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FIBRE REINFORCED CONCRETE: A BRIEF REVIEW OF EXPECTATIONS AND ACHIEVEMENTS AFTER FIFTY YEARS OF DEVELOPMENT

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Abstract

Development of 'modern' fibre reinforced concrete on a large scale began about fifty years ago. It had been hailed as one of the most promising 'new' materials in construction, offering many advantages when compared with traditional reinforced concrete. The paper outlines the original forecasts for the properties of FRCs based on laboratory research and compares them with what the author sees as actual achievements in construction practice. Selected cases of typical expectations are briefly analysed and reasons explaining why some have not been achieved are proposed. Areas where additional research is needed and technical challenges are still to be overcome are indicated. The paper concludes that FRCs are still developing, albeit at a slower pace then in their early decades. A substantial scope still exists for a major and highly worth-while R&D, necessary to maintain the advance towards eventually exploiting fully the numerous benefits FRCs can offer to construction practice.

Keywords: fibre reinforcement, cement and concrete, composite action, bond, performance, expectations, achievements, challenges for research and development

1. Introduction

Reinforcement of traditional, brittle construction materials by fibres in general has very ancient origins. Even its specific application to concrete goes back more than a century (e.g. asbestocement). However, a genuinely systematic, wide-ranging research into concrete or other cement-based materials with finer or even no aggregate into which fibres or fibre-like materials had been added did not begin until early 1960's. The principle of fibre-reinforcement became widely appreciated, it begun to attract international R&D interest and in late 1960s the author himself became much involved.

The range of fibres, which are or have been mixed into cementitious matrices at present is so extremely wide, that **when fibre reinforced concrete (FRC) is mentioned in any context, at least he type of fibre used must be always clearly identified.**

Traditional recommendations for concrete always warned against using aggregate of unsuitable shape, including very elongated particles such as fibres! It is therefore not surprising that there are inherent difficulties when FRCs are produced and used.

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Reviews of achievements, such as [1,2] should be from time to time complemented by critical appraisals of shortcomings and practical obstacles in FRC developments [eg.3]. This helps the industry and agencies supporting construction R&D to focus funding on the most important areas. It should also help to avoid the very negative impact of over-hyped marketing or research-based expectations not being fulfilled (real failures do occur) with end-users then feeling misled and becoming averse to consider any FRCs.

2. Brief history of FRC development

A brief outline of history facilitates comparisons between expectations of performance and practical use of FRCs raised in the early days and genuine achievements as of today. Development of the FRCs reflected that of the fibre technology itself, which began to advance very rapidly. Achievable values of mechanical/physical properties such as tensile strength, modulus of elasticity, durability and chemical stability of the new fibres (alkali-resistant glass fibres, carbon fibres, high modulus polymeric fibres, amorphous steel and other metallic fibres etc) kept rising and offered a potential for production of new FRCs of high performance.

The first half-a-century of FRC development has not been a case of uniform, steady advance, there were significant ups and downs, at different times for different types of FRCs. Early FRCs in 1960-70s were based on steel fibres (SFRC), glass fibres (GRC) and to a lesser extent on polypropylene and natural (organic) fibres. The first three still make up the bulk of FRC produced today.

Discovery in 1970s of strong carcinogenic effects of most types of asbestos fibres made asbestocement, an already widely used and well established FRC, a serious health hazard. The situation was made worse by the composite becoming very brittle with age (eg. The very common corrugated roof cladding). Replacement of asbestocement then became yet another driver behind the intensive research into new FRCs. It was difficult, as there is no other fibre with asbestos-like properties and existing very large investment into original mass-production process (Hatchek) had to be retained as much as possible. It took more than a decade to achieve it by using mixtures of glass and cellulose fibres.

Licensing restrictions attached to the break-through invention of the zirconium containing alkali-resistant glass-fibre (Pilkington plc and BRE in UK) applied in first two decades. However, production control by some of the licensed GRC manufacturers was not of the higher standard required, leading to construction failures. Specifiers lost confidence and it took about two decades for the GRC industry to fully recover.

