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Case study

High performance fibre reinforced cementitious composites: Six memos for the XXI century societal and economical challenges of civil engineering

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ABSTRACT

Worldwide increasing consciousness for sustainable use of natural resources has made "overcoming the apparent contradictory requirements of cost and performance effectiveness a challenging task" as well as a major concern. High Performance Fibre Reinforced Cementitious Composites, by providing tailored and multiple functionalized performance can represent an asset for the construction industry to face the challenges imposed by the needs of our continuously and fast evolving society. The paper, moving from a parallel with "Six memos from the next millennium" by Italo Calvino, the author will provide his own perspective on the current state on the topic, trying to highlight the benefits achievable through a reliable and consistent incorporation into a design and construction practice for both new and existing buildings and structures.

1. Introduction

The construction industry, which accounts for about 6% of global GDP (from 5% in developed countries up to 8% in developing ones) is called to play a significant role towards a sustainable and inclusive global worldwide growth, money invested in the infrastructure sector being expected to feature a Keynesian multiplier equal to 1.5 [1,2]. This is also due to the peculiar feature of construction industry, which, with total annual revenues of about 10 trillion USD and 3.6 trillion USD added values and more than 100 million people directly employed worldwide, serves all the industry verticals. Actually 38% of global construction volume accounted for by residential housing, 32% by transport, energy and water infrastructures, 18% by institutional and commercial buildings and 13% by industrial sites. With such figures, it is no surprise that the construction industry is not only the single largest global consumer of resources and raw materials but also one of the largest generators of solid waste as well, with, e.g., about 40% of solid waste in the US and 35% in EU28 countries (Eurostat 2014 estimate) being produced by construction and demolition activities [1].

With about 10 billion tons (corresponding to about 4 billion cubic meters) produced each year, which are larger than the total of all other building materials, including steel, wood, aluminium and plastic, concrete is the main actor of the whole construction industry. Its production and consumption feeds the demand for a likewise high production and consumption of the main constituents of concrete, including cement (more than 4 bln t/y), aggregates (about 48 bln t/y) and water, the latter representing a highly sensitive societal issue, competing with the access to water needs of the world population.

It would be anyway deceptive and misleading to limit oneself to these gross figures as an indicator of the "sustainability" of concrete as a construction material, most of all with reference to its carbon footprint. As a matter of fact, "the reason concrete has a high footprint as a whole is that there are just such huge concrete quantities used", and the reason for which it is used in such large amounts and "has been used in [. . .] pioneering architectural feats for millennia" is that "it is, simply, a

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remarkably good building material" and "is in fact a very low impact material" [3]. Moreover, "if you replace concrete with another material, it would have a bigger carbon footprint" [3]. This, besides the good performance of concrete in terms of, among the others, compressive strength, thermal inertia and cost effectiveness, is mainly due the worldwide local availability of its raw constituents.

The aforementioned environmental footprint of a construction material is only one aspect of the "sustainability" of the engineering application employing that same material, being it either a structural element or subassembly, a building structure or an infrastructure unit or network.

With the aim of providing a quantitative measure of the "sustainability index" of a construction material and/or of any kind of engineering application made with it, two methods have been recently proposed, which define either a Sustainability Potential Index [4] or an A(pathy) Index [5]:

$$SUSTAINABILITY\ POTENTIAL\ INDEX = \frac{ServiceLife \times Performance}{Environmentalfootprint} \tag{1}$$

$$A(PATHY)\ INDEX = \frac{Environmentalfootprint}{Performance} \tag{2}$$

the latter being obviously lower in the case of a better performing solution.

Both indices encompass the three traditional pillars of sustainability, namely the environmental aspects, through the environmental footprint, and the social and economic ones, through the performance and service life considerations, thus incorporating into a unique "decision making tool" information concerning impact resulting from the production of building materials, the erection of buildings and structures and the subsequent use thereof.

With the aim of providing a concrete answering to the sustainability challenges, the concrete industry in the last decades has been intensively working to the development and use of a new broad category of advanced cement based materials, namely High Performance Fibre Reinforced Cementitious Composites (HPFRCCs), which are able to provide tailored and multiple functionalized performance which can represent an asset for the construction industry to face the challenges imposed by the needs of our continuously and fast evolving society.

While not entering into specific quantitative assessment of any of the multiple solutions provided by the research and in several cases already available on the market, the paper, through an overview of what has been currently done to improve to sustainability performance of concrete materials and structures by acting on either one or the other factor of the afore defined indices, also wants to provide a modest contribution to dispel the myth of the construction industry as a sector traditionally regarded as highly inertial in implementing innovation. Through this, without any presumption to be exhaustive, the paper will provide the author's personal perspective on the topic. This perspective ventures into a parallel with the *Six memos for the next millennium*[1], a series of six lectures that the Italian writer Italo Calvino was expected to deliver for the *Charles Eliot Norton Lectures* at Harvard, which he never did because of his premature death. The lectures, which but the last one were ready at the time of Calvino's death and were published in a posthumous book, addressed the values (memos) of literature that Calvino felt were important for the coming millennium, *i.e. Lightness, Quickness, Exactitude, Visibility, Multiplicity.* All that is known of the sixth lecture is that it was to be on *Consistency.* These six memos will be taken as a reference to highlight, still from the author's personal point of view, the most exciting challenges that the civil engineering community can face through a reliable and consistent incorporation of advanced cement based materials concepts and performances into design and construction practice for both new and existing structures.

2. Reducing the environmental footprint of concrete and cement-based materials and structures

Efficient reduction of the environmental footprint of concrete and cement based materials and structures can be achieved through combined action aimed, on the one hand, at using materials with a reduced footprint themselves and, on the other, to the development of "environmentally" friendly material and structure concept, production and construction techniques.

In such a framework, the production of cement, as a primary constituent of concrete, plays a role of paramount importance, also considering it requires large quantities of raw materials (approximately about 2 tons of limestone and shale, where available, per ton of cement), and high energy (about 4 GJ per ton of cement) and produces about 1 ton CO_2 per ton of cement. This makes the cement industry responsible of about 5% not energy related greenhouse gas emissions worldwide.

It well worth remarking that both cement and concrete industry are really making giant leaps forward in improving their sustainability signature through the reduction of environmental footprint of cement production. The adopted measures range from optimization of cement production processes, including, e.g., reuse of waste heat or use of secondary fuels such as waste tires in cement kilns. Moreover, formidable research and progresses in concrete technology have promoted a tremendous optimization in the use of cement and binders. As highlighted by Damineli et al [6], a binder consumption per unit strength of concrete as low as 5 kg/[m^3MPa] is nowadays possible, thanks to mix-design concepts based on optimum

[1] Italo Calvino. Lezioni Americane. Sei proposte per il prossimo millennio. Garzanti, 1988. ISBN 88-11-59815-X (in Italian).

particle packing models as well as to the development and use of tailored admixtures. Moreover, the constant efforts in the reduction of cement demand for the production of concrete, the "performances" of interest holding the same, has long resulted into consolidated use of supplementary cementitious materials as replacement of cement in concrete and in the production of multi-blended cements, including fly ash, ground granulated blast slag, silica fume, natural pozzolans and by-products from a range of industrial and waste reclaiming/combustion processes [7]. Though expected to undergo a compound annual growth rate of about 6% in the coming five to seven years [8], the market of supplementary cementitious materials, whose largest share is currently detained by fly ashes, will have to face in the next short to medium term future the progressive shifting of power production from fossil fuel sources, which are one of the major sources of SCMs, to alternative ones as well as of the production of steel from ore to scrap.

