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DESIGN OF ENGINEERED CEMENTITIOUS COMPOSITES (ECC) FOR PROCESSING AND WORKABILITY REQUIREMENTS

Gregor FISCHER*
Shuxin WANG**
Victor C. LI**

* Department of Civil and Environmental Engineering, University of Hawaii
2540 Dole St, Holmes Hall 383, Honolulu, HI 96822, USA
email: fischer@eng.hawaii.edu

** Department of Civil and Environmental Engineering, University of Michigan
2340 Hayward Ave., Ann Arbor, MI 48109, USA
email: shuxinw@umich.edu, vcli@umich.edu

ABSTRACT

The design of fiber reinforced cementitious composites (FRCC) is typically governed by their mechanical properties in the hardened state, such as the tensile and compressive strength and strain capacity. The intricacies of processing and workability of FRCC, with fiber volume fractions ranging from 1.5 to 20% depending on the particular composition, are often of secondary importance in small-scale laboratory production. However, the fresh composite properties significantly influence the performance of the composite in the hardened state, often leading to substandard mechanical properties due to non-uniform fiber dispersion or inconsistent compaction. More importantly, the large-scale application of FRCC in practice is often not feasible since special mixing equipment or processing techniques are required to overcome the difficulties associated with processing and workability.

In particular, the uniform dispersion of short, randomly oriented fibers in the cementitious matrix at fiber volume fractions of more than 1.5% typically requires force-based mixing equipment, such as high speed pan mixers, planetary mixers, or so-called omni mixers, which are commercially available at the laboratory scale ($5dm^3$ to $200dm^3$). These specialized mixers are relatively expensive for large capacities and are rarely on hand in most concrete mixing plants and at construction sites.

This paper focuses on the fresh mix design of Engineered Cementitious Composites (ECC), which represent one type of high performance FRCC with strain hardening and multiple cracking behavior. The particular version of ECC described in this study utilizes PVA fibers (d_f=39μm, l_f=12mm) at a volume fraction of 2%. The presented approach is guided by consideration of the practical requirements of producing cementitious composites at large scale under field conditions. The goal of this study is to design the composite such that mixing can be conducted in a conventional, gravity-based drum mixer while retaining the required workability and mechanical properties observed when mixing in a specialized, small-scale laboratory mixer.

A case study is presented for the development of a flowable ECC with self-consolidating consistency. This paper will present possible approaches to meeting these requirements, including control of the particle size distribution and chemical composition of the cementitious matrix, adjusting the mixing sequence and intervals, and proper utilization of cement types and common chemical admixtures.

Keywords
ECC, processing, liquefaction, workability, self-consolidating

INTRODUCTION

The fresh properties of concrete in general and fiber reinforced concrete in particular are of vital importance for workability in the fresh (plastic) state as well as for the material properties in the hardened state with respect to the stress-strain behavior and durability.

Fresh concrete should satisfy requirements pertaining to mixing and transporting, uniformity within and between batches, flow properties, compactability, avoiding segregation during placing and consolidation, and surface finish [1]. In case of fiber reinforced concrete (FRC), the requirements on mixing equipment and mix processing as well as uniformity of the material in particular with respect to fiber dispersion are essential to the application of FRC and its reliable performance in the hardened state.

Successful production of FRC hinges on proper fiber dispersion as well as workability and can be carried out by three general methods: 1) The addition of fibers to the cementitious matrix during the mixing process in a conventional, gravity-based drum mixer, which is typically limited to small fiber volume fractions below 1% and is viable for common construction purposes due to the wide availability of the required mixing equipment. However, for most FRC composites, a fiber volume fraction below 1% does not significantly alter the mechanical properties with respect to tensile strength and strain capacity. In method 2), the addition of fibers during the mixing process at moderate fiber volume fraction up to 3% in customized, force-based mixers, such as pan mixers, planetary mixers, or so-called omni-mixers is not practical for large-scale construction purposes and limited to laboratory applications due to the limited availability of large-scale mixing equipment. Similarly, method 3) placing of fibers at large volume fraction up to 20% in the formwork prior to infiltration with cementitious slurry (SIFCON) is not practical since it requires a specialized construction process.

