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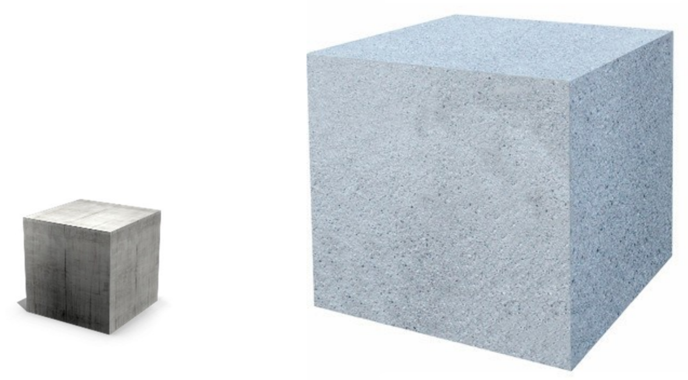

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ULTRA HIGH QUALITY GRC FOR THE 21ST CENTURY

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ABSTRACT

Glass fibre reinforced concrete has been in use since the 1970s, however over the last 10 years it's application in both in the UK and globally as a facade material has grown considerably. Designed and manufactured correctly it is an extremely robust and durable material with a typical design life of 60-80 years. When compared to traditional precast alternatives it offers significant weight and environmental benefits. The material is, however, a complex composite which requires high levels of knowledge, process control and testing validation. Despite this, current standards only provide for minimum levels of quality assurance and testing. This paper presents an alternative approach to provide specifiers and users with greater confidence in GRC products.

Keywords: GRC, quality, durable, composite, testing, quality assurance.

INTRODUCTION

Development of GRC began in the late 1940s; however early attempts at providing reinforcement were unsuccessful due to the aggressive nature of the highly alkaline cement-based matrix on the fibres. It was not until the 1960s that Pilkington Glass, working closely with the Building Research Establishment, were able to develop alkali resistant fibres which provided more durability and formed the basis of the industry as it exists today.

GRC and the associated production methodologies required to manufacture products were pioneered at the extensive laboratory facilities operated by the participating parties. During the development period it became apparent that very high levels of process and quality control were required to produce products which were fit for use in the construction industry. Comprehensive testing was also considered essential due to the highly variable nature of both the equipment used and the fact that products were made by hand in a relatively artisan manner.

The testing methods developed consisted primarily of those required to correctly set up the mix, introduce the required amount of chopped alkali resistant fibres, and to verify, whilst in a wet state, the actual fibre content. Hardened testing as part of quality control was restricted to flexural strength, density and water absorption. Additional proof tests were also introduced to determine volumetric movement and decline in ultimate flexural strength.

Reversible and irreversible movement in GRC is much higher than in typical concrete due to the very high cement content. Initially the recommended mix designs contained typically 75% cement although over time this has reduced to 50%. It is however still considerably higher than most other concrete mix designs and results in movement of between 1 and 2.5mm per linear metre. Given the size of some GRC panels this is critical to the design of fixing systems. Any system which restricts this movement will cause structural cracking of the GRC element.

Equally important was the decline in the ductility of the material. Extensive laboratory and natural exposure tests were conducted by Pilkington and BRE which showed that the modulus of rupture (ultimate flexural strength) would decline to the limit of proportionality (elastic strength) over a relatively short (10 year) period. Again, this information is critical to the design engineer.

The result of all this research and development was a material which, although offering the ability to manufacture thin and therefore lightweight cladding panels, required very strict controls during manufacture. Investment in getting to this point had of course been considerable and in any business, commercial considerations are always at the forefront of any leadership team. It was therefore necessary to recoup the considerable investment, and the method of choice to do this was by issuing manufacturing licences to those companies wishing to gain a foothold in this new technology.

Unfortunately, commercial considerations and quality excellence are not always compatible. The early licensees were generally either start-ups with no experience or established precast manufacturers with little knowledge of quality systems and testing. The system of issuing licences or franchises, it would appear, did not extend to effectively auditing and assessing companies' compliance. As a result there were many product failures and GRC gained a terrible reputation as more and more claddings and dressings were removed from relatively new buildings.