Research on alternative binders, whose use may contribute to a further reduction in the demand of Portland cement and hence in the resulting use resource depletion and environmental footprint, including, *e.g.*, Calcium Sulfo-Aluminate cements [9], Alkali Activated Materials [10] and Limestone Calcined Clay Cements (LC3) [11,12]. The market penetration of these new potentially attractive technologies has anyway, on the one hand, to cope with the geographical proximity of supply chain of precursors, which is one of the most formidable advantages of Portland Cement technology. In some specific cases, the competition with other well developed industrial sectors, such as the aluminium industry in the case of CSA cements, has also to be considered. On the other hand, it has to be remarked that all the existing standards on concrete materials and products and concrete structural design codes have a cascading dependence on the assumption that Portland Cement is the main concrete constituent, even in the presence of supplementary cementitious materials.

These same statements hold true in the case of replacing natural aggregates with recycled ones obtained, e.g., from construction and demolition and/or other kinds of wastes or in the likewise interesting case of employing as dispersed reinforcement fibres obtained, *e.g.*, from scrap tires, waste PET bottles or natural vegetable ones from food and agriculture industry residuals [13]. In all the latter aforementioned cases the different properties of a recycled constituent from a natural (in the case of aggregates) or industrially produced one (in the case of fibres) have also to be carefully considered. This surely refers to the regularity and constancy of the physical, chemical and mechanical properties of the aforementioned constituents and, even more importantly, to the relation between the microstructure development and characteristics and its link with the macroscopic properties of the cementitious composite, which may even significantly differ from the ones on which structural design codes are based or implicitly rely upon.

Last but not the least the issue of water has to be considered. As a matter of fact, the prescription contained in standards and structural design codes worldwide referring to the almost exclusive use of potable water for concrete production may enter into not seldom dramatic conflict with the water needs of a fast growing population mainly in, but not exclusively, areas affected by permanent scarcity of water and/or droughts. In this respect, the use not only of water resulting from washing out concrete mixing equipment but also of treated waste water and even sea water in the mix-design may be deemed as conditionally possible, if not fully legitimized [14].

When designing and building an engineering and/or architectural feat, the "sustainability signature" of the employed material(s) has also to be analysed in the sight of their structural use. As a matter of fact, a higher level of performance can allow, *e.g.*, for the use of reduced quantities of a given material, the "sustainability signature" of the final application having thus to take into account not only the signature of the material but also its used volume. Moreover, a better performance can also imply reduced maintenance needs, which, all along the service life of the building and/or structure, do also contribute to the overall sustainability signature. The advent on the market of advanced materials in a starting phase is often accompanied by the simple improvement of existing structural concepts and construction techniques. Though, if the material aims to represent a breakthrough in the construction industry, the development of new advanced construction technologies implemented into suitably likewise innovative tailored structure concept, design and analysis procedure, which have also to consistently incorporate the life-cycle assessment of the performance, in a cradle-to-grave or even cradle-to-cradle approach, thus also addressing issues related to the recyclability of the employed materials.

3. What performance for what scenario? High Performance Fibre Reinforced Cementitious Composites pushing ahead the boundaries of structural concrete concept

A thorough evaluation of the sustainability of a construction work, in the framework of the built environment as a whole, has to consider the performance of the construction in service conditions all along its life cycle, including its durability, which is, as of today, one of the major concerns, if not the most dramatically serious one, of the construction industry. Reinforced concrete structures more and more frequently exhibit earlier and faster and more and more severe decay of their level of performance in the service scenarios and conditions they have been supposedly designed for.

Though a comprehensive analysis of the causes of the aforementioned problem is so far lacking, several issues can be called for to justify the somewhat premature decay of structural performance and anyway their higher durability sensitiveness, including, e.g.:

- current construction technologies, qualification of the workmanship and in some cases the same structure concept have not adequately paced up with the development in material concept and technology of concrete and cement-based materials;

- climate change and environment pollution issues, which accompany also a progressively increasing urbanization of the world population, together with the fact that the material and design concept together have pushed ahead the service stress boundaries, are going to threaten more severely the material, when in service in the structure [15].

Concrete is expected to crack because of its inherent brittleness and low tensile strength; for this reason, it is generally used in combination with, prevalently steel, reinforcement, which takes the tensile forces generated by the applied actions. Cracks open an ingress pathway for aggressive agents to penetrate inside a structural element, reaching the reinforcement and the inside bulk concrete, and activating complex degradation mechanisms, among which the corrosion of the same reinforcement is surely among the most threatening ones. Unexpected and/or not correctly predicted decay of the structural performance results into unpredicted maintenance needs which, besides being costlier than if correctly predicted and planned, hardly can restore the pristine level of performance, thus implying also an increased frequency of the subsequent following maintenance actions and an uncontrolled growth of the life cycle costs. Recent estimates have shown that, e.g., the cost of repairing corrosion damages (including also automotive and aircraft industry) sums up to about 3.5% of the world GDP [16] and that currently represents a significant share of the year budget of construction industry in developed countries accounts for maintenance and repair of existing structures. At the same time, the lifespan of the same maintenance and repair works is dramatically shortening, as from a case history analysis recently provided by the CON-REP-NET project [17], which has shown that 50% of the repaired concrete works failed again, 25% of which in the first 5 years after repair. A percentage share which increases to 75% and 95% respectively if the time observation frame is extended to 10 and 15 years after the repair.

A true "durability based" design approach is actually far from being formulated in current design codes, though it is appropriately recognized that the achievement of the required durability is the complex outcome of the suitable choice of structure concept and shape, material selection, as well as of the enforcement of "operational" design criteria, which limit the crack width under the anticipated actions to suitable scenario-based threshold values [18,19]. Limitation of crack width being hence recognized as the major requisite for the intended durability, concrete technology has developed, over the past fifty years, Fibre Reinforced Concrete (FRC). Thanks to the dispersed fibre reinforcement, an effective control of crack width can be achieved throughout the entire structure and starting from the very early ages. As a matter of fact, because of their wire-like features, fibres are able to interact with cracks much finer than what obtainable with the smallest commercially available bar diameters [20]. The boundaries of this concept have been pushed forward up to the formulation of the so-called High Performance Fibre Reinforced Cementitious Composites (HPFRCCs), whose composition is designed through micro-mechanical concepts based on fibre pull-out and crack tip toughness balance. Thanks to this, after the formation of a first crack, fibres effectively provide a through crack stress redistribution which enables new multiple cracks to be formed while controlling the opening of the previously formed ones, which are basically stopped from further widening, up to the unstable localization of one major crack. This makes the material able to "spread" the entity of a single damage (crack) into a series of tightly spaces and narrowly opened multiple cracks, whose single width is hence much less detrimental to the structural durability [21].

