Glassfibre Reinforced Concrete: a Review

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Abstract. Introduced to construction about 40 years ago, GRC has come of age. It is now widely used all over the world and in quantities very likely greater than most of the other types of fibre reinforced concrete, although it remains less known. A brief history of GRC is followed by review of the basic make-up of this complex composite. Methods of production are identified, properties reviewed and modes of fracture which are unique to GRC are explained. Benefits which are already available and exploited by its users are summarised and the wide spectrum of current applications of GRC is outlined.

1. Brief history and introduction
Reinforcement of brittle matrices by fibres in order to improve construction materials dates back millennia; there is nothing new in the current exploitation of this principle. Beginning of the 20th century brought about advances in production of glass fibres mainly of the borosilicate type (E-glass). The first production of Glassfibre Reinforced Cement dates from late 1950s, when the E-glass fibres were combined with non-alkaline matrices [1]. It was already understood, that the alkaline environment of hardened ordinary portland cement caused corrosion and loss of tensile strength of the E-glass fibres. The earliest GRC production therefore required unusual cements and it remained very limited.

Special glass formulations, which generated alkali resistance had existed but it was not until late 1960’s that such fibres became commercially available. The new fibres and their applications were covered by patents and production of the GRC in early years was subject to licensing.

Production methods for GRC were relatively simple but the material itself was sophisticated and a much greater quality control was required than that used for ordinary precast concrete. Inadequate quality control of early GRC production had led to problems with performance of the composite and its rise in acceptance was temporarily curtailed. Early versions of GRC also showed a loss of the initial pseudo-ductility with age (embrittlement) when exposed to wet environment. Manufacturers of the AR glass fibres responded in early 1980s by developing a new generation of fibres, with different surface treatments. EN standards were also developed, the quality control was tightened and the best practice in production and design became strongly promoted by the International Glassfibre Concrete Association (iGRCA). The new fibres improved significantly the long-term performance of hardened GRC. Beginning of the new Millennium saw a very rapid increase in production of GRC, fuelled by the construction boom world-wide. The post-2008 global economic crisis slowed the pace of the rise for a time, however the GRC industry has now recovered and GRC is firmly established as a high-tech material of choice for leading architects and other end-users world-wide.
This paper is aimed at both construction practitioners and potential researchers with a limited knowledge of GRC. It provides the basic information and highlights a few points of special interest. More detailed information, supported by additional sources, can be found in the newly published book [2] and extensive technical guidance and data are available from the International Glassfibre Reinforced Concrete Association [3].

Concrete reinforced principally with a glassfibre fabric or textile (TRC) differs significantly from GRC. Principal reinforcement of TRC are glass fibre strands acting as very long, continuous reinforcing elements interwoven as a fabric/textile. Position of reinforcement in a textile-reinforced concrete is therefore pre-determined by the nature of its 'textile' pattern. Both the production processes and fracture mechanisms in TRC differ from those of GRC. Existing GRC manufacturers are rarely involved in production of pure TRC and practical production of TRC is currently limited to a few, namely German, specialist companies. Textile reinforced concrete is outside of the scope of this paper. Widder information can be obtained from publications focused specifically on the TRC [e.g. 4].

2. Basic constituent materials

2.1. Binders
Suitability of a hydraulic cement for production of matrices for GRC depends on how compatible it is with the type of glass fibre used as reinforcement. All common varieties of Portland cement produce matrices which remain strongly alkaline throughout their service life. Such matrices can be only used in combination with alkali-resistant (AR) glass fibres. White Portland cement is used where brighter colouring of GRC surfaces is required.

Alkalinity of portland cement based GRC matrices can be reduced by using pozzolanic additions such as microsilica (silica fume), pulverised fly ash (pfa), ground granulated blastfurnace slag (GGBS) and metakaolin. Such additions reduce alkalinity and modify the microstructure and properties of the hardened matrix but do not replace the basic alkaline binders. An adequately performing GRC can be made using alternative binders which produce non-alkaline matrices. These include cements of the aluminium-silicate and sulpho-aluminate type, such as the High Alumina cement (HAC), Calcium Aluminate cements (CAC) and Supersulphated cements (SSC). However, higher costs of such very low-alkali matrix materials tend to outweigh the saving in the cost of fibre reinforcement and other negative side-effects occur. Such alternative binders are currently little used, although applications have been reported from China.

2.2. Aggregates
The aggregate content of a typical mix has increased over time to the currently prevailing cement : aggregate ratio of 1:1 or more. The preferred shape of the particles is round and the maximum size is generally limited to 1.2 mm (spray-up process) and 2.4 mm (premix process). The content of very fine particles (passing 150 µm sieve) is limited to 10% of the total weight of the sample. Silica sands with SiO₂ content > 96% are widely used. Moisture content of the aggregate must be controlled. Mix designs are usually based on moisture content < 2% and an allowance for the free water in aggregate is made in the mix design.

2.3. Fibres
Tensile strength of glass in the form of very thin individual fibres/filaments (dia. < 20 µm) is very high (> 3GPa) compared with that of the glass in bulk. It relies on the glass fibres retaining their pristine, undamaged surfaces with very few, if any, defects. Production of the fibre itself and that of the composite is designed to maintain the fibres undamaged as much as possible throughout the GRC production process. The freshly drawn filaments are immediately coated - a 'size' usually tens of nanometres (10⁻⁹ m) thick is applied for protection and keeping the fibres in a bundle. It is important
to note, that the content of glass fibres in GRC is traditionally given in % by total weight (mass) of the composite. Spraying or sprayed-premix processes permit a higher packing density of the alkali-resistant fibre strands and an optimum content of approx. 5% b.w. The premix process has the optimum alkali-resistant fibre content of about 3.0 %. Higher than the optimum contents of fibres for each of the production processes reduce workability of the fresh mix which becomes difficult to compact adequately.

Tensile strength of fibres influences the ultimate direct tensile and flexural strength of the composite. The high strength of the fibres can be exploited only if bond between the fibre and the matrix (and between the fibres within the strand) were high enough and the fibre was long enough (and bonded adequately to the matrix) to enable the high strength to be fully utilised. Tensile load-bearing capacity of the fibres decreases when their effective cross-sections are reduced by corrosion caused by a reaction between the glass and the surrounding highly alkaline cementitious environment. The alkali-attack also creates localised weak spots on the fibres which also substantially reduce the very high strength of the initially pristine fibres. These reductions in load-bearing capacity are minimised by using alkali resistant (AR) fibres. Level of performance of fibres, which makes them suitable for GRC is specified [5] and relative performance of fibres in different alkaline environments is assessed by the standardised Strand-in-Cement (SIC) test [6].