Between the 1980s and the beginning of the second decade of the 21st century there was very little activity, certainly in the traditionally conservative UK construction industry. In 2008 there was only a very small handful of manufacturers producing GRC and virtually no reference projects. Indeed, in London the only real remaining GRC clad building was what would later become a RIBA listed property, 30, Cannon St, London. This is probably the only example of the durability of correctly designed and manufactured GRC. Approaching half a century old, the GRC cladding shows no real sign of requiring replacing.

However, the second decade of the 21st century has seen an explosion in the use of GRC worldwide. The move towards more expressive architecture, as demonstrated by leading architects, such as Zaha Hadid, along with a new generation of architects and designers who have not heard of the earlier failures has propelled GRC into being a mainstream construction material. Lightweight and environmental friendliness are prerequisites of modern methods of construction. Add to this that GRC is a non-flammable material that can be manufactured in virtually any shape, size and colour, it has become the material of choice on many, if not most, major construction projects.

Unfortunately, history may well be repeating itself. Many GRC manufacturers, again, do not understand the importance of a correct and methodical approach to quality and testing. Cost cutting and a relaxed attitude to testing by non-accredited supply chain participants solely to present a compliant position is an unfortunate characteristic of the GRC industry. It is a sad reflection of a UK industry which may well be worth £100 million that there is currently only one UKAS accredited GRC testing facility operating across the UK market. Paradoxically, considering the complex nature of GRC, virtually all testing of traditional concrete is carried out by laboratories accredited by UKAS or, in other countries, similar ILAC MRA member bodies.

There are currently several projects in the UK, all completed within the last five years, where all the GRC is having to be removed and replaced; this trend again puts in jeopardy the future of a material which ultimately, when correctly designed and manufactured, is highly durable and long lasting

Ultra-High Quality GRC has been developed as a specification/process whereby significant levels of quality control and accredited testing verification are introduced in the realization process when considering GRC façade solutions. Such an approach can be adopted by any GRC manufacturer following prescribed methods of work, manufacturing procedures and testing processes as detailed in the design and manufacturing specification.

COMPLIANCE

GRC falls into the category of an advanced composite. As such it follows that the same level of accredited and externally verifiable processes and testing should be part of the design and manufacturing requirements.

The starting point is a compliant quality management system fully meeting the requirements of ISO 9001:2015[1] which is assessed and annually audited by a suitably accredited conformity assessment body who is deemed to meet the requirements of *ISO 17021:2015: Requirements for bodies providing audit and certification of management systems* [2]. Note that there are many organisations who claim to offer these services; however only those accredited by UKAS or other similar national bodies who are signatories to the International Accreditation Forum can be considered acceptable.

Daily, independent and impartial quality control checks are essential. Where quality is the responsibility of the production management there will always be a conflict of interest between maximizing production output and sales revenue, and achieving high levels of quality. For this reason, it must be clearly identified that random quality checks and supervision of the daily factory activities are undertaken by someone who can be proven to be impartial and independent of the manufacturing management.

Testing is currently the most important aspect of offering compliant products to the marketplace. However, in the GRC industry this is an area which is woefully inadequate. Unlike the rest of the concrete industry where external testing by accredited laboratories is considered the norm, the GRC industry relies on a manufacturer's own testing or that provided by the suppliers of fibre and polymer. This is neither independent nor impartial and possibly not competently carried out. A further issue is that in order to encourage manufacturers to carry out testing, the recognised trade body, the International Glass Fibre Reinforced Concrete Association (GRCA), has simplified the European Standard's testing methods. Whilst this has been successful in improving quality, the new generation of ultra-high quality GRC production requires an approach more consistent with the British and European standards as well as alignment with the American Precast/Prestressed Institute Manual for Quality Control (MNL 130)[3]. The latter is far more demanding than either the GRCA requirements or those published by CEN. In the USA most architects will not consider the use of any GRC from a manufacturer who is not PCI certified as meeting the MNL 130 requirements.

