
Fibre-reinforced Concretes for High-performance Structures

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**Building a more sustainable
future**

Dr Andreas Lampropoulos

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Dedication

*To Rania, Maria & Panagiota
and to my parents Panagioti & Rania*

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Preface

Concrete is one of the most commonly used materials in the construction industry. This is attributed to its high compressive strength and relatively low cost. However, there are drawbacks with the use of concrete which are mostly linked to the fact that cement – one of its key ingredients – releases enormous amounts of carbon dioxide during its production phase (1 tonne of cement emits almost 0.8 tonnes of carbon dioxide). Worldwide, there is an ever-increasing pressure for countries, governments and companies to become ‘greener’ by decreasing their carbon dioxide emissions, which are the main cause of global warming. In addition to environmental aspects, enhanced structural performance is always a key priority and, therefore, there is a need for the extensive use of new forms of sustainable and high-performance concretes in construction.

This book deals with recent developments in the production of types of concrete with enhanced structural performance and sustainability. In the last decade, there have been significant advances in the development of novel types of concrete for structural applications. Research studies have focused mostly on the enhancement of the structural performance and durability, although substantial efforts have been made to reduce the environmental impact linked to concrete production. Despite the significant amount of research and the very encouraging results in this area, the construction industry has been very slow to adopt new concrete types, the reason for which is mostly linked to the limited knowledge of practitioners in this field and the lack of available standards. This book focuses on addressing this gap by presenting key information about the development, performance and design of three main materials: (a) fibre-reinforced concrete (FRC), (b) ultra-high-performance fibre-reinforced concrete (UHPRC) and (c) geopolymer concrete (GC) (including fibre-reinforced GC). Recent research findings are collected and critically analysed to highlight the key parameters for the development and production process and to characterise the properties of the materials, with a focus on the mechanical properties and durability characteristics. Design aspects are also covered using both research outcomes and available guidelines/code provisions. Critical evaluation of the mechanical properties of all of the examined materials are presented, in addition to environmental and economic considerations, which makes this book a key resource for the selection of suitable types of concrete for structural applications. It is expected that this publication will facilitate the quicker adoption and the extensive use of these novel types of concrete in industry.

In closing, the author would like to express his appreciation and sincere thanks to Professor Kypros Pilakoutas for providing valuable information about one of the case studies presented in the book.

About the author

Dr Andreas Lampropoulos is a Principal Lecturer in Civil Engineering at the University of Brighton. He obtained his Diploma (2003), MSc (2005) and PhD (2010) degrees in Civil Engineering (Structural Division) from the University of Patras in Greece.

His main research agenda spans the areas of novel construction materials and seismic strengthening/retrofitting of existing structures. His research interests are focused on a wide range of cementitious materials such as ultra-high-performance fibre-reinforced concrete (UHPFRC), steel-fibre-reinforced concrete (SFRC) and cementitious materials reinforced with nanoparticles, and he is also working on the development and application of cement-free concretes. He has conducted extensive experimental and numerical work on the development of novel strengthening techniques for the structural upgrade of reinforced concrete (RC) and unreinforced masonry (URM) structures.

Dr Lampropoulos currently serves as the Chair of the International Association for Bridge and Structural Engineering (IABSE) Task Group 1.1 'Improving Seismic Resilience of Reinforced Concrete Structures' and Task Group 5.5 'Conservation and Seismic Strengthening/Retrofitting of Existing Unreinforced Masonry Structures', and he is an active member of various task groups of IABSE and of the International Federation for Structural Concrete (fib).

He has had more than 80 works published in international research journals, books and conference proceedings, and he is an editorial board member of international journals in this field. In addition, he is a reviewer for more than 35 world-leading international journals, a member of the scientific committee of more than 20 international conferences, and he is an invited reviewer for research proposals for national centres of various countries.

Lampropoulos A

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Chapter 1

Fibre-reinforced concrete (FRC)

1.1. Introduction and historical developments

Concrete is one of the most commonly used construction materials. It is characterised by superior compressive strength, relatively low cost and ease of application. The main drawbacks are linked to the relatively low tensile performance and potential for cracking along with the subsequent durability issues. In addition, the extensive use of concrete in construction gives rise to significant carbon dioxide emissions which has catastrophic environmental consequences.

