ENGINEERED CEMENTITIOUS COMPOSITES (ECCS): EVALUATION OF DIRECT FIELD OF APPLICATION IN ROMANIAN PRESENT INFRASTRUCTURE (ROAD AND CIVIL)

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ABSTRACT

The today Romanian infrastructure, road and civil, evaluated both in terms of existing or identified need of structures (buildings of different importance class and with different functionalities, roads, highways, viaducts and bridges, etc.), represents an essential part, with major and synergetic role in the society life and evolution. As consequence, its preservation and future development are major topics of interest in order to ensure the progress of Romanian space as part of European Union and European Community. Identifying the optimum solutions and the best materials for this major goal should become priorities for all parties involved in the process: research and industry, academia, economic and political entities. Engineered Cementitious Composites (ECCs) are therefore mentioned as a new type of cement-based composites, with unique features and superior performances, which can be developed, tailored and adjusted according to specific needs, destination and structural design. This paper presents a general introduction of them, their potential towards a sustainable infrastructure and also a review of ECC development in Incerc Cluj, with local raw material and with respect to some proposed fields of application.

Keywords: infrastructure (road, civil) Engineered Cementitious Composites (ECCs); crack control; self-healing (SH) potential.

REZUMAT

Infrastructura actuală românească, rutieră şi civilă, evaluată atât din perspectiva infrastructurii existente cât şi a necesarului identificat (clădiri de diferite clase de importanţă şi diferite funcţionalităţi, drumuri şi autostrăzi, poduri şi viaducte, reprezintă un element esenţial în viaţa şi evoluţia societăţii româneşti. În consecinţă, conservarea şi dezvoltarea acesteia devin sarcini strategice pentru asigurarea progresului spaţiului românesc ca parte a Uniunii Europene şi a comunităţii europene. Identificarea soluţiilor optime şi a celor mai bune materiale pentru acest obiectiv major ar trebui să se constituie priorităţi pentru toate părţile cu implicare în proces: mediul de cercetare şi industria, universităţi, entităţi economice şi politice. Compozitele de tip ECC sunt menţionate ca un tip nou de compozite cementoase, cu caracteristici unice şi performanţe superioare, ce pot fi ajustate şi induse în funcţie de domeniul de utilizare destinat precum şi de cerinţe de proiectare structurală. Această lucrare oferă o prezentare generală a ECC ca şi soluţie spre dezvoltarea unei infrastructuri sustenabile şi un scurt istoric al dezvoltării lor în laboratorul Incerc Cluj, cu materiale locale.

Cuvinte cheie: Infrastructură (civilă şi rutieră) Compozite cementoase ECC; controlul microfisurării sub sarcină; potenţial de autovindecare (SH).

1. INTRODUCTION

Worldwide, concrete and generally cementitious composites represent the most used building material category, due to their beneficial characteristics: versatility availability of local raw material, reasonable cost, high strength and good durability, mankind cumulated experience on concrete, developed along centuries of use and improvement. Concrete practice and use along years determined implicitly the need to improve it and counteract its weaknesses: modest tensile performance, brittle failure under loading, crack occurrence due to several causes, leading to severe durability issues; as consequences, the cementitious composites were developed: reinforcement was introduced for taking over tensile and shear stresses, resulting the reinforced concrete elements and structures; different type of fibres were added to the cementitious matrix, as disperse reinforcement, in order to prevent the brittle failure (Romualdi and Batson, 1963; Romualdi and Mandel, 1964). The synergetic performance of different combined materials, working together as a whole, developed the concept of composite materials, namely the cement-based composites.

2. ENGINEERED CEMENTITIOUS COMPOSITE (ECC) – GENERAL OVERVIEW

The concept of Engineered Cementitious Composites (ECCs) was established in the last decade of the last century, at Michigan University USA, by Professor Victor Li (Li, 2008); the fibre contribution within the cement-based matrix was carefully analysed in order to determine the optimum fibre content and the best fibre to cementitious interfacial contact in such way as to facilitate that fibre would be active even during SLS (Serviceability Limit State). The novelty of the concept is assuming the normal functionality of a multiple micro-cracked concrete, which is perfectly able to self-consolidate itself via active fibre bridge effect. The steady state typology of multiple microcracks cracks is thus successively generated under loading increase, the material still being far from reaching the failure zone. The prejudice against cracks is overcome by the fact that this specific, crack-controlled typology, their successive development under loading actually provides the ductile, metal-like behaviour of the composite, so unusual for cement-based materials. In the same time, the fine, small width multiple crack network generated within the composite does not involve durability issue, as the compositional design of the matrix allows fast closing (sealing) of cracks, due to its autogenous self-healing potential (Li, 2008).