As part of the specification for Ultra High Quality GRC all testing must be carried out by accredited laboratories who have been assessed by a signatory to the International Laboratory Accreditation Cooperative (ILAC). Such laboratories or conformity assessment bodies will have been fully assessed to have structural and operational systems meeting the requirements of ISO/IEC 17025: 2017[4] which is the international standard for testing and calibration bodies. Such laboratories must hold a schedule of accreditation covering the test methods to be carried out. It is not acceptable to use a laboratory accredited to ISO/IEC 17025:2017[4] if they have not been assessed and certified to carry out the specific tests being undertaken.

ACCREDITED BODY TYPE TESTING

Prior to the commencement of any design work the manufacturer must provide the design engineer with the relevant and reliable properties of the material.

The most important of these is flexural strength. Unlike standard concrete, GRC relies on its flexural strength. Under the specification this must be calculated over a minimum of 50 tests in order to determine an accurate characteristic strength. In addition, testing is required at 1, 7 and 28 days - representing the de-moulding age, the shipping age and the typical long-term strength attainment age. This is very different from all other published standards and requirements where only 28-day strength is considered.

The reason for this enhanced programme is that GRC panels are generally subjected to their highest stresses whilst they are being de-moulded, finished, packed, transported and installed. It therefore would seem illogical to only consider testing at an age when most GRC panels are installed on the building. This is especially true if the design approach is to consider limit state design at a service limit lower than the ultimate.

Another critical set of testing is to determine the pull-out capacity of any embedded anchors. This is not required under the GRCA Specification nor indeed BS EN 1169 (5), however is an integral part of PCI MNL 130(3). Again 50 tests should be carried out using the specific anchor system to be used in the design. In the absence of any recognized standards GRC Synergies has developed LDM (Laboratory Developed Method) 1201 which forms part of the company's UKAS accreditation.

Dimensional movement testing is, in 95% of cases, ignored by the industry preferring to take a generalized figure of approximately 1.2 mm per linear metre. However, different formulations will shrink and expand at different rates, and so in the opinion of the author they cannot simply be estimated. For over 20 years there has been a European Standard for this test (BS EN 1170-8)(6) however this has been ignored as the equipment needed to carry out the test is very specialized, expensive and possibly not actually available in any laboratory. For this reason, GRC Synergies have introduced a modified version of the test which measures movement using different but equally accurate measuring equipment. All other aspects of the test, especially the conditioning of specimens remain the same.

The decline of ultimate strength is one of the most intriguing aspects for the GRC industry. Early long-term exposure tests indicated that the ultimate strength (MOR) declined to the yield strength (LOP). Developing a laboratory test to replicate ageing was one of the most challenging areas in the development of GRC. Initially this was simply immersing a GRC specimen in hot water over a period, which was then tested for flexural strength and compared to a specimen cut from the same test board which has not been subject to such ageing.

This test was, however, found to be unreliable, especially for polymer modified GRC. As a result, a cyclic weathering test was developed which became a European Standard in 1999. Unfortunately, the test equipment was, apparently, only available in one laboratory and involved substantial costs to the manufacturer. The consequence was that very little, if any, testing was carried out and the test was ignored by the

GRCA. Interestingly the PCI continued with a requirement for hot water ageing tests (ASTM 1560-03)[7].

Because of this the GRCA adopted a design approach of limit state design based on the lower LOP strength. This was supported by the view and the early (1970s) testing that the MOR strength would decline to the LOP strength over time. In effect the composite would lose all ductility. So, what really was the point in using fibres in the first place?

To answer this GRC Synergies Ltd have developed a modified version of BS EN 1170-8 which only deviates from the published standard in that the specimens are manually transferred from one environment to the other rather than be contained within one weathering chamber as specified. UKAS accredited Tests carried out in accordance with GRC Synergies Ltd Developed In House Method SOP 13[8]on various polymer modified mix designs show the equivalent of 10-20 years ageing only reduces ultimate strength by 15-20% and opens a range of engineering options to the designer.

The final proof testing requirement is that of fire classification. Most GRC formulations are non-combustible; however, the use of polymers and other additives or admixtures can affect if a GRC is A1 or A2 classification (BS EN 1305:2007+A1:2009)[9].

The whole purpose of all the above pre-start testing is to provide the design engineer with an accurate picture of how the specific mix that he/she is designing will behave. It is also important to realise that slight changes to mix designs, such as adding colouring pigment, can have an effect on the behaviour of the material with regards flexural strength, dimensional movement, ageing and fire performance.