Polypropylene fibres enjoyed a degree of success early on, providing much better impact resistance of concrete in practical applications, such as piling. However, progress was for a number of years hampered by an argument with SFRC and GRC manufacturers about the polypropylene and similar fibres being marketed as 'reinforcement' for concrete; having low modulus of elasticity a genuine reinforcing action by such fibres was impossible. Lately, the matter been resolved, with polypropylene fibres now finding an increasing market just for its beneficial effects on fresh and hardened concrete, at a low cost.

Many new high-performance fibres appeared within the last three decades, and it is likely that all have been put into concrete to see if such a composite would perform well. The field of FRCs have therefore broadened enormously, large numbers of novel fibre-concrete combinations were examined in postgraduate research projects and to a lesser degree by industry, with countless papers and reports published.

Overall volume and number of practical applications in construction did not follow the big expansion of research and record-breaking laboratory test results. Since late 1980's it gradually Practical production of FRCs reached a relatively stable level from late 1980s and significant 'niche' markets in construction were established, for example GRC cladding and SFRC floors. Construction boom of early 2000's led to a noticeable overall expansion, as both the end-users and specifiers (eg. architects) gradually acquired the necessary knowledge and there were adequate financial resources available to cover the inevitably higher risk of proposing buildings and structures, which exploited new materials, including FRCs.

The post-2008 global economic slump has hit many industrialised countries, being felt disproportionally hard in the construction sector. Exploitation of innovative materials, including many FRCs, is therefore at present at its best in countries largely unaffected – typical examples are projects completed in China and the oil-rich Middle East.

3. Original expectations and practical achievements

A wave of optimism had been created by outstanding results from laboratory tests on FRCs. Widespread applications in construction, leading to performance better than that of 'traditional' materials such as ordinary reinforced concrete and eventually to lower costs, were expected. However, the outstanding laboratory results often failed to find practical applications or could not be achieved in real construction practice. Typical characteristics included:

3.1 Strength and toughness of the FRC

Expectation was that it will be greatly increased simultaneously, compared with that of plain matrix material. Impact resistance and resistance to dynamic loading in general were to be of raised by orders of magnitude. Achievements varied, depending on the characteristic / parameter concerned. Best results were obtained for:

- ***Ultimate strength*** – derived from the maximum load, which an element could bear, was raised very significantly above that of an unreinforced matrix. This was achieved to a varying degree with all FRCs containing fibres with moduli of elasticity significantly higher than that of plain concrete and adequately bonded or anchored into the matrix (genuine 'reinforcing' fibres). However, the very high ultimate strength, namely in bending, was invariably reached only after a substantial strain / deformation took place.
- ***Ultimate strain*** – derived from the point at which an element lost its integrity and fell into pieces, also rose very significantly. Presence of adequately effective fibres dispersed in a cementitious matrix generated multiple, narrow cracks which they bridged. This mechanism was responsible for ultimate strains greatly exceeding that of an unreinforced matrix.
- ***Toughness and impact resistance***, based on the total amount of energy required to produce a complete fracture (ultimate strain being reached) showed the greatest

increase of all strength related parameters. It was often several orders of magnitude greater that of the unreinforced matrix.

Expectation of a simultaneous improvement of both toughness and strength, particularly a substantial ***increase in the stress at which the first crack appeared in the composite has not been achieved.*** Strength at the first crack is of primary importance for practical structural applications of FRCs. It indicates how much load an FRC structural element can bear before it begins to crack – usually coinciding with the limit state of serviceability. The difference between it and the higher ultimate strength then provides a safety margin against collapse of the element (structure). Strength at first crack of most FRCs tended to remain very similar to that of an un-reinforced matrix alone. Small increases have been achieved in some FRCs, however, at the cost of a much reduced ultimate strength. The composites then became brittle and their practical applications were very limited. Glass-fibre reinforced concrete is a typical example of a FRC, where a significant initial improvement of strength and toughness was lost with age. Reasons for this are linked to the type of 'composite' action between the reinforcing fibres and the matrix, where bond plays a key role, determining not only the type of fracture mechanism but also the extent to which mechanical properties of the fibre are usefully exploited in a given FRC. This is dealt with in more detail in part 5.