The HPFRCC concept is rooted into those which can be considered the three major innovations in the field of concrete technology in the second half of twentieth century, namely, besides Fibre Reinforced Concrete as recalled above, dating back to the early sixties, Self-Compacting Concrete, dating back, also through some precursors, to the late seventies and early eighties [22], and High Performance Concrete, also going back to some pioneer ideas put forward between the seventies and the eighties of the last century [23]. The combination of the performance benefits of the three technologies into a unique material, besides the well-known advantages in terms of more efficient and worker-friendly concrete production and application [24], results into one-of-a-kind features, an idea of which will be provided in the forthcoming section, which make HPFRCCs a valuable asset for the construction and civil engineering sector to face the challenges of the societal and economic needs of XXI century.

4. High performance fibre reinforced cementitious composites performing Calvino's six memos for the next millennium

4.1. Lightness

Committing to a sustainable built environment implies the "namesake" goal of "lightening" the burden on the environment by the activities related to the production, use and disposal of construction materials and engineering buildings, structures and infrastructures.

The effectiveness of the efforts ceaselessly lavished on improving the compressive strength yield by binders have been already recalled above [6]. Though, focusing only on the material compressive strength may be limiting if not misleading since it is the structure concept and the resulting structural use of the material which governs how much of the achieved and potentially "in-structure" available compressive strength is actually used and exploited.

In classical "beam" elements such share is limited by the tensile performance of the material, because of the need of sectional force equilibrium. In this respect, rather than the three-digits compressive strength of HPFRCCs, it is their signature tensile behaviour, featuring almost constant load bearing capacity up to significant strain levels (strain-hardening) that enables a remarkable tensile stress redistribution capacity over the cross section. This makes it possible, even continuing to adopt classical beam elements mainly working in bending, to significantly reduce the depth of structural elements, holding the load bearing capacity constant. Moreover, since the dispersed fibre reinforcement may even completely replace the conventional reinforcement in few specific applications, the depth of the element is not even longer constrained by durability-related minimum cover thickness requirements dictated by the need to provide adequate protection to the steel bars (See Fig. 1).

In Fig. 2a a typical application is shown, as proposed in [25], where, in the roof-deck arrangement of a precast reinforced concrete building, an 80 mm thick reinforced concrete slab, deemed to support its self-weight and, in case, snow load, can be effectively replaced, as also confirmed by experimental tests (Fig. 2b) by a 25 mm thick HPFRCC slab (the employed HPFRCC mix composition is provided in the inset Table). The resulting about 70% weight reduction does not only compensate for the high dosage of cement and binder in the bulk “per cubic meter” composition as well as for the expectable higher “per cubic meter” cost of the material (50% of which is due to the binders, 35% to the fibres, 10% to the admixture, sand and water accounting for the rest). This only considering the “material delivery” cost and deliberately omitting to consider aspects related to its durability, which will be dealt with later.

Such a remarkable “lightening” would also imply benefits on the design of the underneath supporting column and foundation structure, to an even more significant extent if the design in case of earthquake has to be performed, a larger mass on the top and its correspondingly higher earthquake induced inertia force resulting into a higher bending moment at the base of the columns and other lateral load resisting elements. Last but not the least, the reduced element thickness would allow also an optimization of the transport and handling operation and costs, the same truck being able to transport three times as much the number of roof slabs than in the case of the traditional reinforcement solution. This would not only allow a faster construction, also through reduced number of cranes with even lower lifting capacity, but also bring a further contribution to the overall sustainability signature of the whole construction process, *e.g.* through reduced impact on traffic and fuel consumption.

4.2. Quickness

The aforementioned considerations about the higher efficiency of the construction process that can be achieved thanks to the use, mainly - even if not exclusively - in precast construction industry, of HPFRCCs brings us into the second memo. The composition of HPFRCCs, resulting from the micro-mechanically based design recalled above targeted to achieve strain-hardening tensile behaviour, is characterized, as also observable from the inset Table in Fig. 2b, by a high content of binder, very low maximum aggregate size and high dosage of superplasticizer, to balance out the effects of the likewise required high dosage of fibres and low water content. This same composition is highly conducing to endowing the material with a superior performance (Fig. 3) in the fresh state, implementing the latin "*Festina lente*" (make haste slowly) motto through an adapted rheology characterized by a low yield stress, for enhanced flowability and self-levelling capacity, and a balanced viscosity, instrumental at guaranteeing an adequate resistance to static and dynamic segregation of aggregates and most of all of the fibres [24,26–29].

4.3. Exactitude

As addressed above, one of the advantages of incorporating fibres into a matrix with adapted rheology is the achievement of a uniform dispersion of fibres within structural elements, not even affected by their segregation [26–29]. This requisite is