Tensile strength is also reduced when products of hydration of the cementitious matrix precipitate on the surfaces of fibres inside of a strand. These cause local damage and act as stress concentrators, reducing the tensile strength of the fibre, namely when a displacement occurs. Both the individual fibres and bundles/strands of fibres are flexible (they can bend), however, when they bridge a crack in the matrix at an angle other than at or near to 90 deg, the 'edge' of the crack begins to act as a severe stress-concentrator and 'tensile' load-bearing capacity of the strand is sharply reduced.

Modulus of elasticity of fibres $E_f$ also has a strong influence on properties of the composite. Fibres with $E_f > E_{matrix}$ can increase both toughness and strength of the composite. Alkali resistant glass fibres with $E_f$ around 72-74 GPa therefore can reinforce the typical hardened cement paste paste with $E_{matrix} = \text{approx. } 35 \text{ GPa}$.

3. Production methods

3.1. Batching and mixing

All the basic ingredients of the matrix are batched by weight. Special dispensers are used for adding precise amounts of small quantities of admixtures and additives. The weighing equipment requires an accuracy within ±2% of the stated target batch weight. Input of glass fibres is usually controlled by the number of strands/rovings and the speed at which they are fed into the chopping mechanism when the spray-up production method is used. Performance is checked continuously by a fibre output rate monitor or the machine needs to be regularly tested for the accuracy of its delivery rates and ratio of the fibres and the slurry.

Most of the mixers used are designed specifically for GRC production. They are usually of a forced-action type, with a batch size of approximately 0.060 m$^3$ or 125 kg of a fresh mix. Larger batch mixers and continuous action mixers are used in integrated batching & mixing plants capable of a high output of GRC in a variety of mix-designs. A typical mixer for the spray-up process is capable of generating a high shearing action by mixing tools rotating at a high speed. Such mixers are usually operated in two modes/stages: first, a high speed (high shear) action produces a highly workable matrix mix (slurry) which is the pumped into a spray gun where it combines with the fibres. The first stage is followed by a period of low-speed (low shear) action for the blending-in of pre-cut fibre strands when the Premix process is used. It is possible to have separate batching, mixing and placing/spraying equipment, however the highest productivity and often the highest uniformity/quality of the GRC are achieved when an integrated system is used.
3.2. Production of GRC elements

3.2.1. Compaction and orientation of the fibres
Production is of fundamental importance as it governs the formation of the internal structure of the composite. GRC is an inherently porous material and the degree of compaction of the fresh mix affects its properties when hardened. A common production method is by spraying, which generates compaction by the impact of the mix hitting the mould. However, an additional compaction is routinely applied, usually a manual one using hand-held rollers. Special care has to be taken regarding corners in elements of complex shapes. Compaction of the premix GRC is usually achieved by the mix being hand-packed or trowelled into a freshly filled mould, which is then vibrated externally. The requirement for compaction is eliminated when a very highly workable, flowing self-compacting mix is used.

It is important to understand that the type of the production process has an effect on the orientation of the fibres. It therefore determines the degree of anisotropy of the hardened GRC produced. Spraying tends to arrange most of the fibres in a 2-dimensional random distribution, parallel to the flat surface of the mould and 'in-plane' of the sheet/panel produced. The length of the fibres usually exceeds significantly the thickness of GRC elements and a random 2-D rather than a 3-D distribution of fibres is achieved. Such a distribution can have a positive effect by improving the flexural strength of a hardened flat, sheet-like GRC. Earlier production methods used twin-head spray guns, which, incorrectly used, could produce non-uniform distribution of fibres 'in-plane' of the sheet, making the 2-D distribution non-uniform. Modern concentric spray heads have eliminated this type of anisotropy.

3.2.2. Simultaneous spray-up
A freshly made cement/sand slurry is pumped to the nozzle the concentric spray gun where it is mixed with chopped strands of fibres and projected out of the nozzle by compressed air. The fibres are cut to a pre-set length, usually between 25 to 37 mm. The chopping rate of the fibres and the pumping rate of the cement:sand slurry are controlled and typically set to produce GRC with 4.0-5.0 % of fibres b.w of total mix.

A 'mist coat' is applied by spraying the first layer as thin as possible, using matrix without fibres. Subsequent layers of fresh matrix with fibres are applied without delay, to ensure integrity. In case of a 'facing mix', the mix is allowed to stiffen before the bulk of the fresh GRC is built-up on it in layers. The facing layer is usually 3-5 mm thick, depending on the type of surface treatment. Each pass of the spray gun deposits a layer approx. 4 to 6 mm thick. Care has to be taken to ensure that an adequate thickness of the GRC is produced in corners and edges of moulds with complex shapes. Thickness is checked using a depth gauge or a template. The 'back face' is then finished as required by either the compaction roller or by a float. Thickness stated in a specification for GRC is the minimum thickness.

3.2.3. Premix and casting process
Fresh cementitious matrix is produced first and between 2% - 4 % b.w. of pre-cut AR glass fibres are then blended in. The length of the pre-cut fibre is usually 6 or 12mm but other lengths are available. The matrix is produced in a high-shear mixer, to obtain maximum workability and the chopped fibre strands are added in the second stage, often in a low-speed mixing regime. This facilitates their dispersion at the highest practical volume content with a minimum of damage to the fibres. The resulting mix can be hand-packed or trowelled into a mould or cast-in. Casting is either accompanied by vibration of the whole element or without vibration, if a self-compacting mix is used.

The fresh premix-GRC can be also sprayed in a process known as sprayed premix using a specially developed spray gun. The method is particularly suited to manufacture of large numbers of standard products. Current production plant is capable of production of up to about 2 tonnes of such a fresh mix per hour.
3.2.4 Other production methods

Filament-winding

Filament winding consists of wrapping continuous AR glassfibre reinforcement, impregnated with fresh matrix material, around a mandrel which defines the final shape of the finished product. It produces GRC with up to 18% volume fraction of the fibres. The process is very suitable for making hollow tubular products. It has been used in practice for GRC transmission poles and for pipes in the U.S.A and Australia.

Extrusion

Panels and similar elements in which one or both faces were to be smooth and which were required in large numbers with a very high repetition, can be made by this method. Trials were carried out but the process has not been widely adopted into GRC production practice, mainly due to the high cost of the equipment and the uncertainty about its adequate exploitation.

Manual lay-up

Simple flat and 3-D shapes can be produced by this process. The mould is coated with a plain matrix and then lined with a chopped strand mat, fabric or a mesh. Another layer of fresh matrix is applied, penetrating the fabric, and the next layer of the mat, or of a glass fibre fabric is placed. The process is repeated until the required thickness is achieved, making it close to that for TRC. A similar technique produces light-transmitting concrete, where a bulk element made of layers of parallel glass strands is made first. It is then cut precisely into ‘slices’ with fibres perpendicular to the cut. Special light-transmitting fibres are used.

