DYNAMIC LOADING PERFORMANCE OF FIBRE ENGINEERED CEMENTITIOUS MATERIALS WITH SELF-HEALING CAPACITY (SH-FECM)

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ABSTRACT

Structural performance under dynamic actions, apart from geometric characteristics, supports loading conditions, design methods, etc., is mainly related to the intrinsic material properties of the structural elements. Earthquake events, as typical examples of accidental dynamic loading, involve strong stress waves, induced in the structure in very short time intervals. Increased loading rates, difficult to withstand, are generated. Therefore, superior complementary characteristics, namely strength and ductility, are required in order to avoid sudden failure and, as direct consequence, casualties and economic losses.

Engineered Cementitious Composite (ECC), a unique type of mortar framed in the category of high-performance fibre-reinforced cementitious composites (HPFRCC), is defined by metal-like behaviour due to the multiple cracking patterns developed under applied loads. ECC proves an increased deformability potential and, as consequence ductility, which indicate a superior performance when subjected to dynamic actions. The multiple microcracking property of the composite, together with some specific matrix attributes and environmental conditions, also ensures an already proved self-healing potential [1], [2]. All these intrinsic material characteristics induce increased durability, considerable material and manpower reduction, improved structural performance and reduced repair and maintenance costs. Consequently, ECC is a valuable building material alternative and it is obvious that will bring a major to future sustainable development.

This paper presents the incipient evaluation of the dynamic performance of Fibre Engineered Cementitious Materials with Self-Healing potential (SH-FECM), developed using the ECC theoretical and applied design principles, in the terms of the strain rate sensitivity, which proves to be an essential and difficult to control parameter.

Keywords: microcracks, Engineered Cementitious Composites (ECC), crack control, self-healing capacity; loading rate sensitivity.

INTRODUCTION

It is generally accepted that dynamic loads act fundamentally different upon structures compared to the static or quasi static ones: there are increased energetic waves transmitted to the structure in relatively short time duration, implying raised loading/displacements, which become an important feature of the dynamic actions. Sudden collapse can occur, leading to life losses and important structural damage.

An earthquake is a complex dynamic loading with increased worldwide occurrence. Counteracting its fatal consequences can be seen as a general research and design challenge. The Cluj-Napoca Branch of the „URBAN–INCERC" National Research Institute for Construction Development in Romania focused since 2009 to develop an innovative concept in seismic design by post-tensioning hybrid precast frame structures. The critical spots of the tested models were identified as the narrow slots at the beam to column interface subjected to high local stresses, induced at raised strain rates. Therefore, it was decided to replace the filling grout with an advanced cement-based composite, with superior physical and mechanical characteristics. The general features of ECCs recommend them as a seismic performing material and a starting point for the development of SH-FECM by using local raw materials. Initial mix designs proved superior potential as intrinsic material characteristics and behaved properly during the full scale tests [3], [4] and [5].

Considering all above aspects, the evaluation of the ECC similar mixes by subjecting samples to dynamic loading was considered necessary to the overall evaluation of this kind of material. Next, first results of the theoretical and experimental program developed to investigate the dynamic performance of ECC are presented. Complementary, their self-healing potential is also assessed.

CONTEXT - SEISMIC RESISTANT HYBRID CONNECTION

Starting with 2009 two models of the hybrid seismic resistant joints were developed: first, the planar model and, starting with 2014, a new spatial model (Fig. 1).