3.2 Size and shape of FRC elements

Expectation was that **thinner structural elements and elements of complex shapes** previously very difficult or impossible to produce would become feasible. This has been achieved, but with significant restrictions. The bulk of FRCs are expected to be reinforced with relatively short, uniformly distributed single fibres. This is practically impossible to achieve in thin-walled elements, considering that:

- In case of elements produced by casting, the orientation of the fibres is affected by the direction of flow of the fresh mix during casting. The longer the fibres, the more likely they will align to the direction of the flow. This produces elements in which most of the fibres are aligned rather than randomly distributed at a specific position within the element at the time of placing. Thin-walled elements of complex shapes are difficult to produce by casting because of the changes in direction of flow and a possibility of creating parts with very low fibre content overall. Most of the genuinely thin-walled FRC elements are therefore made of GRC, using a spray-up process and glass fibres, which are much more pliable than metallic 'wires'. Here the fibres on impact also change direction and tend to align with the plane of the formwork/mould. The fibres may maintain an acceptable 2-dimensional uniform distribution, at optimum dosage rates, with only a small fraction in the 3rd dimension (across the section of the element). The resulting FRC becomes very anisotropic.
- The 'wall-effect' of formwork/moulds inevitable and automatically reduces the concentration of fibres in a zone near to the wall. Fibres will tend to align with the plane of the wall. The non-uniformity and therefore an overall anisotropy of the FRC increases with longer length of fibre and thinner cross-sections. Even if a large piece of FRC is cast, with fibres distributed in three dimensions, any subsequent 1111111cutting out a structural element still produces near-surface 'edge' zones where the fibre reinforcement of the composite will not be as effective

as within its inner part (reduced embedded lengths). The 'thinner' the element in relation to the length of the fibres, the greater will be the adverse 'wall-effect.

- - Anisotropy of thin-walled elements can be exploited, provided the preferred orientation of the fibres enhances required performance of the element, such as its bending strength. This is the case of GRC and sprayed SFRC, and to a lesser extend of SFRC applications in floors and segmental precast tunnel lining. Problems arise when the very low 'transverse strength', perpendicular to the plane of aligned fibres, has to be considered. This is particularly relevant to design and installation of fixings.

3.3 Durability of concrete elements

Improved durability was expected, mainly by *reduction in cracking due to presence of randomly distributed short fibres.* Indeed, this has been largely achieved and, overall, durability of FRC is not a problem, especially if the composite remains uncracked.

- All genuinely 'reinforcing' fibres in adequate quantity and appropriate distribution produce composites which fail in multiple cracking mode, instead of a single crack typical of a brittle matrix alone. This is exploited in several of typical existing applications such as SFRC floors and tunnel lining.
- Durability of fibres when embedded in a cementitious matrix was a potential problem with glass fibres and steel fibres. Invention of the alkali-resistant (AR) glass enabled GRC to develop. Unlike ordinary steel reinforcing bars in concrete, corrosion of steel fibres was found to be surprisingly limited to exposed parts only, it does not affect the embedded parts. There is a lack of consensus regarding the maximum width of a crack which would not induce corrosion of steel fibres bridging it.

3.4 Concrete production and construction process

Reduction of overall construction costs of load-bearing concrete was expected by a partial and preferably complete replacement of traditional steel reinforcement with relevant fibres. Partial replacement has been achieved in a number of practical applications but a complete replacement remains very rare. There are a number of production related factors, which affect the overall costs:

- *Production time of structural elements*, namely in precast form and when a self-compacting SFRC can be simply poured into formwork, is shorter compared to that of traditional reinforced concrete (steel bars, ties and stirrups etc.). However, the advantage is often reduced by the process for batching and mixing of the fresh FRC being more demanding
- *Maximum fibre content* of a fresh FRC produced by traditional mixing varies between approx. 3% for glass fibres and 2% for steel fibres. Non-traditional production methods for SFRC such as the slurry infiltration process (sifcon) can incorporate between 7% to 12% of steel fibres. Practical production of a FRC with a fibre content between 2 to 6 %, which is common for ordinary reinforced concrete is almost impossible. Steel in the form of fibres costs more than an equivalent mass of traditional reinforcing steel.