3-D printing

Production of GRC using 3-D printing has been developed very recently in China, e.g. by WinSun Co. [7]. Thin 3-D elements are 'printed' at this stage and then joined up by stacking to make a structure or a large structural element [2]. ‘Hollow’ printed elements can be also stacked and used as permanent formwork, with the voids in-filled with concrete (Fig.1). Complete buildings have been assembled in this manner.

3.3. Curing

GRC has a high cement content and it is mostly used to make elements with thin cross-sections. The curing regime for GRC has to be controlled much more accurately than in the case of ordinary concrete. It must ensure that the composite attains an adequate strength by the time it is to be removed from moulds/formwork and handled and that an early drying shrinkage and any subsequent distortion are minimised.

Early production methods relied on curing GRC elements by sealing them in polythene sheets or keeping them in warm fog-rooms. Current production processes avoid it by an adjustment of the mix design. Small amounts of acrylic polymers in the fresh mix keep the internal moisture in and prevent its loss by evaporation. Curing environment still has to be ideally at approx. 20 °C and 95% R.H. Sudden and rapid drying-out or large temperature changes must be avoided to ensure that the GRC reaches adequate strength adequate strength for the element to be safely removed from a mould.
3.4. Moulds and formwork
The exceptional capability of GRC to manufacture products of very complex shapes requires very high quality moulds/formwork. Performance requirements for moulds and formwork for GRC are greater than in ordinary concrete technology. The mass of the material placed is less and formwork pressures are lower in case of GRC and the moulds can be much larger, more complex and re-used more often. However, greater accuracy and tighter dimensional tolerances are also required. The moulds have to be designed with an appropriate allowance for the expected volume changes of the GRC element (shrinkage or changes in temperature).

Two-component moulds, in which a rigid base is lined with another material, such as timber lined with a polymer resin or steel lined with polyurethane rubber are now common. Such moulds or mould-liners are usually based on silicone rubber and polymeric elastomers [2] and produce elements even with very deep textures and under-cuts (Fig.2). Mould-release agents are also used for GRC. The mould must be shaped in such a manner that it can be lifted or stripped easily and without damage the finished GRC product. The recent trend to use curved elements for flowing, free-form shapes of buildings generated new challenges for the mould-making. The latest developments integrate the digital design of facade elements with new 'adaptive-mould' forming technology [2,8] and reduce significantly the amount of manual work required.

3.5. Surface finishes and treatments
The initial surface finish of the GRC product reflects the surface of the mould used. It is essential that there are no defects and visible joints in the surfaces of the moulds. The original surface of the GRC can be subsequently treated to produce an even greater range of finishes.

Surface finishes vary from very smooth, glossy ones to a flat matt one and a wide array of textured and patterned surfaces with or without pigments. GRC can be made with:

► An ex-mould finish, either smooth or textured, according to the mould surface.
Texturing makes minor imperfections less visible.

► An exposed, fine aggregate finish (with or without a texture)

Water-washing away a freshly set, but not hardened, cement paste is sometimes assisted by an application of a coating by a retarder onto the mould surface prior to the facing mix being applied. In a typical treatment, the thin top layer is removed by a water jet to reveal a specially selected decorative fine aggregate (the 'exposed aggregate' process) on the external surface of a panel. Strong acids can also be applied to the surface to expose the decorative sand or fine aggregate. This is usually done immediately after demoulding as the surface of GRC rapidly becomes impervious and difficult to penetrate. Mechanical treatments aim to produce a surface with a texture simulating natural materials such as either a rough or polished stone. This can be achieved by wire-brushing and grit-blasting or grinding / polishing at a suitably early age of the composite.

Surfaces of GRC can be painted. The paint is usually applied onto a pre-pigmented GRC of a similar base colour. There are a number of suitable proprietary paints and penetrating stains now on the market which can be used to finish the appearance of a GRC product. Hydrophobic coatings and surface sealants can be applied and must be adequately permeable to water vapour. They can reduce lime-based efflorescence on the external surfaces and a reduce the effects of a polluted environment.

Figure 2. Polyurethane rubber mould being stripped-off [2]

3.6. Handling, transport, storage and repairs
Thin-walled GRC, particularly very large panels are vulnerable to permanent damage if not handled, transported and stored in an appropriate manner. Handling of a GRC panel, including the effect of an asymmetrical lift should be considered as part of its structural design. It is essential to use only lifting points identified in design and special lifting frames are used for handling of large panels. Embedded fixings can be used for lifting of GRC elements only if they were also designed for this purpose. Care must be taken to minimise any vibration and to restrain their movement during transport. All the points of support must be vertically aligned and in correct locations if the units are stacked. Incorrect storage may lead to permanent distortions and unacceptable deflections/deformations and lead to a rejection of otherwise perfect products. Any damage to load-bearing GRC elements must be assessed. Minor damage, if not structurally significant, can be repaired using fresh GRC mix similar to that used for the production of the element.

4. Fracture mechanisms
Microstructure of GRC is determined largely by the composition of the mix and the effects of mixing and production processes. It continues to change and develop with age in a non-linear manner, highly dependent on service environment. A cross-section of a typical GRC in Fig.2 shows the primary reinforcement: bundles/strands of glass fibres embedded in a matrix.
Internal stresses, including tension, develop when an external load is applied to a GRC element. The tensile stress becomes critical when it exceeds the tensile strength of the matrix and causes it to crack. Mode of fracture (failure mechanism), which follows the first cracking of the matrix, depends on properties of the matrix and fibres, and on the bond between them [9]. As these change with age, so does the mode of fracture. Interaction between a fibre strand and the matrix which it is embedded in, is measured by the strength of their bond. The mode of fracture also reflects bond between individual filaments within a strand. Ageing and conditions of exposure affect both the strand/matrix bond and bond between fibres within a strand to a different extent. Bond between fibres within a strand determines the degree to which the strand acts as a single ‘solid’ element or as a ‘composite’ fibre bundle.

The first crack in the matrix occurs when the internal stress approaches the level of stress corresponding to the LOP and the tensile strength (or strain capacity) of the matrix is exceeded. Three basic categories of failure mechanism which follow the first crack were identified [9,10,11]. At this point the stress, which until then was taken by the matrix, is instantly added to that already carried by strands of fibres crossing the crack. How much of the additional stress an individual strand crossing the new crack can take depends on many factors, such as its embedment length, angle in relation to the direction of the stress and, importantly, its peripheral and internal bond. A further increase in load (stress) leads to an eventual failure of the strand.