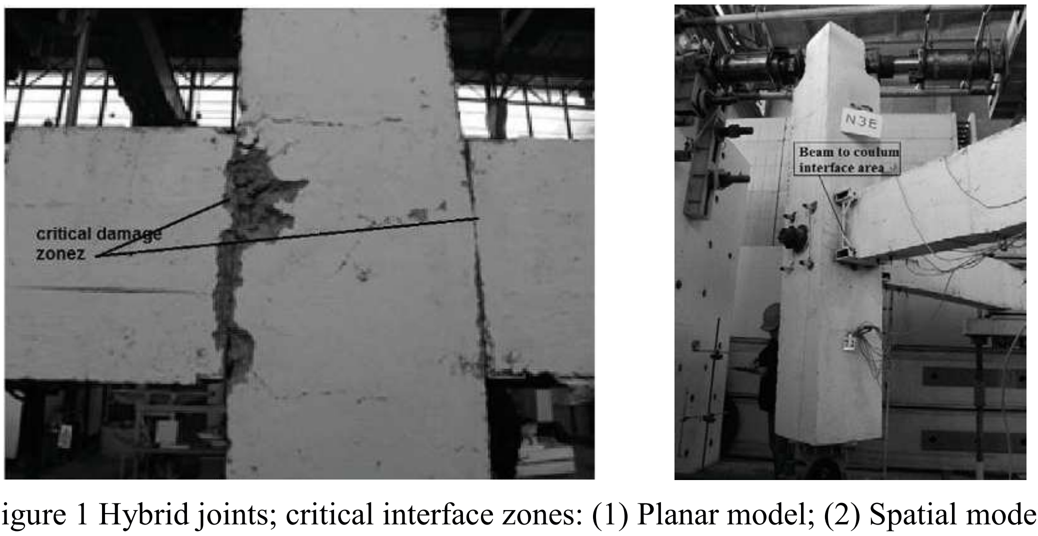

Figure 1 Hybrid joints; critical interface zones: (1) Planar model; (2) Spatial model

SELF-HEALING FIBER ENGINEERED CEMENTITIOUS MATERIALS (SH-FECM)

The critical areas at the beam-column contact interface require a superior filling material, with adequate workability and ability to fill narrow slots. Moreover, a good behaviour with regard to high-rate compressive and tensile stresses is needed, by ensuring deformability capacity for energy absorption [6], [7].

The first mixes proved good performance when tested to quasi-static loading, like tensile and compression tests done in accordance to EN 196-1 procedures. The same adequate behaviour was noticed during quasi-static alternant loading (see Fig. 2). The tensile strength determined at the age of 20 days (when the first element was tested) using the 3-Point-Bending (3PB) loading scheme, was 5.0 MPa and the compressive strength, 60 MPa. The composite showed good bond strength to the support layer, more than 5 MPa as the rupture took place in the support, namely the concrete beam/column of the element. Figure 2 shows the important degradation signs induced in the concrete structural elements, like large visible cracks and material spalling but impressive behaviour of SH-FECM as interface material [8].

Figure 2 Hybrid spatial joint model after testing - critical interface zone, bottom view: good performance of SH-FECM, no spalling or large visible cracks

The Self-Healing potential of the composite was evaluated after 50 wet and dry curing cycles, considering both complementary directions [8]: (1) Self-Sealing – the prismatic specimens showed partial crack-closing under visual analyses (Fig. 3, a);

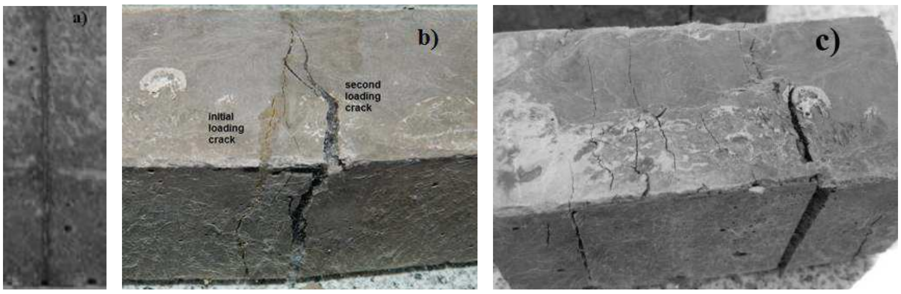

Figure 3 Self-Healing of SH-FECM specimens: a) Self-Sealing of cracks; b) Self-Repairing (distinct failure path when retesting); c) Micro-cracking under compression

(2) Self-Repairing – the prismatic specimens, initially loaded in 3PB until reaching the 90% of the bearing capacity were re-tested in the same condition after exposure to the curing cycles, showing tensile recovery ranging from 85 up to 100%, with respect to the strength determined at the age of 20 days. Supplementary, the healing products

developed in the cracks were strongly enough so the re-testing of one specimen produced a different crack as failure pattern, distinct from the initial one (Fig. 3, b).The compressive resistance, determined on the half prisms after the tensile re-testing, is of 72.0 MPa (Fig. 3, c) [8].