An enormous amount of research has been conducted in the last few decades on the development of novel high-performance and environmentally friendly types of concrete that are reinforced with different types of fibres.

In the case of fibre-reinforced concrete (FRC) the concept is quite similar to that of conventionally reinforced concrete (RC) with steel bars. The cementitious matrix, which can be either concrete or mortar, is normally characterised by high compressive strength and has numerous additional benefits such as enhanced fire resistance, sound insulation and protection against vibration. However, the weak tensile strength characteristics make it prone to tensile failures and cracks, and therefore the addition of steel reinforcement is essential for the enhancement of the structural performance and durability of concrete structures.

A key parameter for the performance of RC elements is the bond between the steel reinforcement and the cementitious matrix, which is essential for the interaction of the two materials and the composite action. The steel reinforcement can be either in the form of continuous steel bars or, in case of fibre reinforcement, the reinforcement is considered discontinuous. Continuous reinforcement has been extensively used in many different types of concrete since 1855, when thin elements of mortar reinforced with steel mesh were used to construct a boat. The use of RC in small-scale structures was also reported around the same period and, since then, further developments have been made, such as the use of prestressed concrete (Figure 1.1).

The concept of FRC is not new. In fact, fibres have been used since about 1500 BC. At that time horsehair was used in mortar and straw in mud-bricks [1]. Systematic studies recording the addition of fibres for the enhancement of the tensile and bending resistance of concrete were made from 1874 onwards (Figure 1.2). In 1874, A. Berard patented for the first time the use of irregular waste iron pieces for the strengthening of ‘artificial stones’ which were made of concrete. In the 1900s, asbestos fibres were used in concrete, but their use was discontinued owing to the high risk of health issues caused by the use of asbestos. After that, the use of

Figure 1.1 Overview of the history of concrete with steel reinforcement [2]

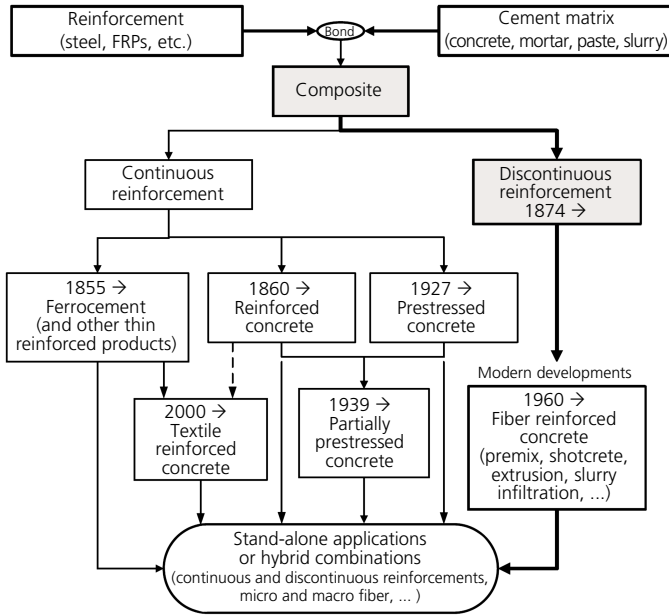
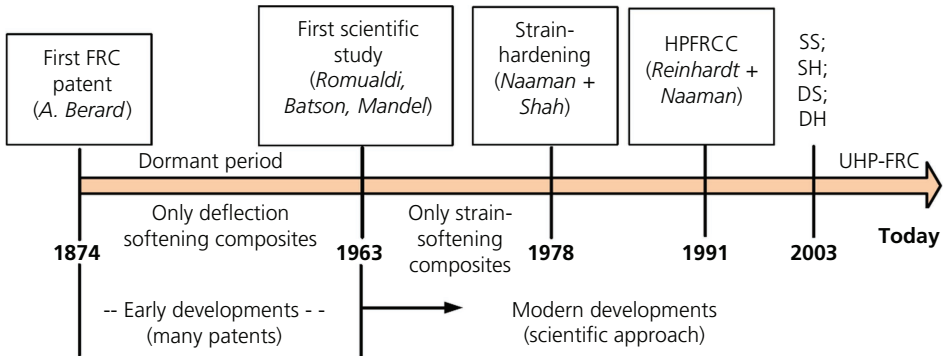


Figure 1.2 FRC developments and overview of the main milestones [2]



various types of fibre was explored, with steel, glass and synthetic ones being the most popular. In the early 1960s, the first scientific papers were published by Romualdi, Batson and Mandel which offered an in-depth understanding of the mechanics of crack arrest and the role of the orientation of the fibres. Then, and until 1978, the behaviour of the examined FRC types was characterised by strain-softening characteristics, whereas, after that period, developments were made on composites with strain-hardening behaviour. High-performance and ultra-high-performance fibre-reinforced composites were first developed in 1991 and 2003, respectively [2].