VISUAL MOCK- UP

A visual mock-up is an important aspect of any successful GRC Project. Many architects compare GRC to other composites and assume that consistency of colour and texture will be different to other forms of precast concrete

This is, however, where GRC is most similar to traditional precast and cast stone. The architectural finish of GRC products is generally created using "face coats". These, described later in this paper, are effectively mix designs containing naturally occurring decorative aggregates, colouring pigments and the like. Although not part of the structural GRC for design engineering purposes they are what provides the finished project with its visual appearance.

For this reason, we strongly suggest a visual mock-up is produced which will reflect what can actually be attained in regards to colour and texture variation. It is also important that the mock-up contains examples of repairs as these are unavoidable in the manufacture and installation of GRC cladding panels.

DESIGN ENGINEERING

Once the material properties of the GRC are determined and the visual appearance accepted by all stakeholders, the design process begins.

GRC is a unique cement-based material with significantly different characteristics to other forms of precast concrete. It is important that anyone designing GRC cladding has a full understanding of not only the material properties of the composite but the manufacturing process. This can only be achieved by experience and for that reason ultra high quality GRC can only be designed by qualified civil or structural engineers who will have had several years' experience working with the material.

The design approach and applicable factors of safety should always be determined by the engineer from a statistical analysis of the material characteristic properties provided by the manufacturer and obtained from accredited and therefore reliable test data.

Due to the ve ry high cement content with its associated alkalinity, only stainless-steel embedded fixings should be used. If the stiffening of the GRC is to be provided by a factory attached stud frame, then all gravity and flex anchors should be stainless steel irrespective of the choice of the actual frame (galvanized or aluminium).

Critically, the shrinkage and expansion of the element determined from valid testing must be considered and allowed for to ensure the GRC has total and unrestricted movement in its connection to the structure or any secondary steelwork, etc.

PLANT FACILITIES

Ultra high quality GRC can only be manufactured in suitable plant facilities which have been specifically constructed or adapted to manufacture GRC products using the spray process technique.

As controlling consistency of the mix is essential there must be a strict control of the water/cement ratio by ensuring all raw materials are stored internally with no moisture ingress of any kind.

The facility must always be capable of maintaining a temperature of at least 10°C during both the casting and curing cycles. This is necessary to ensure correct film formation of the polymer admixture contained within ultra high quality GRC. In countries where temperatures can exceed 35°C we strongly recommend the use of water which is maintained at lower temperatures through refrigeration measures.

As with any polymer modified GRC the finished goods must be protected from external environmental influences such as wind and rain for at least 2 days. There must therefore be sufficient space to store at least that amount of production before transferring it to outside areas

Although external and accredited testing of dried GRC material should be carried out, testing of the GRC in its wet state should be carried out at the factory and a suitable testing area provided for such use. This is to carry out fibre content verification in accordance with BS EN 1170-2 [10]. Testing to BS EN 1170-1 [11] and BS EN 1170-3 [12] is carried out in the batching area and spray area respectively. Suitably compliant weighing equipment should be provided at these locations.

MOULDS

As with any architectural concrete, finished products are only as good as the mould they were produced from. GRC is no different to any form of concrete in this respect; however, specifiers and users have a tendency to believe that because GRC is a modern composite the expectation of tighter tolerances, etc. is always prevalent.

Full clarity must be provided at the outset as to what can and cannot be achieved in respect of dimensional accuracy, always giving consideration to the actual physical movement of the GRC as described earlier. This is another reason why accurate measurement of dimensional movement by testing to BS EN 1170-7[13] (modified) is an essential part of managing user expectation.

RAW MATERIALS

All raw materials used for the mix design must meet the appropriate British, European or National standard. There is, however no such standard for the most suitable silica sand.

The specification for ultra high quality GRC, therefore, contains a prescriptive list of compliance requirements (Table1) which must be carried out by accredited laboratories on all deliveries. These include verifying moisture content to ensure consistent water/cement ratios (BS EN 1097-5)[14], checking for impurities using the loss on ignition test developed by the Silica and Moulding Sands Association (SAMSA) and finally ensuring consistency of grading by sieve testing to BS EN 993-1[15]. None of these reception tests are required by either the GRCA Specification[16] or EN 1169 [5]. The PCI MNL 130[3] does, however, require similar reception controls.