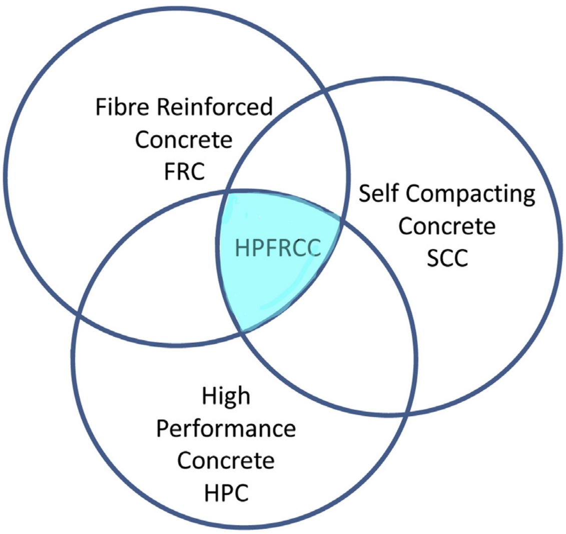
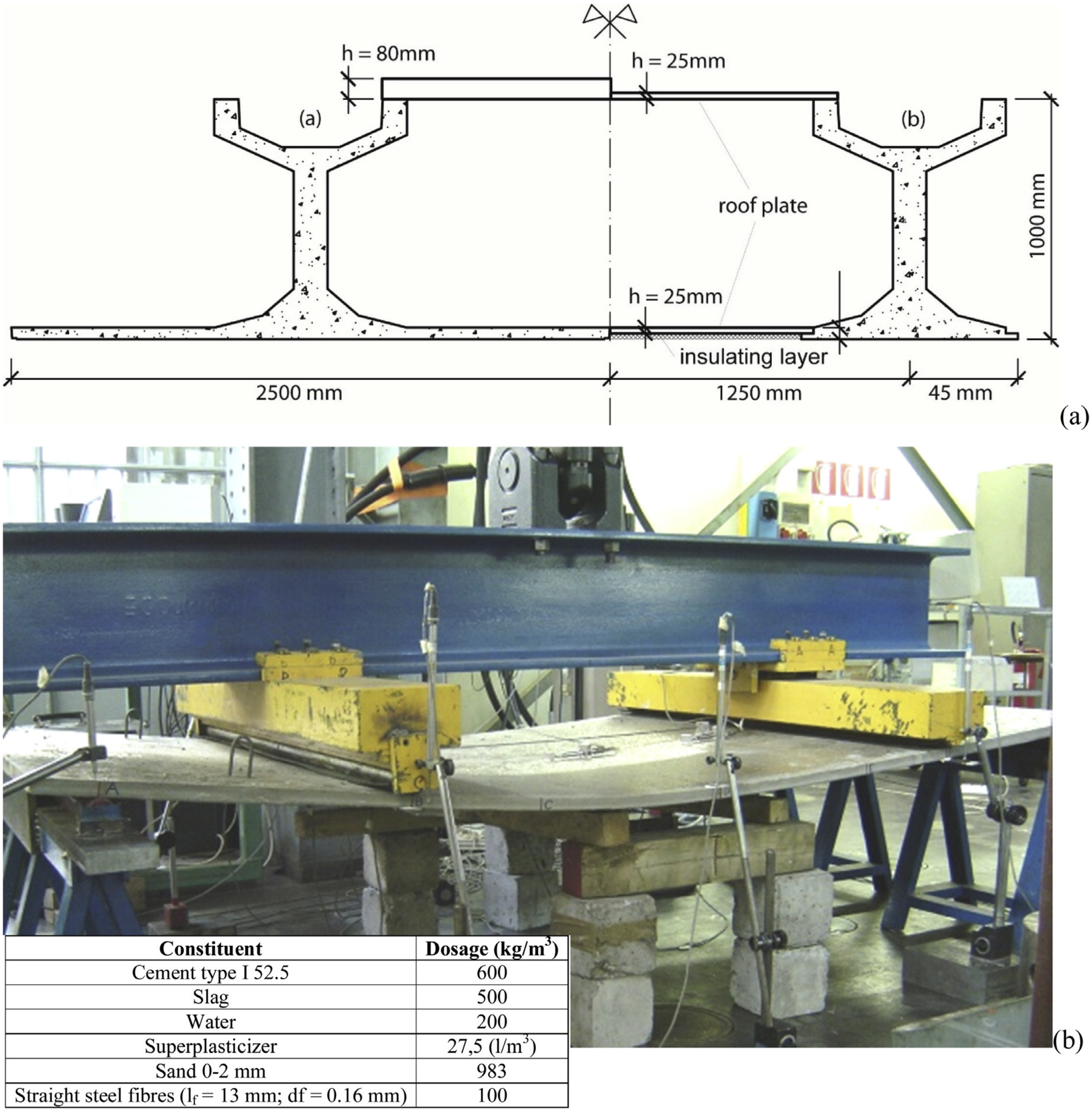


Fig. 1. FRC, SCC and HPC as precursors of HPFRCCs.



Constituent	Dosage (kg/m^3)
Cement type I 52.5	600
Slag	500
Water	200
Superplasticizer	27,5 (l/m^3)
Sand 0-2 mm	983
Straight steel fibres (l_f = 13 mm; df = 0.16 mm)	100

Fig. 2. (a) traditional precast roof deck arrangement (left) vs HPFRCC one (right); and (b) experimental testing the load bearing capacity of the HPFRCC slab [25].

of paramount importance for a reliable structural performance of elements made with Fibre Reinforced Concrete and Cementitious Composites.

A suitably adapted rheology, i.e. an adequately balanced performance of the fluid mixture as above, could also imply the possibility of effectively aligning the fibres along the casting-flow direction [28,30–34]. This preferred orientation of fibers is due to two concurrent causes: 1) the profile of the drag forces induced by the flow and 2) the wall effect [35]. Flows dominated by shear stresses feature a parabolic flow-velocity cross profiles with an associated distribution of drag forces (Fig. 4). This alignment can be practically considered, at the industrial scale, as an almost instantaneous phenomenon, since it occurs in a “maximum fiber orientation characteristic time” which is of the order of a couple seconds, which is far shorter than the duration of any real casting process [35]. The second cause for preferred alignment of fibers is the so called “wall effect”, since it is “not possible to find a fiber perpendicular to a wall at a distance lower than half the length of the fiber” [35].

By suitably tailoring the casting process to the intended application, i.e. combining Computational Fluid Dynamics modelling of the casting process [36–40] with classical finite element structural analysis, the flow direction of the fresh

Fig. 3. adapting the rheology of FRCCs (a–b) for enhanced fibre dispersion (c) [24].

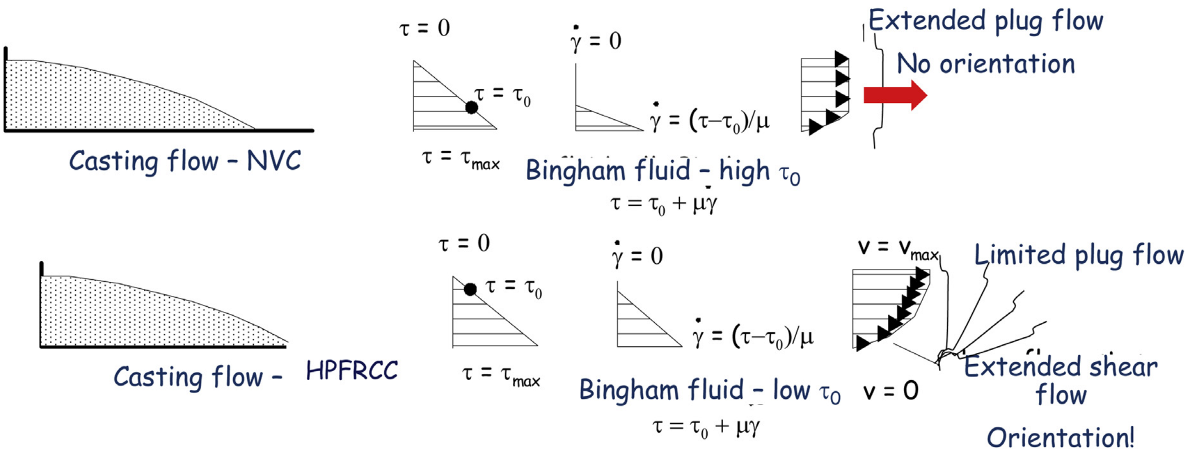


Fig. 4. Interaction of fibres with the casting flow of a Normal Vibrated Concrete (NVC) and of a HPFRCC with adapted rheology.

concrete, along which fibres tend to be aligned, can be made to coincide, as closely as possible, with the anticipated stress pattern (i.e., the direction of principal tensile stresses) within the structural element when in service. The fibre-alignment dependant material behaviour (Fig. 5) can be exploited through a better structural efficiency further contribution to the element size and structure optimization [25].