Beyond the mixing process, the flowability, compactability, segregation resistance, and surface finish of the FRC are interrelated parameters as in conventional concrete but are additionally affected by the presence and volume fraction of fibers. While the workability of FRC with low fiber volume fractions (<1%) is similar to that of conventional concrete, High Performance FRC composites (HPFRCC) with enhanced mechanical properties in terms of tensile strength and strain capacity typically entail moderate or high fiber volume fractions (>1%), which consequently requires design of the composite fresh properties for adequate workability and reliable performance in the hardened state. In particular for applications of flowable HPFRCC with self-consolidating capabilities, the adjustment of the composite fresh properties is necessary.

Previous research on the fresh properties of self-consolidating Engineered Cementitious Composites (ECC), with poly vinyl alcohol (PVA, V_f=2%) [2] and polyethylene (PE, V_f=1%) fibers [3] focused on the rheological design by adopting a complementary electrosteric dispersion and stabilization technique to obtain cement pastes with desirable flow properties at constant particle concentrations. This technique involved the optimal combination of superplasticizer (melamine formaldehyde sulfonate, MFS), which acts as an electrostatic dispersant with a water-soluble polymer (hydroxypropylmethylcellulose, HPMC), which acts both as a steric stabilizer and viscosity-enhancing agent [2]. This approach lead to a fresh composite mix (Table 1) with desirable deformability, cohesiveness, and high consistency and is used as a benchmark reference (M-ref) for the work described in this paper.

In essence, the combination of polymeric admixtures (MFS and HPMC) is used to limit the flocculation between cement particles with appropriate dispersion (MFS) while achieving stabilization of the cement particles (HPMC), which consequently reduces the shear viscosity of the fresh cement paste and leads to a high deformability (flowability) of the fresh cementitious matrix without gravitational sedimentation (segregation) [2]. Mixing of the cementitious composite was conducted in a high-speed mixer with planetary rotating blade. The deformability of the resulting ECC was determined utilizing a conventional slump test cone and deriving a flowability index Γ.

While the use of HPMC was found beneficial in achieving a flowable ECC mix, it also introduces a relatively large air content in the mix (~20%). This air content consists of small pores (<1mm) as well as of relatively large voids (<10mm), which are entrapped during the mixing process and cannot escape due to the high cohesiveness of the mix.

OBJECTIVE AND CONCEPT

The activities presented in this paper aim at developing an ECC mix, which can be processed in a conventional drum mixer and has a flowable consistency with self-consolidating capabilities. The challenges in meeting this objective are: 1) avoiding the use of a stabilizing polymer (HPMC), 2) achieving uniform fiber dispersion in a gravity-based mixer, 3) obtaining a flowability index Γ exceeding that of the reference benchmark [2], and 4) obtaining a hardened ECC with tensile strain capacity of at least 3%.

The concept pursued in this study to meet the workability requirements under the given conditions is to design the fresh composite to be susceptible to liquefaction.

Liquefaction is a phenomenon known in geotechnical engineering as a major cause of ground failure during seismic events. This mechanism occurs when saturated, cohesionless soils under undrained conditions are subjected to monotonic, transient, or repeated disturbance. The tendency for densification of these particular soils causes an increase of pore pressure in between the solid particles, which effectively reduces the shear strength of the soil and causes it to behave like a fluid.

The utilization of this mechanism in the context of composite workability can be adjusted to result in a fresh mix with a relatively low viscosity in the disturbed state during the mixing process to achieve proper particle and fiber dispersion, flowability and self-compaction during the placing process, and the ability to maintain a stable microstructure in the undisturbed state after being placed in the formwork.

The design strategy is to create a densely packed, cohesionless, and well-dispersed particle system consisting of cement, mineral admixtures, and sand, which will liquefy at a water content within a range of appropriate values of water to cement ratio.

The micromechanics–based design framework for hardened ECC provides an upper limit for the maximum particle size of solids in the composite (d_{max}=200μm) and a lower limit for the fiber volume fraction (PVA, l_f=12mm, d_f=39μm, V_f=2%) to achieve strain hardening and multiple cracking behavior of ECC in the hardened state. While the water to cement ratio in the previous study was kept constant at w/c=0.45 to achieve a satisfactory first cracking strength as well as fiber/matrix interfacial bond strength [2], in this study the w/c ratio is in a similar range (0.36-0.45) but is primarily determined and optimized by the targeted liquefaction mechanism. The tensile stress-strain behavior of the composite is consequently verified for a selected candidate mix proportion with optimal workability.