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- *Distribution and orientation of the fibres is difficult to control adequately* and unlike in case of tradition reinforced concrete where all the reinforcement is placed in the most effective position, a proportion of the fibres is inevitably wasted. There is a greater risk of parts of a structural element being 'under-reinforced' in case of FRC, and verification of distribution and orientation of fibres in a completed structure is more difficult and more expensive.
- *Novel and uncommon production processes* have been tried in production of FRCs such as that for production of 'sifcon', where fibres are placed into a mould first and then infiltrated by a special cementitious grout. Original invention from 1980s required an intensive vibration to achieve infiltration, which greatly limited its practical use. A follow-up of research into self-compacting concrete in early 2000's produced also grouts which reliably penetrated fibre layers up to 600mm deep without vibration. This has opened applications of 'sifconised' FRCs in in-situ concrete construction, however practical applications are hindered by the system being completely outside of existing design standards for structural concrete. Other processes include extrusion and pressing, sprayed premix, high-shear mixing of fresh matrix mixes, the latter two being widely used in production of GRC.

3.6 Natural organic fibres

Serious housing problems existing in developing countries were expected to be alleviated greatly by provision of inexpensive structures based on production of concrete elements reinforced with a variety of natural, organic fibres. Such fibres were to be sourced locally, at low cost and from sustainable resources. Considerable amount of funds have been directed to development of FRCs from organic fibres, such as coconut coir, oil-palm fibres, sisal and other forms of basically cellulose fibres of a plant origin. There were a number of research projects, often with encouraging laboratory results, indicating that adequately load-bearing elements can be produced using organic plant fibres in controlled trials.

However, all attempts to establish a commercially sustainable production of such FRCs appear to have failed. There were several reasons, including:

- Difficulty to ensure reliable supply of the raw materials of guaranteed quality for the extraction of fibres in commercial quantities. This reflected conditions in generally poor developing countries where such projects appeared to be appropriate.
- The processes for extraction of fibres were technically demanding, including too sophisticated and expensive equipment, not suitable for a tropical developing country.
- Personnel involved in production of the composites required training, a problem already known from commercial FRC production in developed countries.
- Quality of the final FRC was low. It was difficult to establish quality control/assurance systems, which require testing equipment and which are stricter than those for ordinary concrete.

Failure to develop viable industry producing cement-based composites based on natural, organic fibres is arguably the greatest unfulfilled expectation concerning FRCs overall.

4. Additional achievements and benefits

4.1 Improved resistance to cracking due to early plastic shrinkage and reduction of bleeding in freshly place concrete

Polymeric and to a lesser extent glass fibres in relatively small quantities were found to be effective. Last two decades have seen a rise in their use, particularly for concrete structures where such cracking was to be avoided (floors, pavements, reservoirs etc.)

4.2 Exploitation of photocatalytic concrete surfaces

The established manufacturing process for GRC (spray-up) provides clearly *the most economical way to produce photocatalytic concrete, the eGRC.* It only requires a very thin 'mist-coat' of matrix material sprayed usually first into moulds to be photocatalytic, thus reducing the extra cost of using photocatalytic cement down to an insignificant level. First projects using the eGRC have been recently completed.

4.3 Very high performance

Short, micro-fibres, which should be theoretically much less effective as reinforcement, were found to produce very high-performance FRCs (eg. Ductal) when combined with special high-strength matrices (reactive powders etc.) This type of FRC, developed in the last decade, has been already used in practice. However, very high costs of the material and licensing agreements, together with demanding production process appear to have curtailed is wider use.

4.4 New mode of fracture

Research into glassfibre reinforced concrete identified a new mode of fracture, the *'telescopic' pullout.* It was later observed in other high-performance composites, where the basic reinforcement was in the form of bundles of fibres (eg. Carbon fibre reinforced carbon). The telescopic pullout provides the FRC with a maximum amount of work of fracture and in an optimum case it offers simultaneously higher strength and toughness. Exploitation of FRCs which can fail in this mode requires further research into measurement and control of bond.