The three principal modes of fracture (Fig.4) are [11]:

a. **Complete pullout of the strands.**

Bond between the fibres at the perimeter of the strand and the surrounding matrix is low but bond between fibres within a strand is high. It enables the whole strand to act as a single, integral reinforcing element. Tensile strength of the inner fibres, which make up most of the strand and their reinforcing capability is therefore poorly utilised. The strand tends to pull out as one single element. The work of fracture is low. This mode of fracture is usually associated with GRC at an early age.

b. **'Telescopic' or 'combined' mode of failure [11].**

Peripheral fibres of the strand, in contact and bonded well to the matrix, take up most of the additional stress transferred from the matrix, and eventually fail in tension. At this point all the stress previously carried out by the peripheral fibres transfers by bond onto the next layer of inner fibres within the strand. The inner fibres then begin to fail in stages, and the process continues until all the fibres are broken. The process is usually accompanied by partial internal pullouts of the inner fibres as they
break at different points and the frictional part of the bond continues to provide additional means for fibre-fibre transfer of some of the internal stress. The highest amount of work of fracture (the highest pseudo-ductility or toughness) are recorded, while the strength of the composite is also enhanced. However, this mode of fracture tends to be a transient phenomenon, associated with current types of GRC at a lower age, when magnitudes of external bond (with the matrix) and bond within a strand are in an appropriate proportion. When and for how long this mode of failure exists depends very much on factors such as external service conditions, mix design and age. The failure of the GRC in this mode is gradual and a complete fracture occurs only after a substantial deformation/extension of the composite. It is the mode of failure most desirable for GRC in practice.

![Figure 4](image-url)

**Figure 4.** A composite of microphotographs of the three typical modes of tensile fracture of strands of glass fibres embedded in a cementitious matrix and crossing a crack. The fractures were observed during tensile tests carried out inside an SEM.

c. **Complete tensile fracture of the strand.**

This mode occurs when bond between both the fibres within the strand and between the strand and matrix is very high. As in the mode (a), the strand then acts as a single reinforcing element and fails in a complete tensile fracture with a minimum extent of pulling out, or with no pullout at all. Strength of the composite is enhanced, but work of fracture is lower than in (b). The composite shows a typically brittle fracture with a sudden failure at a much lower ultimate strain/deformation then in (b). Fractures in the mode (c) are typical of a highly aged GRC, particularly in a humid environment.

A pseudo-ductile composite with failure modes (a) or (b) is much preferred to a brittle one (c) in structural applications. There are no sharp boundaries between the three basic modes of fracture and one type can be present in a given GRC at any age. Moreover, the fracture mechanism is also influenced by factors other than bond, such as the position of a reinforcing strand in relation to the applied stress and the line (or path) of the crack in the matrix.

Fractures shown in Fig.3 are typical of a strand bridging a crack in a position perpendicular to the fractured surface of the matrix and the modes of fracture can be identified. However, in practice, only a very small percentage (5-8%) of strands would be in such a position.

Fracture processes of strands crossing a crack at a more acute angle is even more complicated. Limited studies have indicated [12] that peripheral fibres of the strand fracture first as the edge of the matrix along a crack concentrates the stress. The broken fibres then provide a 'cushion' over which the
inner fibres can still pull out at an angle (Fig. 5). There are indications [12], that strands at a slight angle to the principal stress provide more 'toughness' than those perfectly perpendicular. Strands lying perpendicularly to the direction of the applied stress and weakly bonded to the matrix may reduce the strength of the composite. Contribution of the strands at higher angles is extremely difficult to examine directly. Numerical modelling of the fracture processes in GRC has been tried. However without an access to values for bond obtained independently (experimentally) for all its different aspects and considering its inherently variable nature, no reliable and genuinely predictive numerical model for GRC has been developed to date.

The fracture process depends very strongly on fibre-matrix bond, which, in turn, depends on the micro/nano – properties of the contact zone (often identified as the interfacial transition zone – ITZ) between either a fibre and the matrix or between fibres within a strand. Two types of bond which control the 'composite' action between matrices and reinforcement can be broadly identified [10], namely:

- **Adhesive bond** between glass and hardened cement. It tends to be low and keeps deformations of both of the fibre and of the matrix proportional / compatible in early stages of loading. When the interfacial stress exceeds that of the adhesive bond, de-bonding begins and proceeds rapidly along the remaining embedded length of the strand.

- **Frictional bond** resists further displacement (pullout) of the strand (or fibres within a strand) during multiple cracking of the matrix, up to and beyond the ultimate tensile or flexural strength (MOR) of the composite. It governs any remaining resistance against pullout of a fibre crossing a crack after the failure of the adhesive bond. Frictional bond is neither uniform nor constant, its magnitude changes with the speed of the loading and displacement and with the fracture process.

Glass fibres in GRC are not provided with any 'anchorage' at their ends, unlike many types of fibres in steel fibre reinforced concrete (SFRC). This type of 'bond' therefore has a negligible effect on the GRC fracture processes.

An accurate quantitative assessment of bond in GRC and its control (design) remain a big challenge on the way to a greater exploitation of the potentially higher performance of GRC. Direct measurements by 'pullout' tests such as are used for ordinary concrete and other fibre reinforced concretes are not practicable in GRC research, where the basic reinforcement is by bundles of fibres. A breakthrough came with first applications of nanotechnology in mid-1990s [13]. A nano-indenter was developed, which permitted precise loads (mN) to be applied onto very small targets (10⁻⁶ m) and enabled displacements to be continuously measured at nano-scale (10⁻⁹ m). Such extremely high precision testing can be only carried out in specialist laboratory premises with very closely controlled
temperature and in a vibration-free environment. The nano indentation technique permitted ‘micro-
mechanical’ properties of the matrix to be assessed both near the fibre-matrix interfaces and within
the bulk of the matrix or the fibre strand and a single-fibre push-out test was developed. In this test, a
very thin (< 0.5 mm) slice was cut perpendicular to the axial direction of a strand of glass fibres em-
bedded in the matrix material. The push-through test specimen was placed into the nano-indenter and
the tip (approx. 5-7 μm in diameter) was positioned above the centre of the selected fibre. The original
sharp tip (diamond cube) of the indenter was later modified by re-shaping it to provide a flat contact
area with the cross-section of the fibre tested [14]. Such shaping was only possible by using focused
ion beam technology. The cost of production of the flat tips was very high and it curtailed further
progress of a systematical investigation of bond. Direct information about bond between fibres with-
in a strand and between peripheral fibres and the surrounding matrix was obtained but much more
work is still required to build up an adequate base of the data on all aspects of bond. Such data on
bond within GRC are a pre-requisite to a substantial advance towards full exploitation of the structural
potential of GRC.