Considering the design complexity which generates the overall behaviour of the composites, ECCs are included in the family of High-Performance Fiber-Reinforced Cemen-titious Composites (HPFRCC) (Fischer et al., 2003; Li, 1993) and represent a reliable solution for a sustainable infrastructure, both in terms of new structures or maintenance and repair techniques. Physical, mechanical and durability characteristics of ECCs generate an overall superior material behaviour under loading.

2.1. Crack control design criteria of ECC

The key of ECC behaviour, namely the strain hardening effect, is determined by the controlled microcracking pattern under loading, which is achieved only if the two design criteria, based on the mechanical interaction matrix – fibres, are simultaneously satisfied (Li, 2008; Snoeck, 2015):

a) The Strength Criterion;
b) The Energy Criterion.

The Strength Criterion is expressed by the simplified equation (1):

$$\sigma_0 \geq \sigma_{cs} \tag{1}$$

where:

σ_0 – the maximum fibre bridging capacity on crack plane;
σ_{cs} – the cracking strength;

The Strength Criterion determines the cracking development within the composite before the fibre bearing capacity is reached. (Fig. 1).

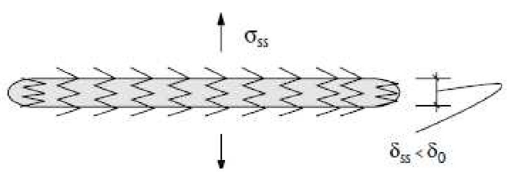

Fig. 1. Cracking pattern propagation within ECC: steady state type of microcracks when the Energy Criterion is satisfied (Li, 1993)

The Energy Criterion, based on energy balance (in terms of energy absorption, debonding and bridging effect, sliding) provides the steady state cracking pattern, namely controlled, constant width along the length type of microcracks, generated under loading, distinct from the Griffith type of cracks (with variable width along the length) (Li, 2008; Snoeck, 2015).

Besides the disperse fibres content within the material, established as optimum around the value of 2% (by volume), another important element for crack control development is represented by the binding system containing besides cement (C), a substantial quantity fly ash (FA), as principal addition to the mix; in case of ECC the specific ratio FA/C ≥ 1.0. It was proven that the raised FA addition in the mix would develop a certain lubricated character to the cementitious matrix, generating the sliding character of the fibres, allowing for the crack to be formed, the fibre to be active and still to bridge the formed crack and limit its width around the value of 60-80 μm (Fig. 2) (Li, 2008; Snoeck, 2015).

Fig. 2. Typical steady-state type of multiple cracks developed in ECC coupon specimen

2.2. Mechanical Characteristics of ECCs

The direct field of application for ECCs is wide and varied due to quite large variations of the used raw materials and mix proportions and that can be adjust considering the necessities in terms of physical, mechanical or durability requests demanded by the structural design. As consequence, the mix design can be adapted according to the specific need and its basic characteristics can be “tailored” (Li, 1993). Characterised by a rather moderate compressive performance, ranging from 20 to approx. 20-95 MPa (Li, 1993), the tensile performance represents a unique feature of the material: the general representative aspect in tension is the ductile, metal like behaviour of strain hardening composites opposing the brittle, single crack failure pattern specific to the cementitious materials. The tensile behaviour is clearly revealed by the means of Four Point Bending Test (4PB), which allows the specimen to develop the multiple cracking (MC) pattern to develop under loading and ensure the specific deformation of the specimen. The typical stress-strain curve, derived from the recorded force – mid-span displacement values, is presented in Fig.3.

