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Future research needs in the field of HPFRCC

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Abstract

Future research needs are presented and discussed. They address mechanics of materials, performance, production, structural design and testing. Although much knowledge on HPFRCC is available there is still a lot to do to facilitate the acceptance of HPFRCC in professional engineering. Research should help overcome this problem.

Keywords: Composite, Concrete, Design, Ecology, Economy, Fibres, High Performance, Mechanics, Performance, Production, Research Needs, Technology, Testing.

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1 Introduction

The title of this Chapter is ambiguous or incomplete because it is not clear who needs future research. Is it the researcher, the research institute, the owner of a building, the code maker, the producer, the state, the society or who? Is research needed for better understanding, for cheaper production, for more reliability, for greater safety, for wider acceptance? Is it the curiosity of the researcher or is it a practical need? All of these aspects are included in the title of this Chapter. An attempt is made to differentiate and to highlight some urgent needs for future research in order to promote the use of HPFRCC. As long as HPFRCC is an exotic type of construction material it will not be widely accepted because the benefits of its use cannot be estimated. Research is needed to make HPFRCC a *normal* material with predictable performance, easy to handle by *normal* engineers. Maybe, this is an illusion because HPFRCC is not a single material but covers a great range due to the many characteristics, such as type, geometry, distribution, and amount of fibres, type and composition of binder, filler, aggregate, admixtures, additives etc. On the other hand, normal concrete also is not all the same. It is ordered in classes to which some standard properties and requirements are attributed. As HPFRCC is concerned a system of *performance* classes could be developed in which various HPFRCCs would fit. To this end, more understanding of the material behaviour is needed, a clearer characterization, standard testing, and standard design procedures are prerequisite. There is a gap between the magnitudes actually measured and considered in research and those needed for design and execution. This makes that the application of HPFRCC is less advanced than research.

The following paragraphs address these items. The Chapter has a long list of authors all of whom have sent written contributions to the first author who has finally composed this Chapter. There exists a certain risk that the research needs here defined will be obsolete after the workshop when discussions have taken place and have generated new arguments.

2 Mechanics

2.1 General

HPFRCC is mainly a construction material to withstand external actions (mechanical, thermal, etc.). In a structural analysis, the behaviour of a component or a structure is predicted using theoretical models. The models have ounce been validated by experiments. The models should be as simplified as possible and as sophisticated as necessary, they depend on the purpose of the analysis. It is usual to distinguish between the micro-, the meso-, and the macro-level of modelling. The first two belong more to fundamental understanding while the last one is typically the practical field of engineering. It is always the understanding on a deeper level which is necessary for the modelling of the next higher one (the nano-level is here not considered). Since the mechanical behaviour is of outmost importance for the structural engineer a special paragraph is devoted to it although mechanics is of course also part of performance which is dealt with in paragraph 3.

2.2 Fundamental

Composite means that several materials are bonded together. The interfaces between two materials are important for the behaviour of the whole material. There is still a lack of understanding of the mechanisms that control the interfacial properties. There is also a lack of modelling the interfacial characteristics. The interfaces control to a great deal cracking, i. e. crack spacing and crack width. Crack bridging by fibres is essential for the post cracking behaviour under tension and shear. A systematic description of the influence of all relevant parameters on crack bridging is not yet available. On a meso-level where individual fibres are considered embedded in a matrix, stresses should be analysed in the vicinity of fibres as function of external actions and time. Creep (or relaxation) and shrinkage play a part in the overall behaviour.

Another aspect concerns the fracture process in HPFRCC and the energy dissipation distribution. Are there fracture process zones uniformly distributed in the composite, what is the size of a process zone, how is the energy consumption of a process zone correlated to the global load-displacement response? Is it enough to study the fracturing behaviour in two dimensions, what are important 3-D effects? The question arises about the existance and importance of size effects in HPFRCC.

What is needed for a reliable analysis or simulation are constitutive relations. Depending on the type and amount of fibres and on the matrix, theory of elasticity may serve at small stresses, theory of plasticity may be the basis at large displacements, but the transition from one to the other will be complex. Strain hardening and softening have to be captured as function of the composition of HPFRCC.

If constitutive relations were available they should be implemented in computer models. Simulations could be validated by experiments and phenomena could be found which cannot be measured on the proper scale. This so-called inverse modelling has proven useful for the understanding of the fracture of plain concrete and could also be exploited in HPFRCC.