5. Future research and development

There is need for further research into many topics related to FRCs. However, two linked topics, namely **bond and fracture mechanisms,** are of fundamental importance for all FRC and include areas where substantial and essential knowledge is still missing.

5.1 Bond

The very high performance expected of the new FRCs assumed a full composite action existed between each matrix and fibre during the service-life of the composite. It also meant full utilisation of properties of the fibres used. All FRCs rely on bond to achieve genuine 'composite' action. Despite bond being the key characteristic, bond continues to be the most elusive one, with the least amount of research effort focused on it. There is still an inadequate knowledge and a lack of data. Fundamental reason for this unacceptable situation are the technical challenges ahead of any reliable measurements of bond. Only then a genuine ability to pre-determine / control the level/magnitude of bond within the FRC during all of its service life can be developed. So far, attempts to produce 'engineered cementitious composites – ECC – appear to be somewhat over-hyped experiments where no real 'engineering', such as selection / control of internal bond in the FRC have been done.

Most of the fibres used in FRCs have very low or virtually non-existent adhesive bond with the surrounding hardened cementitious matrix. The composite action therefore relies on mechanical interlock between a fibre and a matrix; the fibre is often mechanically anchored at both its ends. Even with good mechanical anchorage, most of the metallic (steel) fibres tend to fail by a pullout instead of a tensile failure, which means that their tensile load-carrying potential is not fully exploited. Fracture mechanism then consists of initial debonding of the anchored ends with a variable frictional bond resisting the pullout of each fibre. This mechanism is responsible for the high level of toughness and large ultimate strains of such composites.

Improvement of bond, namely of the 'adhesive bond' would increase strength of the composite, namely the strength at the first crack of the matrix. Such strength is the most important parameter in the great majority of potential applications of FRC. It relates directly to the magnitude of load a structural FRC element can carry while its deformation is still within the range of strain within its serviceability limit state.

5.2 Mechanism of failure of inclined fibres

Most of FRCs expect the fibres to be in a genuinely random 3-dimensional distribution. In reality, true 3-d random distribution is probably impossible to achieve, although what is the 'acceptable' level of randomness is very rarely stated. In many FRCs, fibres are distributed in all directions and most are not parallel to the main tensile force.

The angle of inclination of each fibre influences its own behaviour and also the response of the surrounding matrix, when under load. This, in turn, governs the overall strength / performance of the composite. Contribution of an inclined fibre depends not only on the angle, it also varies greatly with the type of fibre. An inclined fibre is subjected to a combined load, beginning as an 'inclined' shear followed by a mix of shear, bending and tensile stresses. Ultimate load-bearing capacity of the same fibre varies greatly with the angle of inclination. It is generally reduced, the reduction depending on the type of fibre. It is possible to establish for each type of fibre its 'inclined tensile strength' (ITS) [4] as an upper limit of what the fibre could take when embedded in a cementitious matrix. Fibres slightly at an angle to the direction of load tend to carry greater load (higher pullout resistance) than fibres perfectly parallel (usual pullout testing position), fibres at higher angles make up the greatest contribution to the post-cracking behaviour of the FRC [4]. In case of GRC, where reinforcement are bundles of fibres, the outer layer of fibres influences significantly the 'inclined' pullout of the internal fibres, which are not in contact with matrix.

Investigation of the actual fracture mechanism of the inclined fibres, which constitute the great majority of fibres in a typical short-fibre reinforced FRC is technically / experimentally very challenging – but it is of fundamental importance. Very little progress has been made here for the last 20 years.

6. Difficulties and challenges

There are many reasons and factors, often significantly inter-related, why many of the original optimistic expectations have not been achieved to-date. Some of the initial aims were simply unrealistic, including attempts to use 'exotic' and very expensive high performance fibres. These were, perhaps, never to be fully achieved, but others can be. It is therefore worthwhile to analyse at least a selection of general factors, perceived by the author as significant obstacles on the way forward for the FRCs.