In respect of the alkali resistant fibres which reinforce the GRC, strict controls must be observed including ensuring full compliance certification for each consignment and recording specific LOT allocation numbers on the day's production records.

It is important that samples of each material are taken and retained in order to identify any contributing factors to non-conformities.

Under the specification for ultra high quality GRC no change of raw material supplier is permitted during any given project. This is because any change of mix ingredients could have an effect on the material properties which have been provided to the design engineer. If for any reason supplies become unavailable or restricted further type testing must be carried out to ensure that no significant changes to material properties are noted as a result of such mix design amendments.

FACE COAT MIXES

The architectural finish of any GRC is not provided by the actual GRC but by a face coat which is applied to the mould surface before spraying of the GRC begins. This may contain decorative aggregates or other such deviations from the actual GRC mix. It should not be confused with a mist coat which is sometimes used in GRC production. Mist coats use exactly the same mix design as the GRC but are applied without the fibre reinforcing. They are generally less than 1 mm thick, where a face coat will typically be 1 mm thicker than the largest aggregate used, generally in the range 3-5 mm.

The technical properties of face coats and their interaction with the GRC are often ignored in GRC production. Such omissions can cause visual defects or even contribute to a structural failure of the GRC. There is no requirement in either the GRCA Specification(16) or BS EN 1169(5) to consider face coats.

Ultra high quality GRC requires a rigid and methodical approach to designing face coats. All aggregates are to be tested for moisture content in accordance with BS EN 1097-5(14). This is to ensure that there is no difference between the face mix and the GRC in respect of water/cement ratio thus minimizing the potential effects of differential movement between the two layers. Where such movement is not considered, surface crazing or cracking of the architectural surface can occur which can ruin the finished appearance of the GRC. Extreme movement differential can induce bowing in the GRC which can overstress the matrix, causing structural failure.

Consistency of mixes should be maintained by ensuring all decorative aggregates are sieve tested in accordance with BS EN 993-1(15). It is important that the amount of fines passing a 75 micron sieve is limited to less than 1%. This is because where higher quantities of very fine aggregate are used within face mixes they can dominate and influence colour, thereby contributing to colour variation.

As the facing mix contains no reinforcement its durability should be confirmed by carrying out standard compression testing of cubes manufactured purely from the facing mix in accordance with BS EN 12390-3(17).

Water absorption should be tested in accordance with BS EN 1170-6(18) and should be similar to that of the structural GRC. This is again to limit the potential for differential movement.

Before the start of any project and after all development tests above have been completed it is necessary to produce two large sample panels as detailed in accordance with GRC Synergies Laboratory Developed Method 1203[(19)]. This is based on the PCI MNL-130-09 Division 5[(3)]. One of the panels is produced with the applied facing coat whilst one is produced without. The panels are made consecutively and are left overnight to cure. They are then demoulded in a landscape orientation and placed in the same orientation in a holding rack. After 28 days both are measured for any bowing caused by shrinkage or expansion. A compatible face/GRC mix should display similar bowing.

By carrying out all the above, the manufacturer can have confidence in the in-service behaviour of the manufactured panel, which is one of the most important aspects of GRC manufacture.

GRC MIXES

Whilst the facing coat is important primarily for aesthetics it is the actual GRC mix that performs structurally and is the only one considered within the design engineering process.

Because of the high cement content it is important that only small capacity, specialist GRC mixers are used. These will have a maximum capacity of 125 kg, which, using an industry standard spray delivery setting, will take a well-run team approximately 10-12 minutes to fully use. The mixer will have a digital display showing current usage. This allows an experienced mixer operative to confirm a consistent mix viscosity.

All weighing of raw materials must be carried out using equipment accurate to 1% of the required mix quantity. The requirement under the GRCA Specification is 2% and EN 1169[(5)] 2% or 3% dependent on type of ingredient. The equipment must be calibrated annually by an accredited conformity assessment body and monthly by the manufacturer using certified weights.