What is already complex in static loading becomes an even greater challenge at extreme loading conditions when time and temperature become an important factor such as fatigue, explosion, seismic action, impact, and fire. Up till now, there are limited models on a scientific basis, i. e. taking account of the micro-mechanics of the composite.

There are questions about the transferability of knowledge from one range to another. For instance, how does the plain matrix change when fibres are added? Is it still allowed to model the matrix as matrix or is there an additional influence? The same can be argued when aggregates are added to a known matrix-fibre compound. What happens with low fibre contents and how to model the beneficial use of a low quantity of fibres? Of course, if the whole picture of interaction was clear these questions would already be answered.

The behaviour of HPFRCC specimens and elements in hardened state is of primary importance and main attention is paid to the research in this field. It is, however, not less important what are the reological properties of the fresh mix. This is valid not only for the execution purposes as various aspects of the workability. The reological parameters as a charcterization of the fresh mix are important for control, specification and forecast of the final material properties. Research in the reology of HPFRCC and other FRC is less advanced than of their solid properties and is very much needed.

2.3 Applied

There is no closed border between fundamental and applied research; it is open for cross-fertilization. Questions with respect to the application of HPFRCC may refer to the reduction of reinforcing bars or the total substitution of reinforcing bars by fibres. Another is how do prestressed HPFRCC elements behave under static loading and impact or explosion.

Another field concerns the repair and upgrading of HPFRCC. How do repaired elements work together as a second generation composite?

Applied research should aim at the development of standardized methods for design, testing and execution of elements and structures. Rules should be developed which take account of the serviceability state in terms of deflection and crack width and of the ultimate state in terms of rupture and instability. The design of HPFRCC should get due attention in research. The design incorporates the shape of an element, the material, the appearance, the production. It is a difficult area but a very important one starting with defining specific design criteria and ending up with an accepted product.

3 Performance

The term performance covers basic mechanical characteristics as well as all properties which are not mechanical in nature such as permeability, diffusion, thermal and hygral actions, corrosion, ecology, life cycle, durability, resistance against frost attack, chemical attack, etc. It is a very wide field which did not get so far as so much attention as mechanical aspects. If HPFRCC elements are used in a mostly dry climate, most performance aspects are irrelevant. However, as soon as HPFRCC elements are exposed to weather, soil, sea water, fresh water, and chemicals, the performance aspects become of paramount importance. Building codes for reinforced concrete contain a table for exposure classes starting with the mildest exposure, which is the dry interior of a building, and proceding via outdoor without and with rain, frost, deicing agents, marine environment, to the most severe chemical attack. These classes of exposure may also be suitable for HP-steel-FRCC but are certainly not comprehensive for all types of HPFRCC.

There is a need for producing an appropriate classification of exposure for HPFRCC. Performance should then be expressed with respect to a cluster of properties which can be tested. The link between these properties and performance - or long term durability - should be established by research and so far as possible validated by field exposure. Models should be developed for the simulation of exposure and prediction of performance.

If HPFRCC are used in structures for liquid or gas storage, permeability, diffusion, capillary absorption are primary properties which should be known for the design. Much knowledge is lacking with respect to HPFRCC. Diffusion of carbon dioxide and oxygen is of particular interest to corrosion of steel and other fibres.

The whole life-cycle covers energy consumption during production, transport and use of an element, consumption of raw material, pollution during use, maintenance, repair, demolition, reuse, recycling, and waste deposition. Since ecological restraints become tighter, these aspects should get more attention in research.

According to their role in the structure, structural and non-structural elements made of HPFRCC should normally satisfy a restricted number of performance requirements which have to be defined in advance.

4 Tailoring and production

Tailoring is understood as materials design to fit a certain purpose or optimization of HPFRCC for a certain mechanical loading and exposure. Components of the material can be improved; one should think about chemical treatment of fibre surface, toughening of the matrix, use of a minimum of fibres, aiming at very high strength together with high ductility. The use of hybrid fibres seems challenging; other applications may ask for a low strength and high toughness material. The density of HPFRCC could be reduced by lightweight aggregates. If fundamental research generated the necessary relations, tailoring could be done economically and may be purpose oriented. Since many relations are still missing a systematic variation of parameters may be the outcome in the laboratory and trial and error may be an inferior substitution.