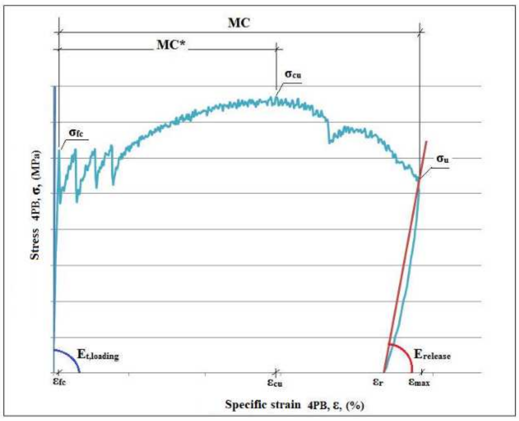

Fig. 3. Typical stress-strain diagram of an ECC coupon specimen subjected to 4PB test (Baeră, 2016)

The succession of stress drops presented on the diagram represent microcrack occurrence under loading (Baeră, 2016); the bearing capacity is not approaching failure, as stress value is rising again, proving that the material self-consolidates and it is able to bear more load. Failure is associated to the stress constant decrease on the diagram (the so-called stress softening interval), and it is associated of the exhaustion of the multiple cracking (MC) potential, which generally happens when one or two of the cracks dramatically enlarge under loading, becoming the failure crack(s) (Baeră, 2016).

The typical cracking pattern of ECC 4PB coupon specimen, which can be correlated to the typical stress-strain diagram, is presented in Fig. 2 and Fig. 5. The correspondent mid-span displacement after failure crack occurred (Baeră et al., 2017), is presented in Fig. 4 and Fig. 5 (after the specimen is removed from the testing device.

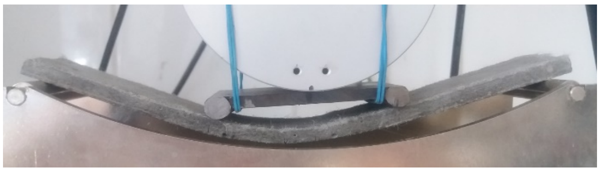

Fig. 4. Mid-span displacement of ECC coupon specimen subjected to 4PB test

Fig. 5. ECC coupon specimens subjected to 4PB test: residual mid-span displacement (after failure and removal of loading)

2.3. ECC – Self-healing capacity

The autogenous capabilities of cement-based materials are generally related to their intrinsic ability of closing (healing) the cracks that unavoidable occur within their structure, as a general feature of concrete or mortars. In the last half of century, it became an important research topic, considering the general attempt of developing a sustainable infrastructure, with superior building materials, requiring less maintenance and repair costs and implicitly prevention of natural resources consumption (De Rooij and Schlangen, 2011). Consequently, the autogenous ability of cement-based materials is analysed and constantly improved via different techniques: mineral or biological additions in the matrix, the microencapsulation of the healing agent, etc. (Van Tittelboom and De Belie, 2013; Dry, 2000; Homma et al., 2009; Mihashi and Nishiwaki, 2012, Snoeck and De Belie, 2012; Yang, 2008; Yang et al., 2009; White et al., 2001; Wu et al., 2012). In case of ECCs, there are considered engineered composites with designed stimulated autogenous healing potential. The superior ability of ECC to selfheal (crack closing and also recovery of mechanical performances with respect to the initial ones) represents actually the superposition of several factors (Baeră, 2016):

- The controlled multiple cracking feature of the material, generating a network of small width, steady-state cracks. According to scientific evidence in terms of self-healing phenomena, the autogenous crack closing efficiency is directly related to crack width: small microcracks, bellow 100-150 μm, can easily develop complete closing (Li and Herbert, 2012).
- The bridging effect of fibres across the formed cracks, not only limiting their width but also favouring the precipitation of healing products, (like calcium carbonate $CaCO_3$ or further hydration C-S-H products) along the fibre's length (Fig. 6).

Fig. 6. Partial sealing of ECC crack: precipitation products along fibres across the crack (Baeră, 2016)

3. DIRECT FIELD OF APPLICATION OF ECC

Considering that ECC design concept offers the possibility of high range interval for adjusting the material characteristics and performance in accordance to the identified need, specified by the structural design, it can be used for all types of application (civil and road) (Li, 2008). The diversity of applicability domains for ECCs (material, elements and structure), clearly demonstrated as highly performing in the purpose they were destined to, in accordance to the reliable experimental procedures worldwide performed and also via the practical applications where they were used, recommend these composites for the Romanian nowadays infrastructure. The ECC developed using local, Romania raw materials could represent new, sustainable solutions for the construction industry, for new structures and also as repair solutions, where ECC could prove itself fit and competitive in terms of performances (long term) and costs (Baeră et al., 2016a, 2016b).