DYNAMIC PERFORMANCE OF FECM

The first testing procedures for the initial SH-FECM mix designs were performed under quasi-static loading, as previously mentioned; for a more complex material evaluation dynamic characteristics should be analysed. Load (-strain) rate sensitivity is identified as a crucial parameter for the material capacity of undertaking increased stress waves developed when subjected to accidental, dynamic loadings like blast, impact or seism [6], [7]. Loading rate sensitivity of Fibre Engineered Cementitious Materials was evaluated at Magnel Laboratory for Concrete Research, Ghent University, Belgium by the means of studying several mixtures of cement-based composites with polymeric fibres as dispersed reinforcement, subjected to specific tensile tests using different loading rates.

1. Materials

The raw materials provided by Magnel Laboratory, are typical for an ECC mix: the binding system (B) is a 1 to 1 combination of Portland Cement (C), namely CEM I 52.5 N and class F Fly-Ash (FA); Silica Sand (S) as aggregate with maximum grain size 250 µm; the High-Range Water Reducer (HRWR) polycarboxylate admixture is the BASF Glenium 51, (concentration 35%). A Belgium bicore Polypropylene (PP) was used as synthetic fibre, with a 6 mm length and 2% (by volume) content, as dispersed reinforcement of the mix. The essential characteristics of the raw materials are fully specified [9].

2. Mix Design

The analysed composite PP-M1.5 was designed taking into consideration as basic points: the classic ECC M45 [2], the initial SH-FECM previously studied [8] and also the specific mix designs previously developed at Magnel Laboratory, including the mixing sequences, that involve shorter, more efficient mixing stages, adapted for small experimental batches [9]. The FA/C ratio was selected 1.0, distinct from the 1.2 ratio previously used. The BASF Glenium 51 HRWR reduces significantly the specific ratios W/B or L/B. Table 1 presents the relevant mix proportions.

Table 1 Mix proportion: ECC M 45 and SH-FECM

C	FA	C +FA	S	W	HRWR	L	PP	W/C	W/B	L/C	L/B
ECC M45											
1.0	1.2	2.2	0.8	0.79	0.01	0.8	0.2	0.58	0.26	0.59	0.27
SH – FECM											
1.0	1.2	2.2	0.8	0.82	0.04	0.8	0.2%	0.83	0.38	0.88	0.40
PP – M1.5											
1.0	***1.0***	***2.2***	***0.7***	***0.6***	***0.023***	***0.62***	***0.2%***	***0.60***	***0.30***	***0.62***	***0.31***

3. *Testing* method

3.1 Dynamic Performance

Prismatic specimens 40 x 10 x 160 mm (Fig. 4) were subjected to the specific ECC tensile tests, namely Four-Point Bending (4PB) using 4 different loading rates induced in the terms of vertical displacement, converted into strain rates by considering the geometrical and the loading characteristics.

The loading/strain rates used for 4PB tests of the PP - M1.5specimens:

I. 0.0011 mm/s converted into the strain rate of 5.00 x 10^{-4} s^{-1};
II. 0.0055 mm/s converted into the strain rate of 2.50 x 10^{-3} s^{-1};
III. 0.0276 mm/s converted into the strain rate of 1.25 x 10^{-2} s^{-1};
IV. 0.1200 mm/s converted into the strain rate of 0.55 x 10^{-1} s-^{1};

The first strain rates are corresponding to quasi-static loading regime, the last two being relevant to the dynamic type: III - multi-cycle, seismic actions; IV – impact [8].

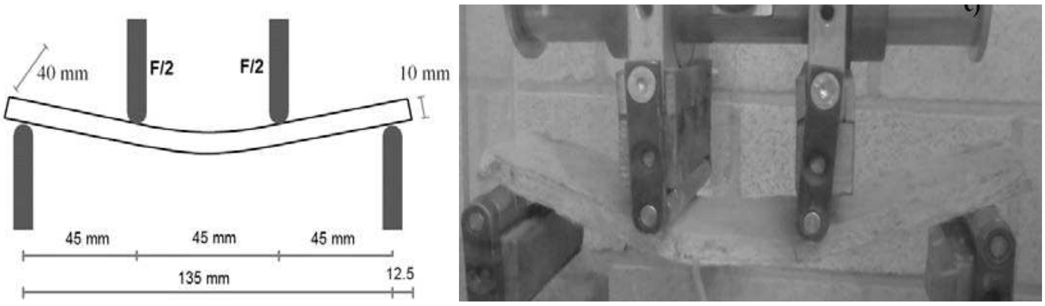

Figure 4 4PB test on PP-M1.5: a) 4PB loading scheme; b) Specimen during 4PB test

The characteristic stress-strain (σ-ε) diagrams were plotted and compared. The relevant mechanical parameters considered for the parallel evaluation are [9]:

- *Tensile strength (MPa)*: (1) the peak strength under loading (σ_{cu}); (2) the first-cracking-strength (σ_{fc}), namely the strength corresponding to the first force drop, producing the first crack in the specimen; (3) Tangent Modulus of elasticity (E), namely the slope of stress-strain curve
- *Ductility, in terms of strain (%) evaluated at the bottom part of the coupon specimens*: the total strain (ε_{max}), recorded from the beginning of loading and till the failure is considered to take place, usually when the force drops below the first crack force value; multiple cracking interval (MC) – recorded as the difference between the total strain (ε_{max}) and the strain corresponding to the first crack (ε_{fc}); multiple cracking interval (MC*) – recorded as the difference between the strain corresponding to the peak strength (ε_{cu}) and the strain corresponding to the first crack (ε_{fc});

3.1 Self-Healing Capacity

The PP – M1.5 coupon specimens were divided into two categories: (*1) Rupture specimens (R)*, loaded until failure at the age of 28 days; *(2) Self-healing specimens (SH)*, preloaded (age of 28 days) to an imposed vertical displacement of 1.5 mm, corresponding to an approximate strain of 1%, cured by exposure to 28 wet and dry alternating cycles and then retested until failure in similar conditions.

The PP – M1.5 Self-Healing performance was evaluated considering [10], [11], [12]: Self-Sealing (evaluation of crack closing efficiency) and Self-Repairing (evaluation of mechanical regain when retesting of the specimens, with respect to the initial preloading and also with the R type samples).

RESULTS AND DISCUSSIONS

1. Fresh State Mix

The fresh state of PP – M1.5 is plastic, with creamy texture and good workability. The PP fibres prove to have an expected tendency of balling which can be counteracted by careful mixing sequences, especially after fibres addition. It was noticed that the mix required a 1-2 min resting interval after mixing, to reduce the initial stiff aspect and became more fluid and proper for casting.

2. Typical Material Characteristics

The tensile and compressive resistances of the PP – M1.5 mix were determined using the EN 196-1 (cement) and EN 1015 (mortar) standard methods, at the age of 28 days and 60 days, respectively. The tensile strength was determined using the 3-Point Bending (3PB) method. Supplementary, the dry bulk density of hardened mortar was determined in accordance to EN 1015-10. Table 2 presents the typical physical and mechanical characteristics with the increase from 28 to 60 days (the retesting age of the SH specimens). The 17% increase in compression and 12% increase in tension are according to the expectation, considering the considerable amount of FA in the mix, with slower pozzolanic reaction and developing later hydration products than the pure cement-based composites [13]. A similar tendency can be observed during the 4PB retesting the SH specimens.

Table 2 Physical and mechanical characteristics of PP – M1.5 mix

Dry bulk density (Kg/m^3)	**Compressive resistance (MPa)**			**3PB Tensile resistance (MPa)**		
	28 days	**60 days**	**Increase (%)**	**28 days**	**60 days**	**Increase (%)**
2160	56.8	66.4	16.9	9.7	10.9	12.2

3. 4PB tensile tests under different strain rates

The 4PB tests were performed as previously described, using four different loading rates. The testing age was 28 days and the obtained results are reported in Table 3.