5. Basic properties

5.1. Mix design and fresh GRC

Properties of both fresh and hardened GRC depend on many factors which include constituent materi-
als such as:

► matrix (type of cement, w/c, cement content, additives and admixtures)
► filaments (size/diameter, strength, modulus of elasticity, surface treatment)
► strands (number of filaments, shape, length)

Their proportions are established in the process of mix-design, which aims to produce GRC with the
required performance characteristics when fresh and hardened.

The mix design takes into consideration additional factors, such as:

► production process - which includes mixing, compaction, curing, distribution and orientation of
fibres/strands
► application of the product - which determines the length of service life (age) and expected expo-
sure / service environment (levels/variations of temperature and humidity incl. freeze/thaw cycles),
chemical and biological attack and chemical/physical fibre-matrix interactions
► development / changes in fibre-matrix interaction over the period of service life and conditions
for a given GRC mix design.

Mix-design of common GRC matrices includes superplasticisers and admixtures developed for
self-compacting concrete. A highly workable fresh mixes are produced without a reduction of strength
when hardened. Workability is fundamental for an effective production and it is monitored and main-
tained within narrow limits. A standardised mini-slump test [2] is used, serving both as an indicator
of optimum workability and as an indirect measure of uniformity of the GRC produced. The content
of glass fibres in an uncured, green GRC can be obtained by using a ‘wash-out’ test [2], to check com-
pliance with specifications.

Freshly made GRC in the form of “green” sheets can be re-shaped by folding and pressing to pro-
duce 3-D elements. Care must be taken to ensure that fibres were not damaged in the process and no
 cracking or another discontinuity is generated in corners and bends.

Guides and aids, which help in the selection of grades (strength) of GRC for a range of applications
are available [e.g. 15]. The choice of the grades has to be confirmed by the specifier, a the GRC
manufacturer and a competent engineer. Mix proportions for a typical grade 18 GRC, both with and
without the addition of a polymer for curing are given in Table 1. Designs with proportions falling
outside of the guidelines may be acceptable but performance of such GRC has to be verified by trials before use.

5.2. Assessment of performance
Assessment of properties of GRC requires an understanding that factors which influence them are both numerous and inter-related to a very large and variable extent. Magnitude of the effect of one single factor on a given property usually depends on the value(s) of other factor(s). Such multi-factorial interactions also tend to be non-linear and of a varied degree of significance. Reliable, general conclusions therefore cannot be drawn from a test-series or from an experiment, in which only two factors/variables are correlated, without regard to any of the other ones.

Table 1. Mix proportions of Sprayed Grades 18 & 18P [3]

| Sprayed GRC Grade                       | Grade 18 | Grade 18P |
|----------------------------------------|----------|-----------|
| Aggregate/cement ratio                 | 0.5 - 1.5| 0.5 - 1.5 |
| Water/cement ratio                     | 0.30 - 0.38| 0.30 - 0.38|
| Glassfibre content (% by weight of total mix) | 4.0 - 5.5%| 4.0 - 5.5%|
| Polymer solids content (% by weight of cement) | Nil     | 4 - 7%   |

Properties of a cement-based matrix change with age. It is impractical to assess the effect of age effect directly and accelerated ageing tests are therefore used. The long natural exposure is replaced by a shorter one in more aggressive warm/hot solutions simulating pore solutions in a specific GRC matrix material. Accelerated ageing tests are useful for comparative purposes, however, performance in real service life may depend on additional factors, such as the history and effects of applied stresses and micro or macro-cracking already present in the composite.

As the hydration of cement continues, at a decreasing rate with time, changes in the fibre-matrix interaction occur simultaneously. It is essential to quote the age and curing/exposure history whenever properties of hardened GRC are mentioned or comparisons made.

Dispersion of fibres within GRC is never completely random or uniform. The composite therefore always exhibits a variable degree of anisotropy, which means that its performance parameters also depend on the direction of the applied load. This is particularly significant for all types of strength-related properties, where the value of a property depends on the angle between the direction of the applied load to that of the prevailing number of fibres.

5.3. Mechanical properties
Typical values at the age of 28 days for current GRC are shown in Table 2
Table 2. Range of properties of a typical hardened premix or sprayed (italics) GRC [17]

| Property                        | Range of properties (kg/m3) | Ultimate strength (MPa) at 28 days in bending (MOR) | Ultimate strength (MPa) at 28 days in uniaxial tension | Ultimate strength (MPa) at 28 days in transverse tension |
|-------------------------------|-------------------------------|----------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|
| Dry density                   | 1900-2100, 1800-2000          | 5-14 ; 18-30                                       | 3-6 ; 8-12                                          | 7-11 ; 5-8                                          |
| Modulus of Elasticity GPa     | 10-20 (both)                 | Tensile strain at MOR %                            | Impact resistance kJ/m2                            | Impact resistance kJ/m2                            |
| Thermal movement              | 10-20 x10 -6 per 1 °C (both) | Drying shrinkage strain 300-1200 x10 -6 (both)        | Poisson's ratio 0.24-0.25 (both)                     | Poisson's ratio 0.24-0.25 (both)                     |

5.3.1. Flexural / bending strength

Bending (flexural) strength is the principal characteristic of hardened GRC. It is routinely assessed by a standard 4-point test [2,17] (Fig. 6) which provides information for safe structural design and indicates fracture mechanisms involved. Practical experience has shown that a correctly performed flexural test provides a good indicator of the strength and variability of GRC, as required for design [e.g. 16]. Performance in bending is characterised by two parameters which survived from the early days of GRC and which are sometimes difficult to fit into a modern context of behaviour of fibre reinforced composites. The first is the Modulus of Rupture (MOR, MPa), which indicates the maximum flexural stress which a test specimen was able to resist. The other one is the Limit of Proportionality (LOP, MPa) indicating the stress at which the stress-strain (load-deflection) curve begins to deviate from linearity.

The MOR is equivalent to the bending strength of the material tested. It is not a ‘modulus’, such as the modulus of elasticity. Neither is it associated with a ‘rupture’. As is typical for a pseudo-ductile composite, the GRC normally does not fail entirely at the MOR level of stress. Instead, it continues to resist gradually reducing flexural stresses until the ultimate tensile strain $\varepsilon_{\text{ult}}$ (%) (deflection, extension) is reached. Only then the composite loses its integrity and its load-carrying capacity is reduced to zero. With the $\varepsilon_{\text{ult}}$ being normally much greater than the $\varepsilon_{\text{MOR}}$, the failure of GRC is usually a gradual process providing a useful safety margin in its structural applications.