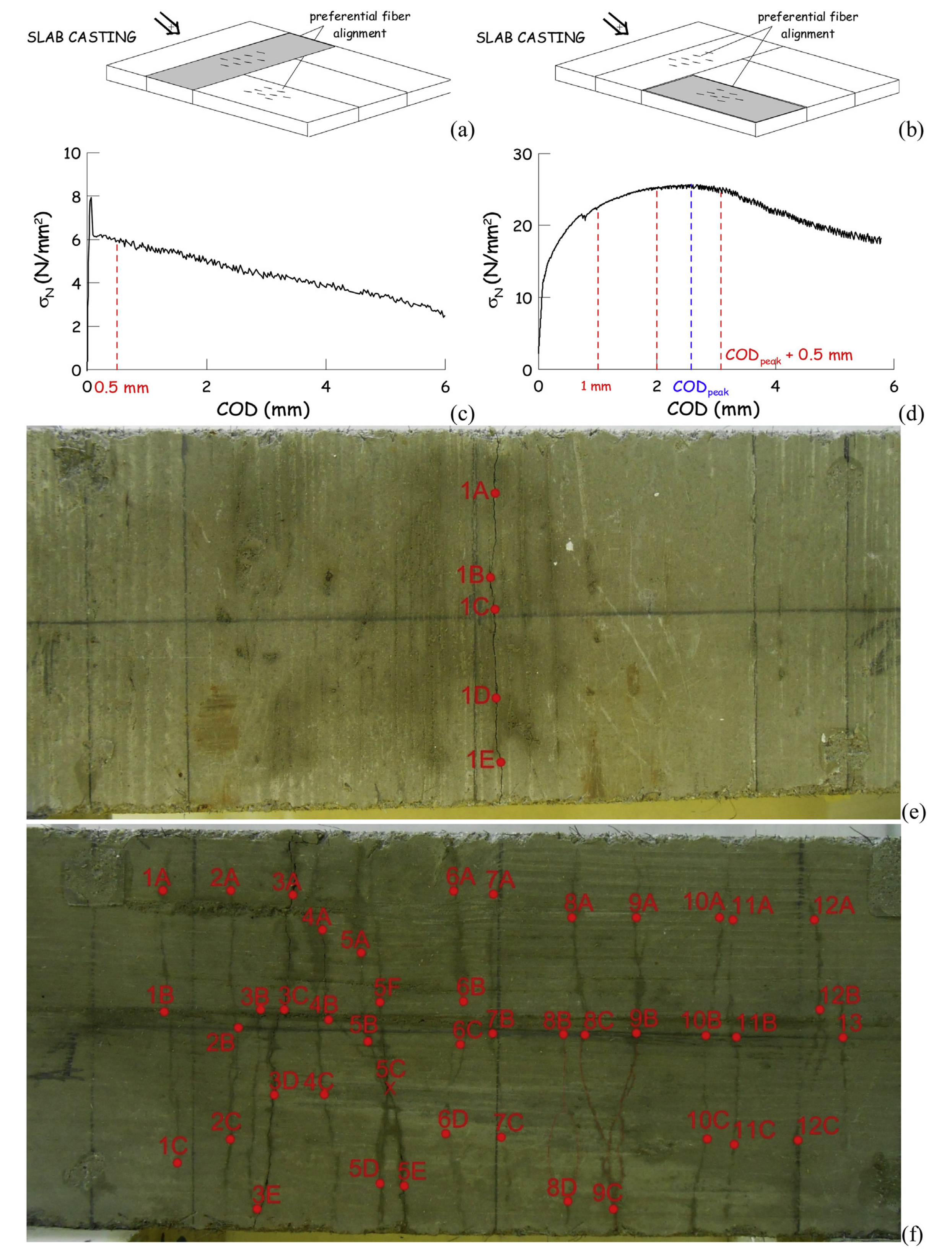


Fig. 5. Aligning the fibres perpendicularly (a) and parallel (b) to the flow and to principal tensile stresses in beam specimens; respective resulting deflection softening (c) vs. hardening (d) stress-crack opening behavior and single (e) vs. multiple cracking (f) [28].

4.4. Multiplicity

The advent and implementation of nanotechnology in the construction field, which is going to enable a metamaterial concept approach to construction materials which, through the manipulation of the most inner structure of the material would allow to obtain properties and/or levels of performance which could not be obtained and achieved through traditional processing [41].

Examples of research in this field range from the uncoupling between compressive strength and Young modulus [42], a topic of extremely high interest in the construction of high rise buildings, to the possibility of endowing concrete with self-sensing [43] or self-curing [44] properties, through, e.g., the respective use of carbon and cellulose nano-constituents, to the functionalization of fibre-matrix interface for tailored enhancement of the material performance.

Among the multiplicity of performance that the HPFRCCs are able to provide, it is worth recalling that the synergy between “extreme” crack width control and material composition, as described above, also results into a high conduciveness to autogenous self-healing (Fig. 6), with synergetic effects on the enhancement of the material and structural durability [45,46].