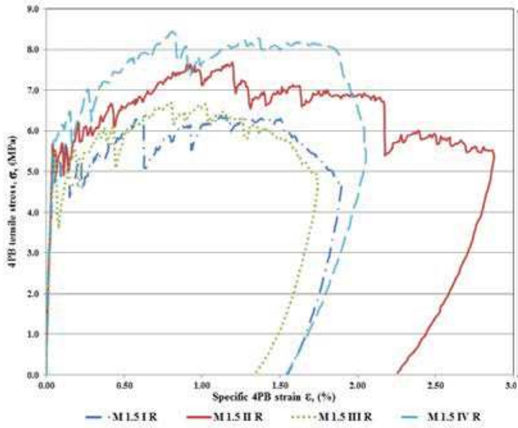

Figure 5 4PB test with 4 different strain rates

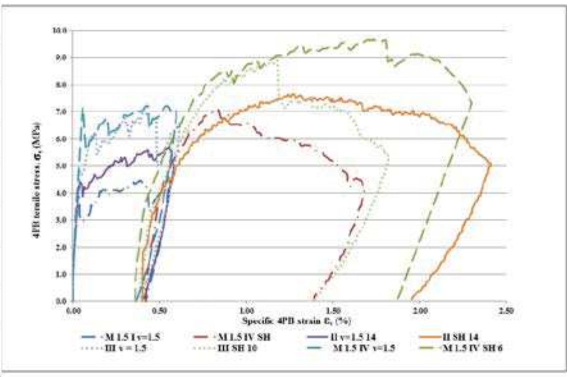

Figure 6 SH capacity: Self-Repairing, preloading and retesting

The results show a small strain rate sensitivity of the material, which is able to maintain approximate constant performance when subjected to slow and also fast loading rates. The IInd loading rate shows the best results in terms of balance strength / ductility.

Table 3 4PB test using different strain rates

Loading rate	Strength / Elastic modulus			Ductility		
	σ_{fc} (MPa)	σ_{cu} (MPa)	E (GPa)	ε_{max} (%)	MC (%)	MC* (%)
I	5.35	6.37	37.7	1.90	1.85	1.08
II	5.68	7.68	30.8	2.88	2.84	1.16
III	5.43	6.70	29.3	1.74	1.69	0.74
IV	6.15	8.44	31.3	2.05	1.95	0.70

4. Self-Healing Capacity Evaluation

The evaluation Self-Healing capacity of the material is still an on-going data analysis. Regarding the *Self-Sealing potential* of the material, the initial microscopic analysis shows complete closing of small microcracks (width less than 20μm) and partial sealing of larger cracks (Fig. 7). The *Self-Repairing potential* is evaluated by the means of 4PB retesting of SH specimens. As expected, there is an increase of maximum peak strength and a small drop in the ductility of material when increasing the loading rate (Fig. 6). Also, there is a clear regain in first-cracking-strength. So, the visual closure of the crack points to the regain in mechanical properties as well. Further evaluation of the results will be performed.

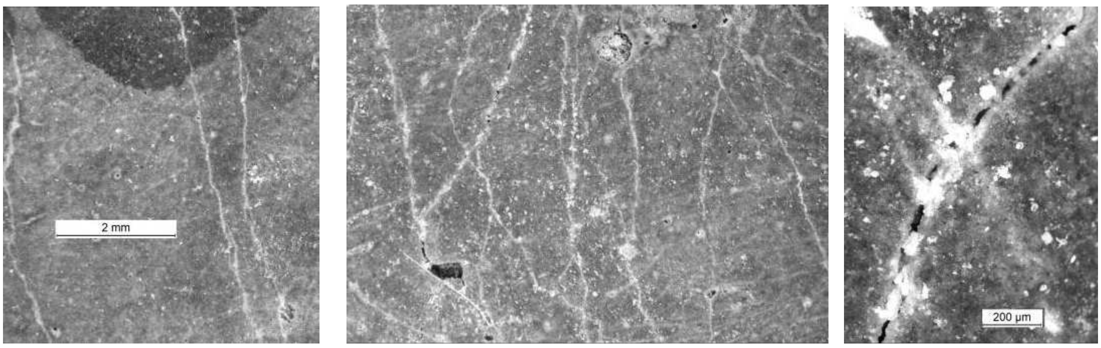

Figure 7 SH capacity: Self-Sealing - partial / complete crack closing

CONCLUSIONS

The theoretical and experimental study regarding the dynamic performance of the strain hardening cement composites (SHCC) proves encouraging results and, as consequence, recommends these materials for structural seismic resistant elements. Their low strain rate sensitivity proves high energy absorption capacity even in case of seismic action or impact, no brittle failure and prevention of sudden collapse threat.

The Self-Healing capacity also proves the effectiveness of autogenous healing, both in terms of visual crack closing (even complete in case of very small microcracks) and good mechanical recovery when retesting the specimens after exposure to 28 wet and dry curing cycles.

Further data analysis and supplementary experimental procedures, involving different types of mixes and testing methods are necessary for better understanding of dynamic potential of SHCC.

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