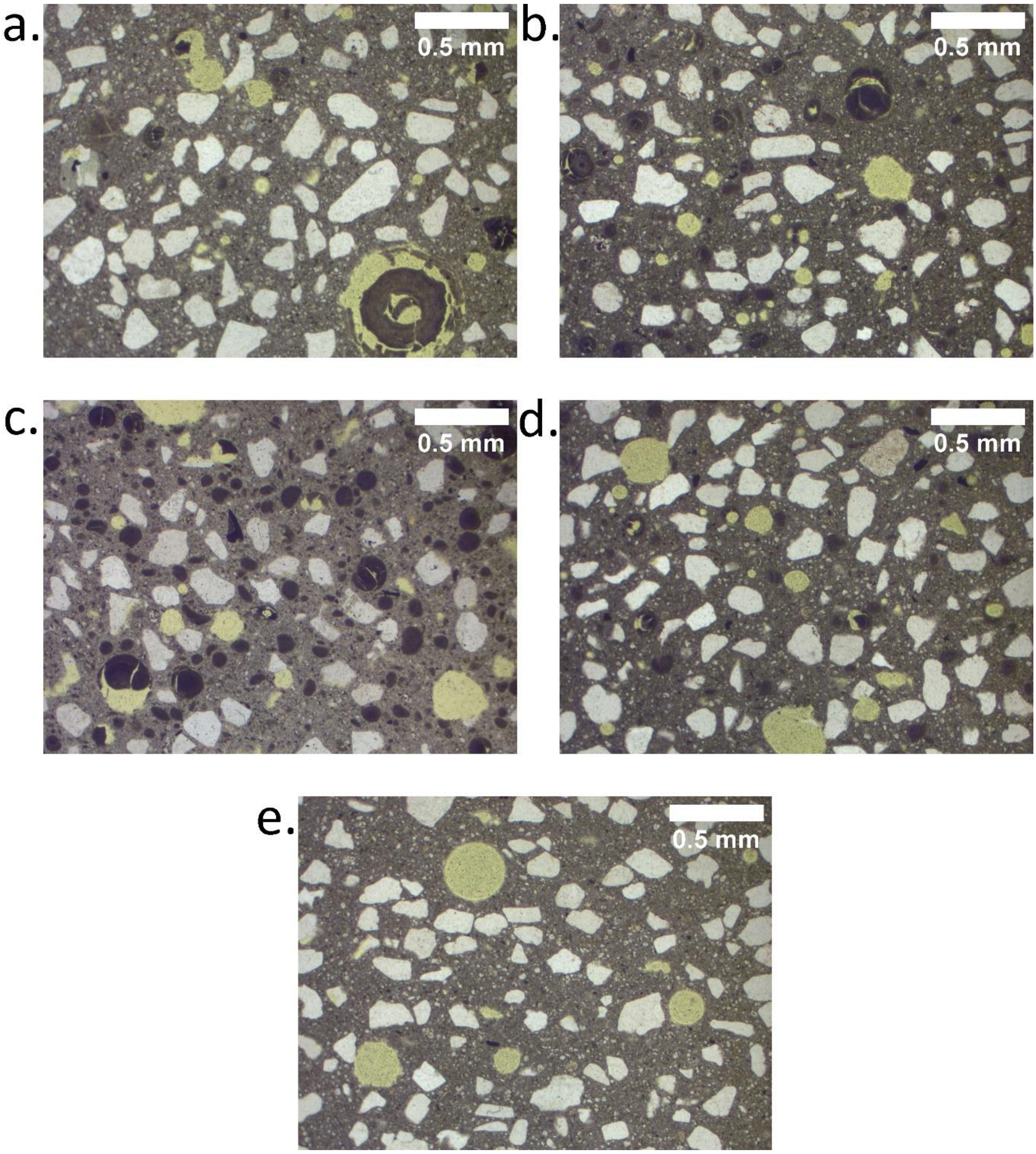

Figure 2. Silica fume agglomerations in dry blended material IM (a), PM (b), DR (c) and FP (d) mixtures, and absence of agglomerations in dry force packed material FP mixture (e).

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