3.1. General directions of applicability for ECC

The most used and versatile ECC mix, namely ECC M45 (Li, 2008; Kong et al., 2003; Lepech and Li, 2008) with self - compacting (SS) fresh state behaviour, is destined for cast-on-place, large scale applications (Fig. 7). The fast strength gain, generally imposed by road (transportation) infrastructure applications (repair or specific structural elements) was achieved for High-early-strength ECC (HES-ECC).

Fig. 7. In situ casting of ECC M45 with self-compacting fresh state behaviour (Li, 2008)

To lightweight structural design, requiring extreme reduction of dead load, was provided the Lightweight ECC (LW-ECC). The high strength and high modulus ECC were also obtained.

The self-healing capacity is mainly considered a general feature of ECC, derived from its basic micromechanical design and also behaviour under loading, as previously explained. Specifically, the SH-ECC, was tested and proven reliable regarding not only for crack sealing (closing), Self-Sealing (SS) but also the recovery of physical (transport) and mechanical properties, consequently functionality regain. The Self-Repairing (SR) potential is essential in terms of future maintenance and life expectations of ECC structures (Li, 2008).

Despite the fact that ECC is still a very new material that needs reliable confirmation for its design performances, independent of the theoretical approach or laboratory experimental evaluation, the ECC full-scale structural applications were already experienced in Japan, Europe and USA, with encouraging results (Li, 2008).

In order to produce precast elements like piping elements, special ECC mixes were developed for extrusion (Fig. 8) or for spraying techniques (shotcreting), proper for repair solutions, used in case of large surfaces (egg. retaining walls) (Fig. 9).

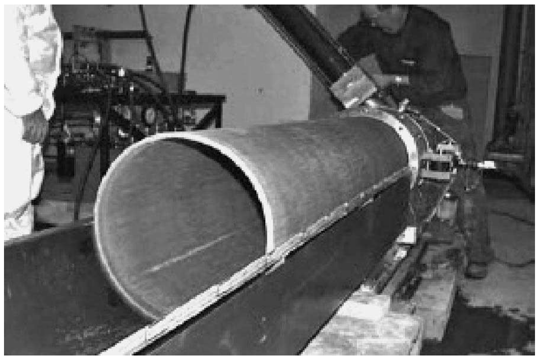

Fig. 8. Extruded ECC mix for piping elements (Li, 2008)

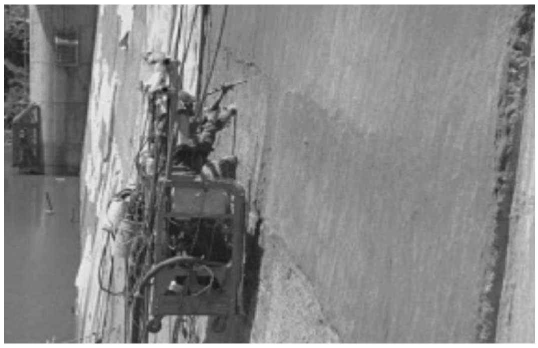

Fig. 9. Spraying ECC mix for large surface repair techniques (Li, 2008)

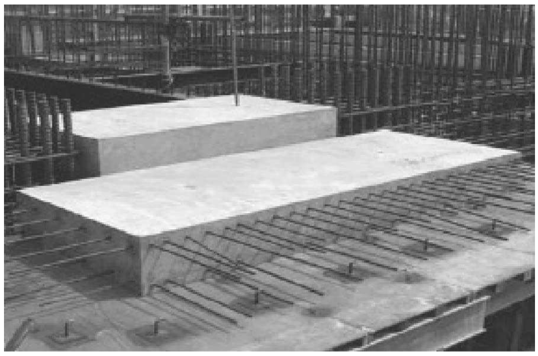

Fig. 10. Reinforced, precast, high performance ECC elements (Li, 2008)

The high fluidity of mixes, necessary for spraying or extrusion techniques, is also required for full-scale production of reinforced, precast, high performance elements (Fig. 10).

3.2. ECC -repair material

The long-term behaviour of ECC performing in real conditions is not really know, considering the novelty of the material. Generally, considering its behaviour under loading and superior tensile performances, of overcoming large displacements without losing the bearing capacities, we can estimate that ECC shows increased potential in the topic of repair and maintenance works.