In a first step, the dense microstructure of the particle system is achieved in this study by optimizing the particle size distribution of the composite using well-known guidelines for the aggregate gradation of conventional concrete [1]. Due to the small size of the particles governing the workability of the composite in the case of ECC, the particles considered for this ideal particle distribution include cement, mineral admixtures (fly ash), and sand. The particle size distributions of the individual solids used in this study are given in Fig.1. The ideal gradation of particles to produce dense packing and good workability was determined by Fuller and Thompson [4] and can be expressed by

$$f_d = 100\left(\frac{d}{d_{\max}}\right)^{0.5},$$

where f_d = fraction of particles smaller than d
d = particle size smaller than D [mm]
d_{max} = maximum particle size [mm].

A particle gradation close to this ideal distribution provides a dense and stable particle microstructure in the fresh state without the necessity for a viscous, HPMC-enhanced water suspension between the particles. The flocculation (aggregation) of cement particles is intercepted by a strong polyelectrolyte, known as a superplasticizer [2]. After the optimal combination of solid particles according to the above expression is determined, the necessary amount of water to achieve the transition between solid and fluid state (liquefaction) will be experimentally determined.

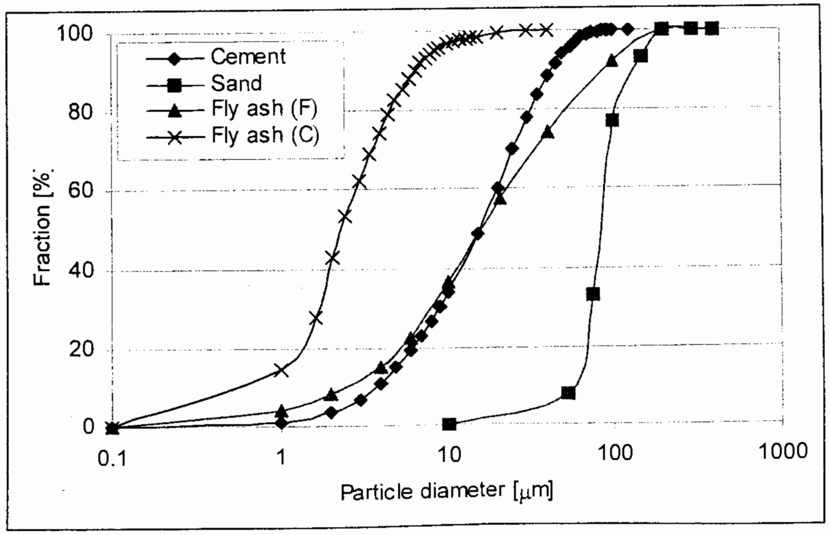

Figure 1 Particle size distributions of solids

Additionally, the cementitious mortar itself must autonomously provide the dispersion of fibers in a gravity-based drum mixer, due to the absence of a mixing blade rotating at high speed. This requires careful fine-tuning of the viscosity of the fresh mortar via the water to solids ratio.

MATRIX COMPOSITION

The materials used in this study were Type I cement, Class F fly ash, Class C fly ash, silica sand, water, superplasticizer (MFS), and PVA fibers. The composition of the solid particle system (except fibers) at the given individual distributions (Fig.1) was determined by fitting the composite particle size distribution to the ideal curve and reducing the deviation (Fig.2) using a conventional spreadsheet program.

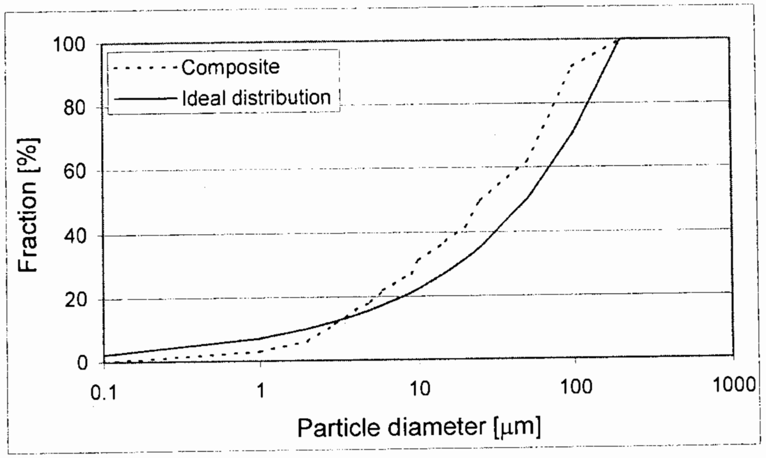

Figure 2 Composite particle size distribution

Using this procedure, the mass proportions between the solid ingredients were determined as follows: cement: 1, sand: 0.8, fly ash (F): 0.5, fly ash (C): 0.3. These solids proportions along with the weight ratio of superplasticizer to cement (MFS/C=0.03) were kept constant throughout this study.