5.3.2. Tensile strength and Poisson's ratio

Behaviour of a GRC composite is best characterised by its stress/strain diagram obtained from a direct uniaxial tensile test [2] which provides a genuine tensile strength (UTS) of the GRC. The test produces the value of the ultimate tensile strength as the stress at the peak of the stress/strain curve. As in the bending test, the ultimate tensile strain does not normally coincide with the ultimate tensile strain and occurs only after an additional strain develops and the tensile stress has already decreased. Uniaxial tensile tests are difficult to carry out reliably by simple test equipment (difficulties with gripping of specimens, size-effect, etc.). Such tests are expensive and limited to specialist laboratories.

Instead, tensile strength of GRC is obtained indirectly, derived from an assumed elastic stress distribution occurring during from the 4-point standard GRC bending test. Poisson's ratio describes ratio between strains parallel and perpendicular to the applied tensile stress, measured in direct tensile tests. The Poisson's ratio of a typical GRC is approx. 0.24.
5.3.3. Modulus of elasticity.
Young's modulus of GRC reflects primarily that of the matrix, with fibres making a contribution. Elasticity of the composite can be adjusted by changing the modulus of elasticity of the matrix. The adjustment is usually downward, to make the hardened composite more 'ductile'. In such case the ultimate tensile strain and the toughness of the composite are increased. A very high-modulus (and usually also a very high-strength) of the matrix tends to make the composite more brittle. Modulus of the fibres has a lesser effect, which depends on the degree of internal stress transfer available, controlled by bond.

5.3.4. Compressive strength
A typical GRC load-bearing product is made of thin sheets of the composite, where the compressive strength alone tends to be only a secondary parameter. Products where 'bulk' GRC is used tend to be largely non-load-bearing. There is no standard procedure for assessment of and little data exists on compressive strength of GRC. Tests are more likely to be carried out on full-scale prototype elements, subject to loads expected in service, instead of on individual test specimens. For approximate guidance, compressive strength of GRC can be estimated as 40-60 MPa or 50-80 MPa for cast premix and spray-up process respectively [2].

5.3.5. Transverse tensile and inter-laminar shear strength
Transverse and inter-laminar shear strength are closely related, both depending largely on the tensile strength of an unreinforced matrix.

Transverse strength resists a tensile load applied perpendicular to the surface of a cross-section of a sheet-like GRC element. Transverse strength relies greatly on adhesive bond between the matrix and the reinforcement. There is no standard test, any measurement is strongly dependent on the size/shape of the test element and on the manner of its support.

Interlaminar shear strength resists loads applied 'in-plane' of a flat thin-walled GRC element. This is of significance during fracture of the GRC in bending. The interlaminar shear strength ensures that the element will not fail by an internal displacement, a 'delamination', when subjected to bending. The value of this strength is estimated as 3-5 MPa, lower than the tensile strength of the matrix [2]. There is no standard test and few data are available.

Shear strength and punching shear strength perpendicular to the plane of a typical flat sheet of GRC are inter-related. The shear strength is difficult to assess as a material's property as it is strongly
dependent on shape/size and support conditions of any test specimen. Punching resistance improves with a higher fibre content and then it follows any changes in the ultimate bending strength (MOR) with age. It is estimated as 25-35 MPa (sprayed) and 4-6 MPa (premix) in a typical GRC. Full-scale load trials simulating conditions in service are required for verification of performance of any structural GRC elements in which punching resistance was considered significant.

5.3.6. Toughness and impact resistance

GRC is unusual amongst fibre reinforced composites in use because the fibre reinforcement is by bundles (strands). Depending on the bond between the matrix and fibres and between fibres within a strand, an applied load generates complex stresses and displacements which provide the composite with a degree of an inelastic behaviour, a pseudo-ductility is observed. GRC is therefore inherently more impact resistant than plain concrete and some other fibre reinforced composites. Fracture of a mature GRC includes both tensile fractures and pullouts, the highest work of fracture occurs when intermediate/telescopic fractures of the glass strands dominate. Impact resistance, combined with the ‘work of fracture’ measured as the area below the stress-strain (or load-deflection) curve, provide a measure of the toughness of the composite.

Toughness does not normally enter into ordinary structural design, however, with all other parameters being equal (bending and tensile strength etc.) a tougher composite is always preferred. Such a composite exhibits substantial deformations before a final break and a general loss of integrity, a useful warning stage before a failure in practical applications.

5.4. Physical properties [2]

5.4.1. Density

Density (bulk density in kg/m³) of hardened GRC reflects density of the matrix which depends on content and density of aggregate, and on the degree of compaction of the fresh composite. Free water content and any trapped/entrained air of the hardened GRC also influence the density. Specimens of the composite for assessment of density and for reliable comparisons should be oven-dry, or of identical moisture content. Density of a typical GRC varies from 1800 kg/m³ when dry to 2000 kg/m³ when wet.

5.4.2. Permeability, water absorption and apparent porosity.

A well-compacted GRC has an inherently low water permeability and it is considered a waterproof material, suitable for use in water retaining structures. Permeance by water, measured on samples of 8mm thick freshly made GRC, is in the range of 0.02 - 0.4 ml/m²/min. Water absorption (5-11%) and apparent porosity (16-25%) are similar for both the premix and sprayed GRC. Standardised tests, e.g. EN 1170 Pt. 6 or the iGRCA test method [17] are used for the absorption.

5.4.3. Acoustic properties

A typical GRC has high density providing it with an inherently good capacity for attenuation of noise. However, the acoustic performance depends not only on the intrinsic capacity of GRC for noise attenuation but also on the geometry and method of fixing of the element. A sheet of GRC 10mm thick, with a density of 2000 kg/m³ subjected to the sound pressure of 0.2 kPa, will provide a Sound Transmission Class of 5.4.4

5.4.4. Thermal properties

Thermal expansion/contraction is described by a coefficient indicating ‘unit strain’ for a one degree of change in temperature, which has a range of approx. 10-20 x10⁻⁶ / °C for a typical GRC. Minimum values of expansion/contraction occur at high and low Relative Humidities. The maximum value oc-
curs at around 50-80% RH. *Thermal conductivity and thermal resistance* depend on density of the GRC and its moisture content.

- **Thermal conductivity** $\lambda$ of a typical GRC with density of 1900 - 2100 kg/m³ is in the range of 0.5 to 1.0 W/m·°C. It is a characteristic of the material.
- **Thermal resistance** $R$ depends on the thickness $(t)$ of the material and its thermal conductivity $(\lambda)$, $R = \frac{t}{\lambda}$
- **Insulating capability of a building element $U$** is an inverse of the resistance $R$ plus the heat losses by convection and radiation. The value of $U$ therefore depends on external factors reflecting the environmental situation of the building element in addition to the thermal resistance of the material.