Modern developments in the types of FRC and the continuous improvement of the mechanical characteristics are attributed to a large extent to the developments in the types of fibres that were introduced in the mid-1980s [3]. The new fibre types, in addition to the development of new types of admixtures and production methods, have led to beneficial effects on fibre concentration and orientation with subsequent enhancement of the mechanical properties [3].

1.2. Materials selection

The selection of the materials and the mix design are the key parameters for the performance of FRC. In this section, an overview of the most commonly used cement, aggregates and fibre types are presented, in addition to the mix design processes.

1.2.1 Cement

In the case of FRC, the concept is quite similar to that used for conventional concrete and there are not specific requirements for the type of cement that should be used. For ‘conventional’ FRC, ordinary Portland cement is normally used unless there are special requirements in terms of structural performance (for example, high-performance concrete (HPC) and ultra-high-performance concrete (UHPC)) where high-strength cement types should be used. The effect of cement type is directly linked to the compressive strength of the concrete and subsequently affects the mechanical characteristics of FRC.

Simões *et al.* (2017) [4] investigated the effect of different types of cement on the characteristics of FRC. CEM II/B-L 32.5 R, CEM II/A-L 42.5 R and CEM I 52.5 R were adopted for 20, 60 and 100 MPa compressive strength mixtures and the results show that an increase in concrete compressive strength leads to an increase in the number of original fibres that fail by tensile strength, instead of slipping and debonding of the concrete matrix. This is attributed to the increment of the interface bond strength and to the enhancement of the strength of the adjoining matrix in the case of hooked-end fibres [4].

1.2.2 Aggregates

The size of the aggregates in FRC is a key parameter for the mechanical performance and durability of the material and this is attributed to the synergistic effect at the interfaces between the steel fibres and the aggregates.

Seleem *et al.* (2020) [5] investigated the effect of various aggregate dimensions with maximum aggregate size 10 mm, 20 mm, 25 mm and 40 mm and two different percentages of steel fibres, 0% and 1%. Compressive, indirect tensile and flexural strength tests were conducted and the results show that all of these mechanical characteristics were increased as the maximum aggregate size was increased, and increments were also observed with the addition of steel fibres. There are various other studies where the increment of the compressive strength and, subsequently, the tensile and flexural strength characteristics were increased for higher maximum aggregate size [6–10].

However, the effect of the aggregate size on the flexural energy in the post-peak region may be detrimental and this depends on the aggregate size and on the fibre geometry. According to Seleem *et al.* (2020) [5], the flexural load in the post-peak region of the load–deflection results was reduced as the maximum aggregate size was increased, which is linked to the reduced bond

between the fibres and the cementitious matrix. On the other hand, Ulas *et al.* (2017) [6] observed a small increment in the flexural toughness around 10% when the maximum aggregate size was increased from 16 mm to 31.5 mm. The fibre length is also an important parameter for the fibre-to-cementitious-matrix bond [8]. Specimens with shorter fibres experience higher ultimate direct tensile strength values. However, the ultimate strain is reduced and there is more likely to be reduced post-cracking performance than in specimens with longer fibres, in which enhanced bonding between the fibres and the cementitious matrix is achieved [8].

According to the study of Han *et al.* 2019 [9], the indirect splitting tensile strength of steel-fibre-reinforced concrete (SFRC) gradually increases with increase in the length of the steel fibre. The splitting tensile strength of normal-strength SFRC increases with coarse aggregate size up to a maximum of 30 mm and then decreases [9]. For high-strength SFRC, the splitting tensile strength increases with coarse aggregate size up to a maximum of 20 mm and then decreases [9]. With regard to the effect of the length of the steel fibres, it was found that the splitting tensile strength gradually increases as the ratio of fibre length to coarse aggregate size increases up to a maximum of 3, and then decreases [9].