MIXING PROCESS AND FIBER DISPERSION

The essential part to successfully mix ECC in a regular drum mixer is to maintain a fluid consistency of the cementitious mortar throughout the mixing process. Due to the lack of coarse aggregates, the grinding force and blending effect when the aggregates drop from the top of the drum do not exist in ECC mixing, and the only blending effect is due to internal shear friction within the ECC mortar driven by gravity and rotation of the drum mixer. Therefore, the raw materials feeding rate has to be carefully tuned such that the dry materials can be blended into the mix and be simultaneously dispersed and stabilized by the superplasticizer before flocculating. Meanwhile, excessive water should be prevented during the mixing process, as a flowable but viscous mixture is preferred to convey the dry powders.

In practice, the following mixing procedure is adopted. First, sand, fly ash and about one third of the cement are dry mixed for one minute. About eighty percent of the total water is then added. At this point, a fluid consistency and flowable mixture is easy to obtain due to the low content of cement in the mixture. Subsequently, cement and the remaining water additionally containing the superplasticizer are fed into the drum alternately at a rate not to cause the accumulation of large lumps of cement. In a mortar batch of 250dm^3, this process takes 8-10 minutes. Finally, PVA fibers are added. To facilitate fiber dispersion, the fibers are supplied in a bundled form by the manufacturer, such that the fiber bundles can be quickly conveyed by the mortar flow to reach a uniform distribution before the glue that bonds the fiber dissolves to further disperse the fiber. Typically, a uniform fiber dispersion can be achieved after 3 minutes mixing time given a proper consistency of the cementitious mortar.

CASE STUDY FLOWABLE ECC

The fresh mix characteristics of previous versions of ECC required special mixing equipment, such as a high-speed planetary mixer and were suitable for conventional casting with subsequent vibration to achieve compaction. The initial development of flowable ECC with self-consolidating capabilities was based on optimizing the combination of polymer admixtures. This approach was successful in improving the flow properties of ECC, as determined by a slump test and quantified by the flowability index $\Gamma=(D_F^2-D_0^2)/D_0^2$, where D_F is the diameter of the ECC cake after flowing and D_0 is the diameter of the bottom of the slump cone (20cm). The benchmark reference mix (M-ref) had a flowability index $\Gamma=12.3$ at a relatively high water to cement ratio w/c=0.45 and water to solids ratio w/solids=0.26 (Table 1).

Due to the relatively large volume of material required for the slump test, the development of flowable ECC in this study was initially conducted using a small-scale planetary mixer (V=2dm^3) and a small flow cone (d_0=10cm) commonly used for the preparation and quantification of the flow properties of cementitious mortar.

Table 1 Summary of selected mix proportions and fresh mix properties

	M-ref	M-1	M-2	M-3	M-4	M-5
Cement	1.00	1.00	1.00	1.00	1.00	1.00
Sand	0.60	0.80	0.80	0.80	0.80	0.80
FA (F)	0.00	0.50	0.50	0.50	0.50	0.50
FA (C)	0.15	0.30	0.30	0.30	0.30	0.30
w/c	0.45	0.36	0.37	0.38	0.40	0.42
w/(c+FA)	0.450	0.195	0.202	0.207	0.220	0.230
w/solids	0.260	0.134	0.138	0.142	0.150	0.158
MFS/c	0.020	0.030	0.030	0.030	0.030	0.030
HPMC/c	0.00150	0	0	0	0	0
d [cm]		13.5	16.0	22.5	25.0	25.0
D_F [cm]	72.9					90.0
Γ	12.3					19.25
Air content [%]	20.0				5.1	4.3

Using the solids proportions determined based on the ideal particle size distribution (Fig.2), a mix M-1 with w/c=0.36 and w/solids=0.134 showed a relatively stiff consistency similar to that of conventional cast ECC with a cake diameter after lifting of the small cone of d=13.5cm. Therefore, the water content for consecutive mixes was incrementally increased to w/c=0.40 in M-4 where the intended liquefaction mechanism was observed. The mix proportions used in M-4 resulted in a stable fresh mix with excellent fiber dispersion and flowability (d=25cm) showing no sign of segregation. The air content of mix M-4 was 5.1%, which is a substantial reduction from the air content of the reference mix (~20%) and due to the targeted dense particle microstructure and the absence of HPMC.