### 5.4.5. Hydraulic and abrasion resistance

Smooth mould-side surfaces of GRC make it suitable for elements used in a variety of hydraulic structures. Manning's roughness coefficient, used in the Manning formula for calculation of a hydraulic flow in an open channel is approx. 0.012.

There is no specific guidance for abrasion resistance of GRC. In cases where the abrasion resistance is of significance, an approach similar to that for abrasion resistant concrete may be adopted (abrasion resistant aggregate is used) although there is much less scope to modify the GRC matrix to make it more abrasion resistant (lower aggregate content).

### 6. Durability

An overall durability of GRC reflects a combination of effects of: 

- (a) alkali-resistance of the fibres,
- (b) alkalinity of the matrix and
- (c) resistance of the GRC to degradation caused by exposure to aggressive service environment.

Degradation under (c) includes a range of factors, such as wetting/drying and freeze – thaw cycles exposure to high temperatures (fire). In addition, durability of a GRC product depends not only on the intrinsic properties of the composite but also on the geometry and durability of fixings adopted for a specific GRC element.

#### 6.1. Frost resistance

GRC specimens are subjected to cyclic freezing and thawing in a water-saturated state as for ordinary concrete. The effect is similar to long-term ageing: the LOP increases, while the MOR decreases. Due to the very low water/cement ratio of the cementitious matrix, GRC performs as well or better than good frost-resistant concrete, without the need for air-entrainment.

#### 6.2. Fire resistance

Basic constituents of GRC are inorganic and non-combustible. Fire performance classification according to standard test procedure is A1 [18]. GRCs with small amounts of organic admixtures (approx. < 6% b.w.) will not sustain burning but fumes will be emitted. Fire tests classification is A2, with a rating of S1 for smoke production and d0 for flaming droplet production. The matrix tends to desiccate in fire and undergoes both drying shrinkage and thermal expansion. Thermal movement develops and when it becomes restrained by fixings or the shape of the elements, excessive tensile stresses may be generated, with the subsequent cracking. In practice, performance in fire is very often dominated by the shape & size of the product and when fire resistance is required, appropriate standard tests for endurance in fire are therefore carried out on prototype full-scale elements.

#### 6.3. Chemical, biological and other exposure

Carbonation of the cement-rich and relatively dense GRC exposed to air is very slow, reaching only few millimetres after many years in service. With no ferrous reinforcement in GRC and with no effect
of the glass fibres, any lowering of the alkalinity of the matrix by carbonation actually benefits the GRC by increasing slightly the strength of the matrix.

Effects of acids on the common GRC (OPC based) are similar to those on ordinary concrete, causing an erosion of the cementitious matrix.

There is no evidence of a biological attack of significance reported for GRC in practice. Effects of other chemicals have not been studied specifically for GRC, its resistance is generally comparable to that of a very cement-rich ordinary concrete.

No reduction of mechanical properties of GRC has been reported when subjected to gamma radiation [19] or another similar exposure.

7. Volume (dimensional) changes
Dimensional changes are of primary significance in design of GRC elements as the systems for attachment/fixing of GRC elements must be able to accommodate not only the self-weight and imposed loads but also all the movement due to changes in humidity and temperature in-service. Shrinkage strain can generate large movements in large elements, the mix design may be then modified using a 'low-shrinkage' matrix by choosing GRC with the highest practicable content of aggregate (sand) and/or by a modification of the binder.

7.1. Effects of humidity: shrinkage / swelling.
Dimensional changes of GRC are all non-linear and time-dependent as for ordinary concrete. Immersion in water causes an expansion / swelling, drying out causes contraction / shrinkage, which are both reversible, non-linear and their magnitudes are time-dependent. Volume changes due to changes in humidity are assessed by a standard test [20].

For design purposes, the initial, irreversible shrinkage $\varepsilon_{ir}$ can be estimated at $300 \times 10^{-6}$ with a total long-term shrinkage $\varepsilon_{total}$ of approx. $1200 \times 10^{-6}$. Values between $1000-1500 \times 10^{-6}$ are used in practical design of joints and fixings [e.g. 16], depending on exposure conditions and the GRC mix-design. As the aggregate used is normally not susceptible to drying shrinkage, increasing the content of aggregate lowers the ultimate shrinkage of the composite.

7.2. Creep and fatigue.
Sustained loading of GRC produces an additional deformation (creep strain) beyond the initial, instantaneous one. It follows a non-linear relationship, where the increase in creep strain diminishes with age. The instantaneous deformation is largely elastic and reversible, when the stress is less than that of the LOP. Stresses at levels very near to the MOR can cause a delayed, gradual failure of the composite, which is difficult to predict. Cyclic and other types of a sustained load of variable magnitude affect the performance of GRC and generate fatigue of the composite. Strength is reduced and the resistance to fatigue is measured by the number of repeats/cycles of the load necessary for a failure to occur.

7.3. Variations in temperature and humidity
Mature GRC reflects changes in ambient temperature in the same way as concrete with a very high cement content. Similarly, the coefficient depend on moisture content of the GRC (matrix), it is lower for very dry and saturated conditions compared to 50% R.H. It is essential to consider dimensional changes due not only to ambient temperature but also due to absorption of sunlight on external GRC surfaces, namely when dark colours were used.

8. e-GRC and environmental performance [2, 21]
The e-GRC is a new type of the composite, exploiting photocatalysis. The photocatalytic activity of the e-GRC is based on a nano-crystalline form of Anatase type of TiO$_2$ present in the facing layer.
8.1. Active de-pollution of environment by eGRC

The photocatalytic surface of eGRC becomes chemically very active in the presence of daylight (or any other source of UV light) and generates a process in which complex organic molecules of common pollutants (e.g. nitrogen oxides (NO\textsubscript{x}), sulphur oxides (SO\textsubscript{x}) and numerous volatile organic compounds) are broken down by oxidation and removed from the air. Such pollutants have adverse effects on human health, namely in densely populated urban centres and industrial zones. Trials [22] showed that the photocatalytic de-pollution of air in a city-centre busy street was very significant. It was calculated [27] that applying results from practical trials and covering 15% of visible urban surfaces with products with photocatalytic surfaces in a large city can lead to an overall reduction of the pollution levels by 50%. The European Commission responded with [23] new measures to reduce air pollution.

8.2. Self-cleaning surfaces

Presence of the photocatalytic TiO\textsubscript{2} also affects the hydrophobic properties of the surface. The UV light changes the original hydrophobic surface (repelling water) into a very highly hydrophilic one (contact angle of less than 5\textdegree), inducing a state of ‘super-hydrophylcity’. A very thin, uniform film of water forms on the exposed photocatalytic surface. The water layer then hinders adhesion of external substances to the surface and helps to maintain the surface clean. A significant level of the ‘self-cleaning’ capability is established.