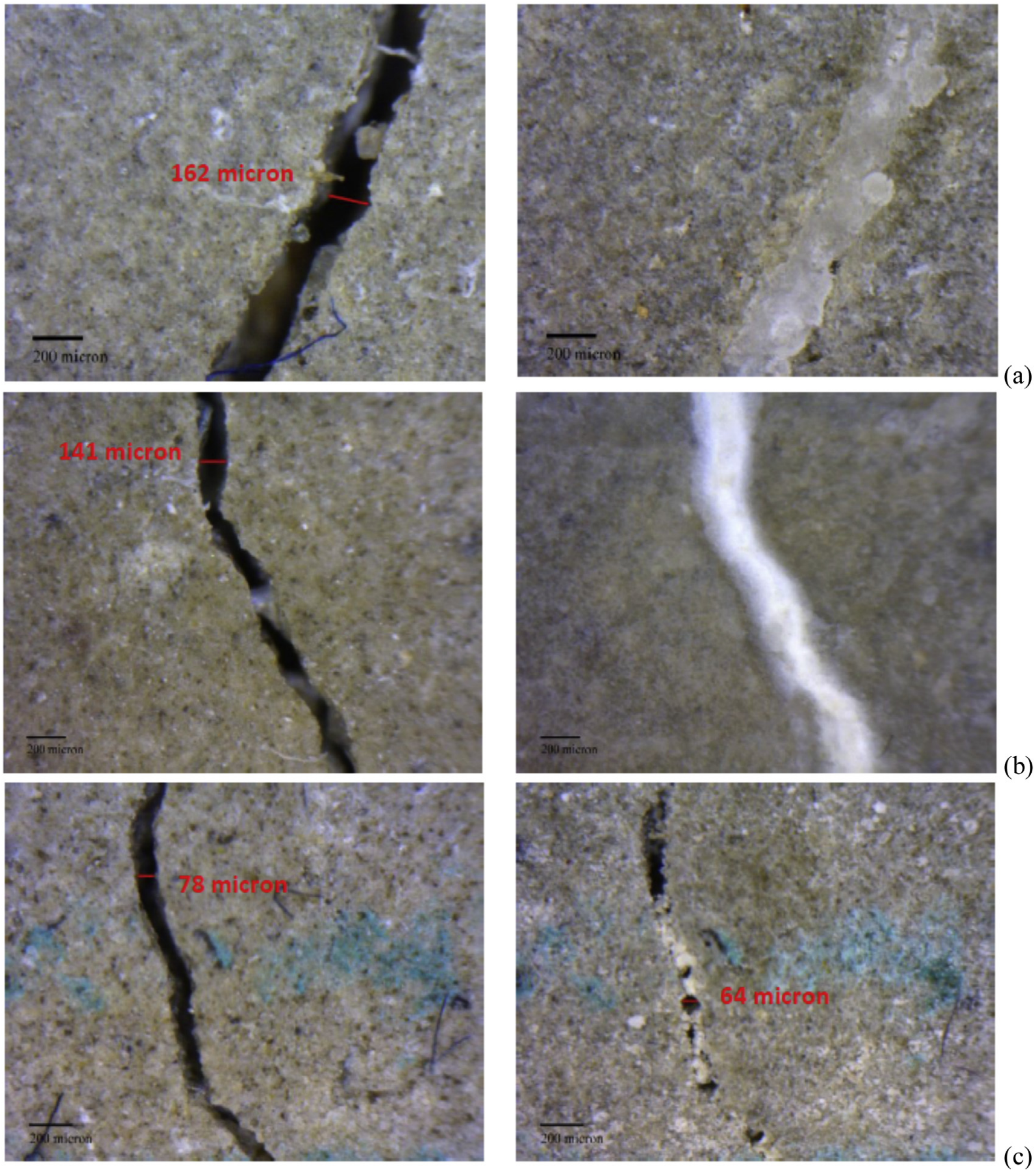


Fig. 6. Examples of cracks healing in HPFRCC specimens cured for 6 months immersed in water (a), subjected to wet and dry cycles (b) and exposed to air (c) [49,50].

As a matter of fact, the matrix is able, on the one hand, through its extremely high compactness and crack controlling ability, to slow down the penetration of aggressive agents into its core structure, and eventually to the level of the reinforcement. Thanks to its inborn self-healing capacity, the matrix is also able to progressively seal the same tightly spaced and narrow opened cracks, thus drawing towards a recovery of its pristine level of performance in the un-cracked state. The composition of this category of advanced cementitious composites features high contents of cement and supplementary binders, with either pozzolanic (fly ash, silica fume) or delayed cementitious activity (slag) and low water content. The resulting high amount of reactive material which remains un-hydrated and entrapped inside the bulk volume of a structural element may be, upon cracking exposed to outdoor environment, in case featuring presence of liquid or vapour water. These can both activate delayed hydration reactions as well as carbonation ones, whose products precipitate onto the crack surfaces sealing it.

Moreover, healing products, besides reconstructing the through-crack matrix continuity, are also likely to improve the fibre-matrix bond. It is furthermore worth remarking that the presence of the fibres and the signature tensile behaviour of the material make the aforementioned recovery of the pristine level of performance referred to the un-cracked state true for both durability and mechanical properties. This may also result, upon reloading a healed specimen, into the formation of new cracks, far from the healed one, instead of the re-opening of the latter (Fig. 7) [47].

Self-healing materials are well known in the field of biology. Blood clotting, skin wound healing and bone reconstruction are “sparkling” examples of self-healing functionalities inborn in biological materials which material science has successfully attempted to incorporate also in man-made ones, including, among the others, polymers, metals, asphalts, paintings and cement-based construction materials as well [48]. It is blatantly undeniable that the possibility of engineering or stimulating the self-repairing functionalities in cement-based materials would enhance the material and structural durability also resulting in reduced maintenance needs over an extended structure service life.

In the whole framework herein outlined self-healing cement-based materials would hence represent an exceptional asset for shaping the sustainability of the cement, concrete and construction industry [46]. The author has intensively participated into research related to stimulated healing through crystalline admixtures, well known and widely employed in modern concrete technology, being classified as a special type of permeability reducing admixture. Significant amount of work on their use as healing stimulators has been done [51–57], also investigating the modifications to the intrinsic concrete micro-structure brought by the crystalline reaction promoted by the additives *(*Fig. 8) [58]. Moreover, an interesting synergy with the dispersed fibre reinforcement has been observed [54]: the filling of the cracks by crystalline healing products is likely to activate a sort of chemical pre-stressing throughout the cracked material, from which the healing induced recovery of the performance is likely to benefit to a greater extent than in the case of ordinary FRC [45] (Fig. 9).

The multiplicity of the performance, so far analysed with reference to the material, can be easily extended to the scale of the structural element.

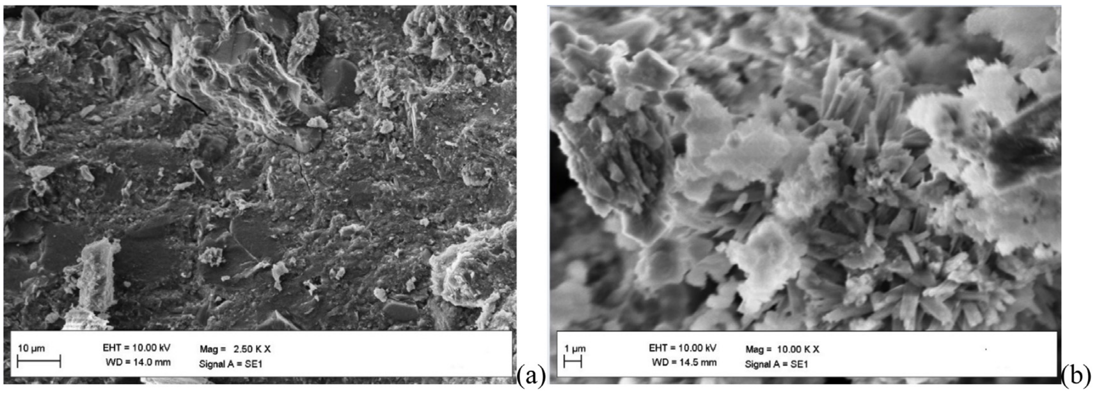


Fig. 7. Microstrucre of healed crack in concrete without(a) and with (b)crystalline admixture [58].

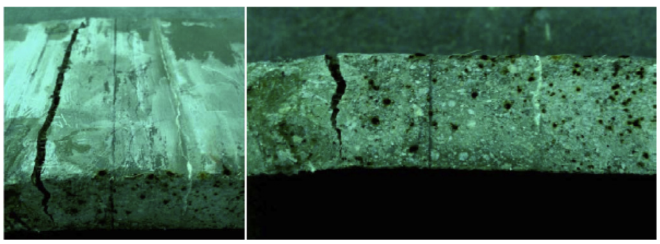


Fig. 8. Healed crack and new crack formed in post-healing tests on a UHPFRC specimen reinforced with steel and sisal fibres [47].

An example is the concept of layered composite element proposed by di Prisco et al. [59] which employs a top HPFRCC layer and a Textile Reinforced Mortar bottom layer, coupled by means of a high density Polystyrene panel, which performs the structural function of transmitting very low shear stresses and is used also for thermal insulation (Fig. 10). The low permeability of the HPFRCC in the un-cracked state and its self-healing capacity even led to avoid the use of a waterproofing layer. These elements are also characterized by a high fire resistance: in fact, when a fire occurs, polystyrene sublimates because the melting temperature of EPS (Expanded Polystyrene) is close to 160 °C. If suitable escapes for the smoke are introduced and a fixing device is designed to hang the textile thin layer to the upper HPFRCC plate, the empty chamber resulting the polystyrene sublimation acts as an ideal barrier against fire and the TRC panel works as a fire shield preserving the structural bearing resistance of the top HPFRCC plate.