Based on the findings of these studies, it is recommended that the maximum aggregate size for normal-strength SFRC (up to 50 MPa) should be 30 mm, whereas for high-strength SFRC (above 50 MPa) the maximum aggregate size should be 20 mm to achieve the maximum compressive strength. In addition, the optimum split tensile strength is achieved when fibres with a length of three times the aggregate size are used. With regard to the workability, the slump of fresh SFRC increases as the fibre length increases from 30 mm to 60 mm and as the aggregate size increases from 10 mm to 40 mm [9].

1.2.3 Fibre types

The type and the geometrical characteristics of the fibres are key factors for the performance of FRC and the effect of these parameters is developed in the following sections.

The main types of fibres currently utilised in the FRC used in construction are steel, glass and polyvinyl alcohol (PVA) fibres (Figure 1.3), although there are various other types such as polypropylene, polyester macro and micro synthetic, natural fibres and cellulose fibres.

Figure 1.3 Steel, glass and polyvinyl alcohol (PVA) fibres



Steel fibres (Figure 1.3) are the most popular type used in construction as they can provide significant enhancement of concrete flexural and tensile strength, toughness and impact resistance and, at the same time, concrete shrinkage and potential cracking can also be addressed.

PVA and glass fibres (Figure 1.3) work in a similar way to the steel fibres but, in general, they are not as effective for enhancement of the flexural and tensile strength characteristics.

Comparative studies [10] have shown that the addition of 1% (per volume) of steel fibres in normal-strength concrete increased the flexural strength by 51% while the respective increment for the same mix using the same volume of glass and polypropylene fibres was found to be 32% and 23%, respectively. This difference was attributed to the enhanced bond of the 'hooked-end' fibres with the cementitious matrix [10].

Fibres have different shapes and lengths. The shape of the fibres is one of the key characteristics for the behaviour of FRC.

There are various geometries of fibres such as the ones presented in Figure 1.4, which, from left to right, shows straight, triple-hooked (5D), double-hooked (4D), hooked-end (3D), corrugated and paddled fibres. The straight fibres rely entirely on the bond between the concrete matrix and the surface of the steel fibres and, therefore, they are prone to slip; pull-out of the fibres is a typical failure mode observed across the cracks. The hooked-end fibres are more effective after the initiation of slip and, therefore, they are more effective in the post-cracking region of SFRC. On the other hand, there are various issues during the mixing process, especially in cases when a large number of fibres with a high aspect ratio (l/d) is used (where l is the length and d is the diameter).

Experimental studies were conducted using various types of fibres with different aspect ratios (40, 60, 80) and dosages (0%, 0.5%, 1.0%, 1.5%, 2.0%) [11] and the results show that as the aspect ratio and the fibre volume are increased, flexural performance is enhanced [11].

Figure 1.4 Various fibre geometries

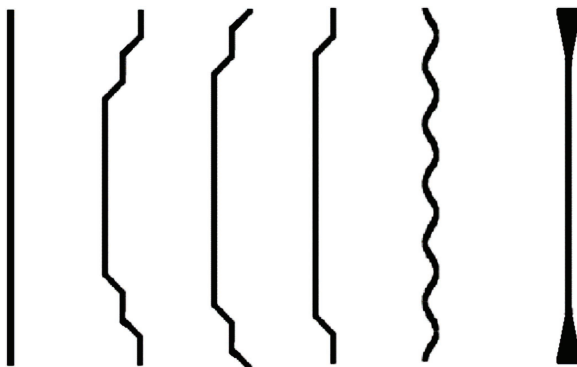


Figure 1.5 Fibre balling [13]



Special attention should also be given to avoid fibre balling (Figure 1.5), particularly when high aspect ratios and high fibre volume fractions are used. More specifically, it was found that the risk of fibre balling in the concrete mixture is reduced when fibres with aspect ratios less than 100 are used [12]. In addition, it was found that the risk of fibre balling is increased when the fibre volume fraction exceeds 1% [12].