A significant bottle-neck in the application of HPFRCC are production techniques, both on-site and off-site. The production should be simple, reliable, and fast. Sometimes it should be automated. The question arises about the necessary and sufficient quality assurance management in order to produce reliable products. The fresh state of HPFRCC deserves fundamental research in terms of rheology, particle dispersion, fluid mechanics, compaction, consolidation. Hardening of HPFRCC and optimal curing including hygrothermal regimes are other fields where knowledge is lacking. Finally, the production may also comprise surface treatment of the product in order to improve tightness and to prevent corrosion stains. Optimal adjustment of surface treatment and HPFRCC should be a topic of applied research.

All properties show a certain scatter range. Production should aim at a scatter which is as low as possible since design values will be based on a 5% quantile (or other statistical value) and this value decreases with scatter at the same mean value. Or the mean value is taken as design value together with a high safety factor. Both situations are not economic and can only be avoided by a tight production control. Research is needed with respect to the production but also with respect to acceptable scatter measured in time (i.e. subsequent batches) and space (i.e. dispersion of fibres, compaction).

5 Economy

The additions of fibres to a cementitious product increases always the cost. On the other hand, the product becomes superior due to increases in toughness, strength, imperviousness etc. The superior quality has to be sold, but can only be sold if the extra quality is appreciated and appropriately exploited. What could be a compensation for the extra quality? Less mass, longer service life, better appearance, sawability, nailability, simplified handling? These aspects have to be quantified in terms of cost, and understood as a sum of execution and maintenance costs.

Quantitative guidelines for the design of HPFRCC members could relax the cost problem because the increased quality could be appreciated. Design charts could for instance help to introduce HPFRCC in areas where other materials are prevailing up to now. If tools for the practicing engineer were ready for use, the application of HPRFCC would be easier. Performance classes would support this effort.

Before HPFRCC will be currently used in practice a complete set of reliable and generally accepted design methods is needed, easily available for professional engineers and designers. It is, however, to be observed that such a set is not available for ordinary fibre reinforced concrete.

6 Testing

Standardization of testing is a matter of agreement between all parties involved. RILEM is one of the organisations which develop, improve, coordinate, and validate testing. Real standardization is done by ACI, ISO, ASTM, CEN, JAI and other national bodies. Before standardization, the test method has to be checked as whether it is objective, powerful, reproducible, sensitive, and accurate enough. A special need concerns the definition and testing of toughness of HPFRCC.

There is a need for accelerated testing and for standardization of testing. Accelerated testing is only permitted if the main mechanisms of degradation are known. Otherwise the result of testing may not correspond with reality. In corrosion fatigue testing for instance, the absolute time has a strong effect and the increase of loading frequency may make the result look better. An increase of temperature during testing may compensate for that. However, the quantitative relations must be known for adjusting the parameters of accelerated testing.

Another aspect is non-destructive testing (NDT) during service life. NDT has proven successful in plain, reinforced and prestressed concrete for detecting flaws, inhomogeneities, or beginning deterioration. Research is needed to apply and validate NDT on HPFRCC members.

7 Conclusion

HPFRCC are still considered as an exotic family of materials. Much knowledge is available, but there is still a need for future research which should aim at making HPFRCC more application oriented. To this end, fundamental research is needed for better understanding and modelling, applied research is needed for supplying the professional engineer with quantitative guidelines and design tools. Fig. 1 summarizes the various scales on which research should be performed. Each scale is a necessary step for sound understanding and modelling. Only via modelling, the huge amount of parameters (constituents, exposure, loading) can be tackled. HPFRCC is a typical field for a multidisciplinary approach including micro-mechanics, materials science, structural engineering, process technology, computational mechanics. Design methods, standard testing, and performance classes have to be developed. It is a challenge for many to help the engineering profession and eventually serve the needs of the public.

CIS Scales			
Construction Materials	micro-level	Atomic Scale	· micro-mechanics · micro-structures
	↓		
	meso-level	Microns	· meso-mechanics · interfacial structures
	↓		
Individual Structures	macro-level	Meters	· beams · columns
	↓		
Infrastructure	Systems integration	Up to km scale	· bridge systems · lifelines

Fig. 1 Civil Infrastructure System (CIS), acc. to K.P. Chong