A significant proportion of research projects focused on FRCs over the last 50 years produced results, which looked interesting but which were of little practical use and sometimes of even lesser use in further research. Large amounts of funding have been therefore wasted, which has not escaped notice of funding agencies over the years. This may be attributed to a combination of factors such as:

- A much greater *complexity of the FRC as a material*, compared with any other construction material. Addition of reinforcement in the form of fibres, which themselves may be composites (viz the GRC), into an already complex composite matrix such as concrete means that an unparalleled number of factors, many strongly inter-related, influence the properties of the resulting FRC.
- An inadequate education and experience of researchers, mostly those working for a higher degree, regarding *planning and subsequent evaluation of experiments.* Researchers frequently fail to set up clear lists of which factors/variables will be considered, which parameters will be kept constant and at what level, what will be the production process used (mixing type and parameters, placing, curing etc.). Very rarely does the analysis of results include effects of important factors which do not have numerical values (eg. type of fibre) and assesses inter-dependence of variables examined.

- Numerical models regarding FRCs are generally of descriptive type (usually follow test results of one project/experiment) without an attempt at a genuinely predictive models. Predictive models of FRC performance invariably require values of key parameters obtained independently. This explains why they are so few, values of bond obtained independently are not available or very rare.

Optimistic predictions of wider use of FRCs failed to appreciate full overall costs of their introduction into practice. In addition to direct costs of materials and production, these include cost of design, specification and verification/quality control of FRC elements. Originally, all guidance in this area came from fibre manufacturers, which could not be considered independent and reliably unbiased. Last two decades have seen development of of both national guidance documents (eg. [5]) and international standards became available. However, few specifiers and designers are keen to engage in the process of a rational selection of a FRC for a given project without adequate knowledge of FRCs and previous experience. The process requires more time – and it therefore costs more when compared to traditional alternative materials. It also involves greater risk of the final product not meeting user's expectations – higher cost of professional indemnity. Design, specification and checking of FRC products are therefore left in hands of a few specialist engineers, a situation which does not help to widen its use.

The whole area of FRC remains fragmented, which is another factor hindering progress, and internal competition often tends to be counterproductive overall. Separation of GRC (GFRC in the USA) industry from that concerned with other FRCs began in 1970s and persists to this day. Almost all manufacturers of GRC world-wide are members of the Intl. Glassfibre Concrete Association (the GRCA) with very little interaction with other FRC producers.

7. Conclusions

7.1 The *achievements listed above took much longer than envisaged originally*. Many of the expectations, including the key one of FRCs replacing a large part of traditional reinforced concrete in general construction practice, have not been fulfilled.

7.2 FRC research has focused far too much on the 'tail' of the stress/strain or load/deformation test curve. It should *re-focus on the initial stages of deformation, with strain/deformation values within the serviceability limit zone* and preferably where both strains of the matrix and of the fibre are still 'compatible'. This is before the matrix cracks for the first time. A much improved performance in this region would make FRCs much more attractive to general structural use.

7.3 *Bond* between fibres and matrices and between fibres needs to be evaluated directly from meaningful tests. Once such test methods are established, selection and control of bond will open up a completely new era of development of FRCs.

7.4 Role of *fibres inclined to the direction of principal stress* in FRCs requires a great amount of additional research. Much of what little information exists are 'plausible' assumptions, not backed up by any experimental evidence. Contribution (positive or negative) of fibres at higher angles (60-90deg) is almost unknown, although a significant proportion of the fibres may fall into this category.

7.5 Independent *guidance documents for specification, design, production and verification of properties of finished FRC products* are needed. The bulk of the FRC producers are specialist SMEs with very small, usually no research facilities, and they cannot fund development of such documentation. Without it, costs of the projects are increased further due to specialist guidance and approvals, making use of FRCs very un-competitive.

7.6 There is a substantial requirement for *training and education,* at all levels involved. This concerns both construction industry at large and the educational sector. University based research should be always linked to an existing or potential industrial partner, this would benefit both the researchers and the users.

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