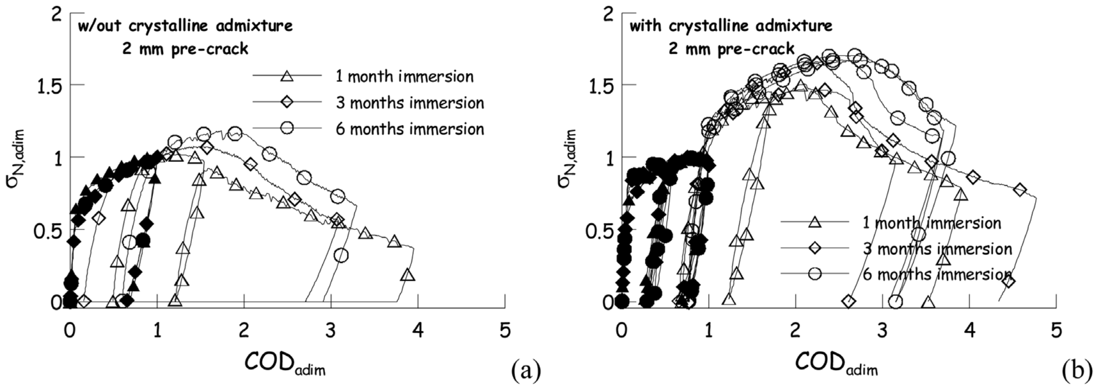


Fig. 9. Pre-cracking/post-healing stress vs. crack opening performance of HPFRCC specimens without (a) and with (b) crystalline admixtures [54].

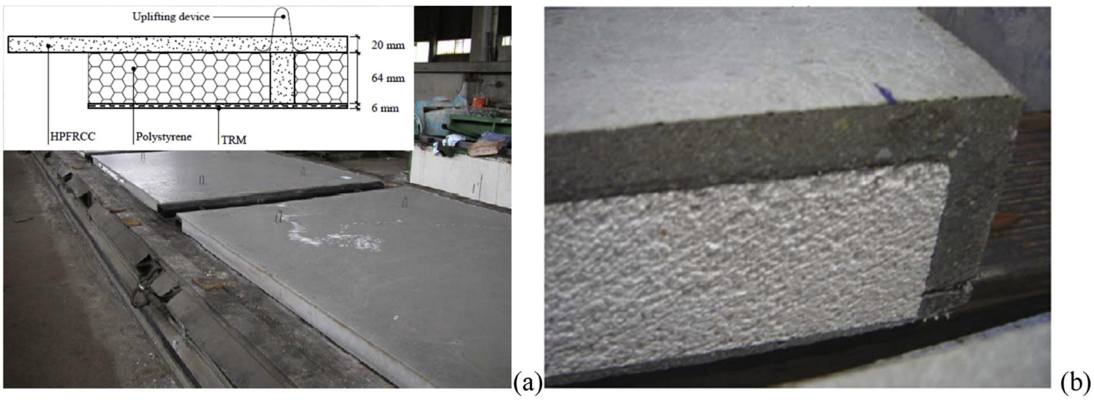


Fig. 10. Layered HPFRCC/TRC elements on the precast runway (a) and detail (b) [59].

Fig. 11. UHPC pedestrian bridge (right) built in Sherbrooke (QC, Canada), with its companion steel truss railway bridge on the left (author's own photo).

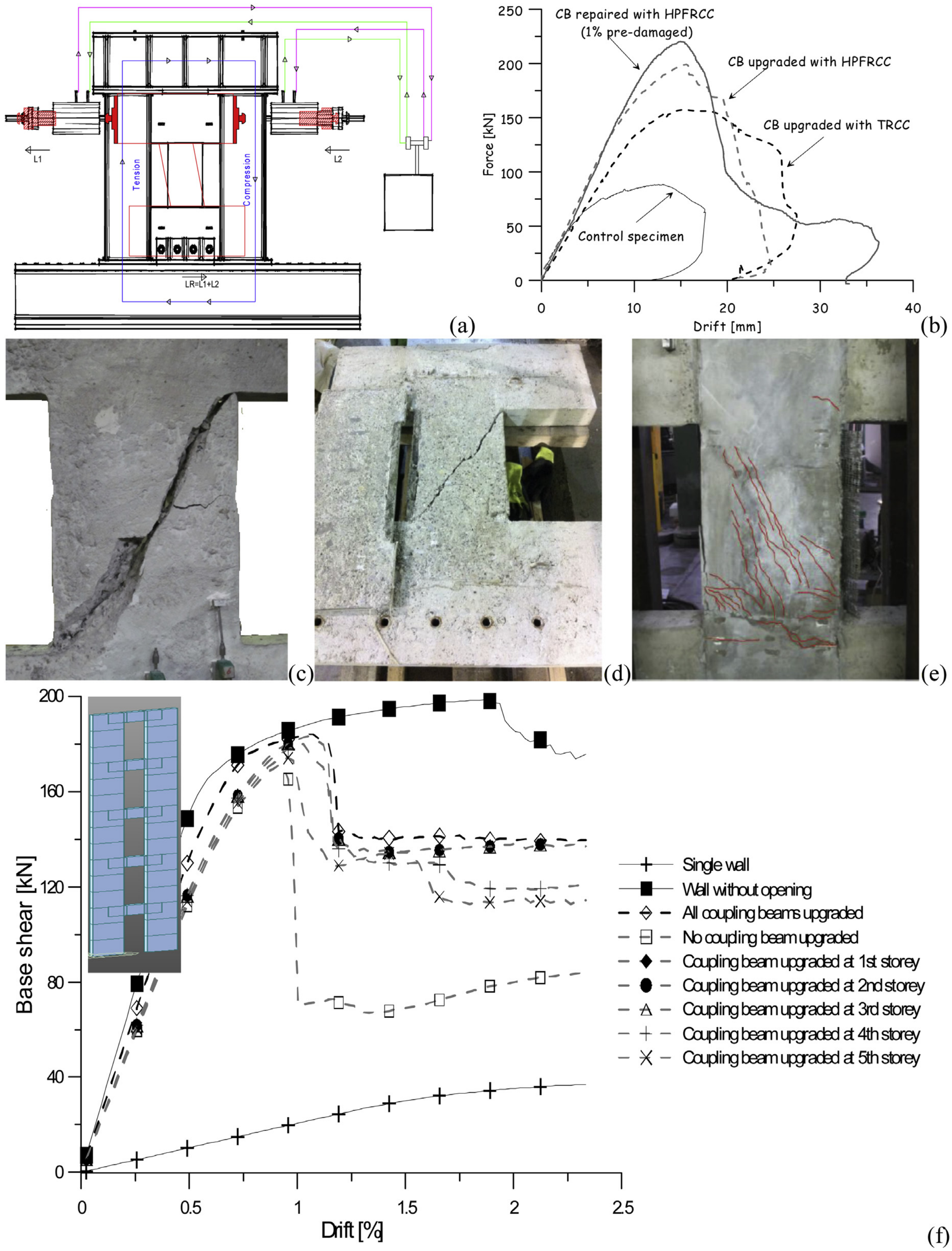


Fig. 12. Retrofitting of shear wall coupling-beams with HPFRCC: test set-up (a); load vs, drift performance for reference and retrofitted/upgraded mock-ups (b); diagonal cracking in an unreinforced beam(c) and in the unreinforced subgrade of a retrofitted one (d) as compared to multiple cracking in the retrofitted layer (e); and numerfical push-over curves for different retrofitting options, as compared to the performance of uncoupled two-shaft wall and monolithic wall [66].