The transition of mix M-4 from the small-scale planetary mixer to the laboratory drum mixer (V=20dm^3), however, did not show the desired results. In the drum mixer, the mortar was found too dry, stiff, and not capable of properly dispersing the fibers. This discrepancy may be caused by a lower degree of particle dispersion in the drum mixer as compared to the planetary mixer. Due to the substandard fiber dispersion of M-4 in the drum mixer, a slump test was not carried out.

The water content was then increased in mix M-5 to w/c=0.42 and initially mixed at small volume in the planetary mixer. Flow properties of M-5 (d=25cm) were similar to those in M-4 (d=25cm), however, the air content in M-5 was 4.3% and further reduced compared to 5.1% in M-4.

Mix M-5 was then mixed in the laboratory drum mixer and all requirements with respect to workability were met. The particle and fiber dispersion were excellent due to a suitable consistency of the mortar. The slump test resulted in a flowability index $\Gamma=19.25$, which is a substantial improvement compared to the benchmark reference ($\Gamma=12.30$). The air content of mix M-5 processed in the drum mixer was confirmed at 4.3%. It is noted that despite a significantly lower water content in M-5 (w/solids=0.158) as compared to that in the benchmark reference mix M-ref (w/solids=0.260), a significantly higher flowability can be achieved. A demonstration of the applicability of this concept in general and mix M-5 in particular was successfully carried out using a conventional 250 liter drum mixer on a construction site.

VERIFICATION OF MECHANICAL PROPERTIES

While the primary focus of the study presented in this paper was on the fresh composite properties, the characteristic tensile behavior of ECC in the hardened state must ultimately be confirmed.

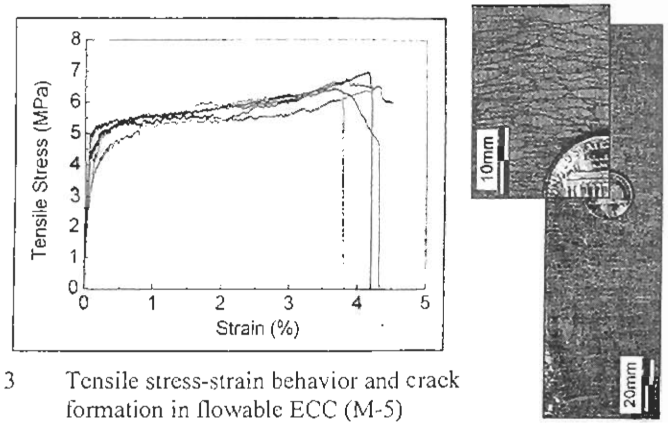

Figure 3 Tensile stress-strain behavior and crack formation in flowable ECC (M-5)

Direct tensile tests [5] were conducted on specimens originating from mix M-5 and strain hardening and multiple cracking behavior were confirmed (Fig.3). This particular version of ECC has an ultimate strength of approximately 6MPa at a strain of 4% with an average crack spacing of approximately 1mm.

CONCLUSIONS

An alternative approach to the design of the fresh properties of fiber reinforced engineered cementitious composites has been introduced in this study. The solid particle system of the cementitious matrix consisting of cement, mineral admixtures, and sand with known individual particle size distribution was optimized to achieve a relatively dense microstructure. At a sufficient water content and a certain extent of external disturbance, the cementitious mortar reaches a state of liquefaction, which reduces the mortar viscosity while maintaining a stable consistency without segregation.

This concept results in a composite design, which can be mixed in a conventional gravity-based drum mixer, does not require viscosity-enhancing admixtures, has excellent fiber dispersion, superior flowability, and self-compacting capabilities.

Strain hardening and multiple cracking behavior of this particular version of ECC in direct tension have been confirmed.

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