When the shape of the fibres is considered, the hooked-end fibres show higher flexural strength and enhanced post-cracking behaviour when compared with straight and corrugated fibres. The hooked-end ones were proved to be the most efficient for enhancement of the flexural strength and the post-cracking performance. Comparisons between hooked-end, double-hooked and triple-hooked fibres using volume fractions of 0.5% and 1% have also been made [13], and the results show that, as the number of hooks was increased, both the ultimate tensile load and the post-cracking performance were substantially enhanced, with the triple-hooked being found to be the most efficient type. The beneficial effect of the number of hooks was more pronounced as the number of fibres was increased.

1.2.4 Mix design process

The mix design process, which is normally followed in case of SFRC, is the same as that used for concrete without fibres and the mixture is designed for specific requirements of compressive strength. Adjustments may be required when a high volume fraction of fibres is used (normally more than 1–2%) to improve the workability. Also, the use of coarse aggregates with large diameters may have a detrimental effect [14].

The range of proportions for normal-weight SFRC for different values of maximum aggregate size are proposed in Table 1.1 [8].

Table 1.1 Typical values for the mix design of SFRC [8]

	Mix design (kg/m ³)		
Cement (kg/m ³)	400	440	470
Coarse aggregates: 10–15 mm	338		
Coarse aggregates: 10–12 mm	–	155	–
Coarse aggregates: 4–10 mm	534	584	719
Fine aggregates: 0–4mm	909	970	953
Steel fibres (vol. %)	1–2%	1–2%	1–2%
Water over cement ratio	0.55	0.55	0.55

Adjustments may be required for the enhancement of the workability, in particular when self-compacted concrete (SCC) is required. Experimental and numerical work was conducted to evaluate the effect of the presence of fibres on the characteristics of SCC and a design methodology has also been proposed [15–19].

The mix design process has been summarised in the literature [15] and is presented below.

Using a target cubic compressive (f_{cu}) and tensile strength (f_t), the steel fibre volume fraction (v_f) can be calculated using Equations 1.1 and 1.2.

$$f_t = (1 + a_{tb} \times a_{te} \times \lambda_f) f_t \quad (1.1)$$

$$f_t = \frac{(0.65 \times f_{cu} - 8)^{2/3}}{3} \quad (1.2)$$

where:

f_t is the tensile strength of a SCC without fibres

a_{te} is a coefficient linked to fibre distribution

a_{tb} is a coefficient linked to the effect of fibre bridging on the tensile strength

λ_f is the fibre factor which is defined as follows: $v_f \times \frac{l_f}{d_f}$, where l_f is the length and d_f is the diameter of the fibres.

The water to binder ratio can be calculated using Equation 1.3.

$$w/b = \frac{\alpha_a \times f_b}{f_{cu,0} + \alpha_a \times \alpha_b \times f_b} \quad (1.3)$$

where:

α_a and α_b are empirical coefficients linked to the aggregate and concrete type (recommended values: 0.53 and 0.2 for crushed stone [20])

f_b is the compressive strength of the binder material at 28 days.

Table 1.2 Range of factors to consider the effect of fly ash and slag (indicative values using published data [20])

Fly ash content (%)	γ_f
0–40	1.00–0.55
Slag content (%)	γ_s
0–50	1.00–0.70

Table 1.3 Water content range (indicative values using published data [20])

Slump (mm)	Indicative water content range (kg/m ³)
10–90	$185 \times c_a - 215 \times c_a$
Aggregate size	c_a
20 mm	1.00
40 mm	0.90

The compressive strength of the binder (f_b) at 28 days can be estimated using Equation 1.4 [20].

$$f_b = \gamma_f \times \gamma_s \times f_{ce} \quad (1.4)$$

where:

γ_f and γ_s are factors for the effect of fly ash and slag, respectively (Table 1.2)
 f_{ce} is the strength of the binder.

The strength of the binder can be calculated using Equation 1.5 [20].

$$f_{ce} = \gamma_c \times f_{ce,g} \quad (1.5)$$

where:

γ_c is a coefficient which depends on the type of cement and is taken as 1.12, 1.16 and 1.10 for cements 32.5, 42.5 and 52.5, respectively
 $f_{ce,g}$ is the strength grade of the cement.

The selection of water is dependent on the requirements for the specified slump and on the aggregate size and type. Appropriate values can be determined using the information in Table 1.3.