The enhanced thermal performance makes them extremely attractive for an energy retrofitting of buildings, not disjoined from a likewise high efficiency vs. earthquake induced actions because of their reduced self-weight [60,61].

4.5. Visibility

It clearly appears, from what synthetically described in this section, that UHPC/UHPFRC can represent the starting point for the development of a consistent material and structural design approach aimed, on the one hand, at improving the durability and reducing maintenance efforts for structures exposed to extremely aggressive exposures. On the other, through a "holistic" design approach, which tailors both the material composition and the casting process to the anticipated structural performance, the orientation of fibres could be tailored to match as close as possible with the direction of the principal tensile stress within the structural element when in service, so to achieve a more efficient structural use of the material. The suitably balanced fresh-state performance of HPFRCCs would allow to mould the shape of an element and, thanks to a tailored casting process, to orient the fibres along the direction of the principal tensile stresses resulting from its structural function. In this way a desirable closer correspondence between the shape of an element and the function it performs in a structure assembly could be pursued in the design.

This result into a high "visibility", i.e. architectural value of structures made of HPFRCC, which, starting from the first UHPC pedestrian bridge built in Canada in 1997 (Fig. 11), are demonstrating on the field their excellent performance throughout the world [23].

4.6. Consistency

The aforementioned superior performance in the fresh and hardened state, also with reference to the expected long term durability, make HPFRCCs able to provide a breakthrough change in the current design and construction practice for both existing to-be-retrofitted [62–64] and new structures.

With reference to the former, the author reports its own experience with reference to the challenging design and application scenario such as the upgrading/retrofitting of coupling beams in earthquake resistant shear walls [65,66]. An adequate selection of the material allowed retrofitting layers as thin as 20 mm to be applied on the side and bottom faces of the coupling beam, as feasible in the practice due to operational constraints, and obtain the required enhancement of the load bearing and deformation capacity (Fig. 12a–b), accompanied by a transition from a brittle diagonal cracking (Fig. 12c) to a failure mode characterized by the ability of spreading the localized damage into the subgrade (Fig. 12d) into multiple tiny cracks (Fig. 12e). The possibility was also addressed of extending the retrofitting design concept from the single element isolated from its structural context to a "model" shear wall, in order to get back, even if not completely, the behaviour one through a tailored retrofitting, applied only to coupling beams at "selected" storeys (Fig. 12f).

With reference to new constructions, HPFRCCs can provide a breakthrough change in the current design and construction practice of infrastructures for energy harvesting from renewable sources, including wind, where also iconic feats characterized by a high engineering and architectural value are possible. Focusing on on-shore wind turbine towers, the projected and planned increase of wind-energy share in the total power need of several countries, is leading to the development and use of higher power turbines (e.g. from 5 to 10 MW) which employ rotors with diameters equal to 100 m or larger. At this height, several of the advantages of the current steel towers are lost due to their larger size, their lower stiffness, and the necessity for on-site completion. Under these conditions, concrete towers become practicable alternatives and economically attractive [67], providing taller hub heights and featuring advantages which, besides a variety of both precast and cast-in-place construction options easily achievable through the use of locally sourced materials and labour, also include lower project costs and potentials for reduction of logistics and transportation constraints, improved service life and, quite interestingly, also for repowering with the next generation of turbines.

Last but not least, HPFRCCs are ideal candidate materials to meet the challenges of implementing additive manufacturing and 3D printing technologies into the construction industry. As a matter of fact, thanks to their composition and behaviour, they can provide a "structural reinforcement" option which would otherwise have to be incorporated through alternative technologies [68], their performance also benefits from a fibre alignment almost inborn into, e.g., layered extrusion processing, at the same time also allowing for shape and structure size optimization [69].

5. Conclusions

In this paper, moving from a parallel with "Six memos from the next millennium" by Italo Calvino, the author has discussed, also based on the most significant results of its research in the last ten years, his own perspective on the current state on the use of HPFRCCs in civil engineering for both new and existing buildings and structures.

The thread-line which, in the author's opinion, has to inform and govern the breakthrough penetration of HPFRCCs into the construction market, moving from a prescription-based to a performance-based material and structural durability concept, aims at the breakthrough target of the overall resilience [70,71] of the engineering feats, which encompass:

- ***material robustness***, i.e. low sensitivity to changes in composition, handling etc., and structural robustness, i.e. the ability to withstand even unanticipated level of actions without disproportionate consequences, also in terms of degradation and

loss of performance; this has to include, on the one hand, the development of construction techniques really "tailored" to the exploit the full benefits of the advanced performance of HPFRCCs and, on the other, address the possibility of recycling the same materials and assess the level of performance obtainable through such a "rebirth" approach;
- ***structural and material redundancy***, through fit-for-the-purpose structure concept and a material able to provide, also thanks to its ability to spread the damage into a set of multiple tiny cracks, multiple-scale barriers to degradation: material imperviousness in the un-cracked state, crack tightness in the cracked state and activation of self-healing functionalities upon cracking;
- ***resourcefulness and rapidity***, through synergy between material functionalities and tailored design.

The vision highlighted in the previous subsections, through the values of *lightness, quickness, exactitude, multiplicity and visibility*, shall be *consistently* scaled up, through a holistic design approach. This has to move from the material to the structural durability level, anticipating the evolution of the structure performance and quantify the resulting increase in the service life of structures made of HPFRCC, and the related outcomes in terms of Life Cycle Cost and Social Life Cycle Analysis, both in cradle-to-grave and cradle-to-gate approach [72–74].

Moreover, it is worth always keeping in mind that new materials traditionally push for the development of new structural concepts and new construction technologies, and not only for improvement of the existing ones. In this respect, advanced manufacturing techniques, such as Digital Fabrication ones, could be really exploited as a key enabling technology to push for further spreading of the category of advanced cement based materials herein dealt with.

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In this paper, which reflects the presentation given at BCCM-4 in Rio de Janeiro, in July 2018, I have tried, in an intrepid parallel, to merge my passion for the Italian writer Italo Calvino with the results of about 15 years of research in the field of High Performance Fibre Reinforced Cementitious Composites. I am indebted to prof. Marco di Prisco, my PhD supervisor at Politecnico di Milano, and to prof. Surendra P. Shah, my supervisor during my Fulbright visiting scholarship at Northwestern University in 2006, who, through their mentorship, have instilled me the will to pursue a one-of-a-kind "holistic" perspective ranging from materials to structural applications which I have constantly tried to pursue in my work.

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