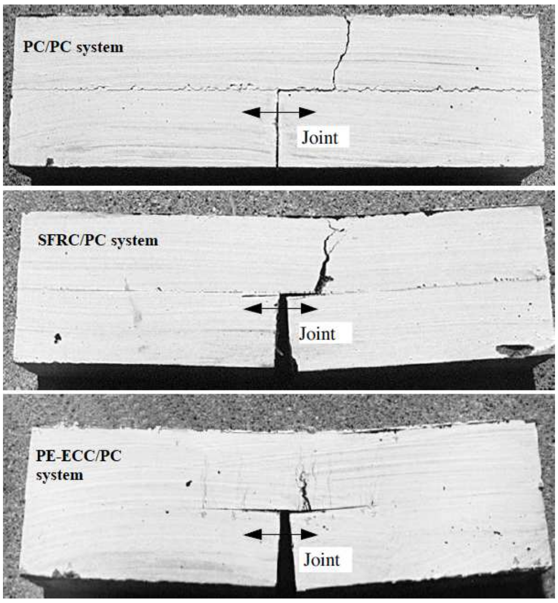

Fig. 11. Comparative analyses of failure modes for three distinct overlay systems: PC/PC, SFRC/PC, PE-ECC/PC (Li, 2003)

Experimental studies (Li, 2003) were performed in order to study the compatibility of ECC layer as repair material to the support layer, generally plain or reinforced concrete, for better understanding and potential improvement of the ECC mixes as repair mortar or also for the improvement of the consolidating techniques, generally. The comparative analyses of three distinct repair solutions: (1) plain concrete (PC), (2) Steel Fibre Reinforced Concrete (SFRC) and (3) PE-ECC overlays systems, concluded that the ECC solution was by far superior to the other two: in terms of spalling and delamination, also in terms of strength and energy absorption and also in terms of durability. The kink-trap phenomenon, generating microcracks trapping inside the ECC layer, will reduce the water penetration and improve the overall durability performance. The distinct failure modalities are graphically presented in Fig. 11.

4. ECC DEVELOPMENT IN ROMANIA

The first studies regarding ECC development in Romania by using local raw materials, took place in INCERC Cluj, starting with 2013, in the context of a complex fundamental research programme concerning optimisation of structures with respect to the seismic action (Baeră et al., 2016a, 2016b). The unique features of ECCs recommended them as column to beam interface material, within the planar and then spatial prototypes of the seismic resistant hybrid joint. The limited narrow spaces between beam and column joint were considered critical, both in terms of accessibility and also stress related (Fig. 11); they would require an advanced cementitious composite with self-compacting behaviour, which could be inserted in the specified areas, and also be able to support high, alternating compressive and yielding stresses, specific to the seismic action. A compositional balance would be needed as well, in order to ensure the sensitive balance of strength, train and energy absorption.

Fig. 12. SH-FECM placed at beam to column interface (Baeră et al., 2016a)

The SH-FECM (Self-healing fibre engineered cementitious materials) were developed, having as starting point the ECC conceptual design (Baeră et al., 2016a; 2016b).

The initial testing and evaluation showed promising results: the cast-in-place SH-FECM (Fig. 12), presented good behaviour during several seismic testing of the structural prototype, no spalling and perforation effects were recorded. The physical mechanical characteristics (specific weight, compressive and tensile performance, cracking pattern, bond strength to mineral support layer, etc.) as well as the Self-Healing evaluation of the material encouraged for further optimisation of the mixes. Present studies at INCERC Cluj are currently developing new and improved ECC mixes (Fig. 2, Fig. 4 and Fig. 5) based on complex and relevant evaluation procedures.

5. CONCLUSIONS

The first ECCs mixes developed in Romania, within INCERC Cluj-Napoca, by using Romanian local raw materials, showed encouraging performances and opened a clear path for future development, namely continuous compositional and mechanical optimisation, targeted application areas and compositional design according to specific requirements. The on-going project includes theoretical and experimental investigations in these specified topics.

Further complex evaluation procedures in terms of continuous compositional optimisation, mechanical performance, durability and self-healing testing, together with bond test and overlay system investigation and structural element testing are the future direction for a clear identification of direct field of application related to Romanian infrastructure (road or civil) specific need.

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