8.3. Energy requirements

It is possible to determine the energy requirements for production of individual raw materials making up GRC. A complete assessment of the energy requirement for production of GRC therefore requires the energy input during its manufacture. A modern auto-spray traverse system can produce approx. 50 m\textsuperscript{2} per hour of GRC about 12mm thick. Energy used is approx. 1.7 kWh per 60 kg batch mix, approx. 29 kWh per tonne of GRC. [24]

8.4. Environmental impact analysis

A typical product, manufactured both in GRC and in traditional reinforced concrete in large numbers and for identical purpose, had been selected to allow a reliable, direct comparison and quantification of the difference in environmental impact to be made [25]. Drainage channels and ducts for communication and other services along railways were examined, as supplied to a typical construction site. Both products were available in traditional reinforced precast concrete and in a premix type of GRC and are already used in very large numbers. On average, the un-weighted impact of traditional concrete unit was 123% higher and the weighted one was 61% higher than that of the GRC. In addition, there are secondary benefits of GRC products and a lower environmental impact due to reduced weight of products made from GRC, reduced demands on transport, reduced breakage, reduced amount of site-work and the ease of handling.

9. Summary of benefits

9.1. Economy through a combination of low weight and high strength.

Self-weight of structures decreases when GRC is used and demands on foundations are reduced. GRC cladding is suitable even for very high-rise buildings and offers good performance under seismic loading.

9.2. Freedom of shape.

GRC is easily mouldable into a wide range of shapes, including intricate grilles, panels with double curvature and 3-D objects. The high freedom of shape permits production of structurally very efficient elements. Easily cast, it can produce items with very fine details and reproduce very complex features and elements of both modern and historic buildings.
9.3. Durability.
Basic reinforcement is non-ferrous and the GRC products are not susceptible to corrosion as in traditional reinforced concrete. Low permeability and a very slow rate of carbonation offer protection against corrosion of steel in adjacent reinforced concrete. GRC has an inherently high resistance to extreme exposure conditions (freeze/thaw, fire etc.)

9.4. Appearance.
An extremely wide range of attractive surface finishes is available, satisfying the highest requirements for an aesthetic appearance of new structures and capable of matching colour and texture of surfaces of existing buildings. Durable and brightly coloured surfaces with enhanced self-cleaning can be achieved in a variety of textures and shapes.

9.5. Environment.
The relatively low weight of GRC products reduces CO2 emissions associated with their transport. There are no VOCs or other pollutants emitted from the material itself, neither in production nor in use.

GRC is fully recyclable into concrete and other applications. In addition, the photocatalytic eGRC reduces directly and significantly the concentration of pollutants in the surrounding air, leading to a better quality of environment, especially in congested urban centres and at a minimal additional cost.

10. Current research
Unlike for other types of fibre reinforced concrete, research into properties and fracture mechanics of GRC in early years had been restricted to in-house research by large companies making the AR glass fibres. Fibres were provided only to licensed GRC producers and not to independent researchers. Combined with inherent difficulties and challenges for research due to the very complex internal structure of GRC, such attitudes almost eliminated independent research for many years. On the other hand, concrete reinforced with other fibres (steel/metal, polymeric fibres, carbon fibres, natural fibres etc.) had been a popular academic research topic for decades. Closer look at the plethora of conferences and multitude of publications on ‘fibre-concrete’ over the last 40 years reveals that in many of the events, glass fibres were not even mentioned. Situation improved since early 1990s, when AR fibres became freely available, however, current research and development is still confined to very few isolated centres with intermittent projects. Recently, independent research on textile (glass fibre) reinforced concrete (namely in Germany) developed and some of the work has overlapped with GRC.

Alongside the rapid rise in the use of GRC there is now a growing demand for development and for an advance to new versions of GRC of an even higher performance. Manufacturers of AR fibres do maintain some R&D in this area, however, a coordinated, systematic research requires additional support, beyond what the small/medium size producers of GRC can afford. External national/international investment and coordination will be required to set up and operate expensive research infrastructure required to exploit further the potential of GRC.

11. Applications
One of the key features of GRC since its first development has been its versatility in use. However, over the last decade the range of the applications continued to grow and it is now extremely large. The most recent broad review of completed projects [2] included eleven categories, namely mature structures, civic/public buildings, office and commercial buildings, residential buildings, religious structures, art and recreation, reconstructions and conservation of historic buildings, interior decorations and furniture, architectural building components and civil & environmental engineering.
It has shown that at one end, GRC is used for mass production of small, simple and unsophisticated items for everyday use (flowerpots, drainage channels, window cills, street furniture etc.). At the other end, it is used by leading international architects for very large scale, high-tech, iconic projects. GRC is able to fulfill demands for highest structural complexity, size of construction elements, freedom of shape to achieve spectacular appearance, durability and the highest quality.

Architects world-wide now enjoy the high degree of design freedom provided by GRC, together with a direct, positive environmental performance it offers. Some of the recently completed projects would have been un-feasible to build just a few years ago. There are many impressive examples, where flowing, curving lines and unusual textures can be identified as common features of the facade structures. Geographically, GRC is no longer limited to the developed world and to a few rich developing countries, it is now found in more remote places such as Bhutan or Georgia.

Two projects have been selected to illustrate the achievements:

**Mature structures** – projects completed more than 20 years ago: The office building at 30 Canon Street, London, UK (Fig 7), remains the best example of a substantial application of the earliest version of GRC. The building is clad with approx. 1900 hollow double-sided GRC panels, produced by an early spray-up process. The facade as shown in Fig 5 has been cleaned and coated.

**Public buildings**
The Nanjing Youth Olympic Centre is a very large development all clad in GRC (Fig 8). A total of 110 000 m² of GRC was used to produce 12000 units, which fell into four categories: 40000 m² of flat panels from 3m x 2m to 3m x 6m in size, 32000 m² of folded panels from basic size of (2+2)m x 2m to (5+2)m x 3m, 30000 m² of double-curve panels from 3m x 2m to 6m x 4m, 8000 m² of single-curve panels from 3m x 2m to 6m x 4m. The panels were designed for installation in inclined lines both for roofs and walls.

Figure 7. 30 Canon St., London, UK. Completed 1974. Architect / Structural Engineer: Whinney, Son and Austen Hall, Ove Arup
12. Conclusions

GRC is already a well-established construction material, however, while there has been an enormous amount of research and a great number of publications on concrete reinforced with metallic and other fibres, leading to a disproportionately limited amount of practical applications, it is the other way round in case of GRC.

There is a very large amount of GRC used in practice but very little research and few publications to support it. A strong case exists for widening of the knowledge of what GRC can do and for research required to improve further its properties.

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