Consistency of the mix is essential in the production of ultra high quality GRC and to achieve this the slump test, which is virtually identical in both BS EN 1170-1[(11)] and GRCA Methods of Testing 5, must be carried out on every mix. Currently both BS EN 1169[(5)] and the GRCA Specification[(16)] only require this test to be carried out once per day.

PRE-START CALIBRATION

The calibration of the spray equipment is an essential aspect of the spray production process. The slurry is pumped to a spray gun whilst continuous fibre roving is pulled through the gun and chopped generally into 25 or 32 mm lengths. The combined fibre and slurry is then sprayed against an open mould in a similar manner to that used, for example, to spray automobiles, etc.

Given the mix formulations rely on a certain percentage of fibre it is necessary to carry out the calibration whenever the equipment has been out of action for even a short time. Many factors can influence the delivery of both the slurry and the fibres and so this "test" is absolutely essential. Methods are detailed in BS EN 1169-3[20] and GRCA Method of Testing 1[21].

Under the UHQGRC Specification this "test" or set-up is to be carried out under the supervision of a quality control person who is completely independent of the manufacturing management. This is to ensure that the set-up is not rushed or in any way compromised purely to increase production outputs.

SAMPLE BOARDS

The production of sample boards for testing is the most critical aspect of any GRC production. These are used to both determine the fibre content (BS EN 1170-2 [10]/GRCA Methods of Testing 1[21]) and the flexural strength (BS EN 1170-5 [22]/GRCA Methods of Testing 3[23]).

The GRCA Specification[16] and BS EN 1169[5]require a daily fibre content test and a twice weekly flexural test. The GRCA does, however, require a flexural test board to be made daily in order to carry out further testing in the event of non-conformities.

The Specification for ultra high quality GRC differs significantly in this regard in so far as three flexural test boards are produced. One is for testing at 1 day which is the point at which the manufactured GRC product is likely to be subjected to the highest stresses in its service life. The demoulding operation can be very aggressive given that most GRC cladding panels will have a minimum surface area of 3 m² with some being as much as 20 m². Panels are seldom flat and are often three dimensional which can cause opposing stresses as they are released from the mould. It is important, therefore, that the design engineer considers what these forces are likely to impart to the GRC and to know the actual flexural strength at that point.

Equally, it is important to know the strength at the age when the product is likely to be packed, delivered and possibly installed. With a modern polymer modified GRC this is likely to be 7 days and therefore testing at this age is also important.

The final test board is produced for testing at the industry standard of 28 days. This is the requirement of the GRCA Specification[16], BS EN 1169[5] and PCI MNL-130-09[3].

Tests carried out by GRC Synergies indicate that ultra high quality GRC has reached 75-80% of its development strength after 1 day and approximately 95% after 7 days.

The production of the test boards, especially those produced for flexural testing, is another important consideration. The test is the equivalent of the cube test carried out to BS EN 12390-3[17]. However, unlike the cube test where the viscous mix is simply poured into the mould the GRC sample board is handmade by sprayed layers of GRC as in the full-scale production. There is also no standard for the preparation of these sample boards as there is with the preparation of cubes under BS EN 12390-2[(24)].

Observations by the author in the capacity of either a consultant or a compliance auditor for the GRCA is that in nearly all manufacturing plants the sample boards are manufactured by the same operative, at the same time and with far more care than the actual products. This can of course produce highly misleading results.

This practice is not permitted under the Specification for UHQGRC. The board must be produced on a rotational basis by all those involved in the spraying and compacting of the finished products. It must also be observed by a party independent of the manufacturing plant management to ensure that the production of the test board fully replicates that used in the production of the product.

PRODUCTION OPERATIONS

The spray process which is used to manufacture UHQGRC is a very complex methodology which requires experienced and skilled operatives. It is not a manufacturing method that should be undertaken by manufacturers new to the industry. Anyone contemplating entering the market should be prepared and allow for a relatively long period of non-productive working. Although the capital investment is low the actual investment to be allowed for training etc. is considerable.

UHQGRC is only manufactured by very skilled operatives who have been fully trained in the manufacturing process. The production methodology does not differ in any way from the systems and techniques that have been developed over many years as best practice.

This is not therefore covered in any depth within this paper.

DEMOULDING

Demoulding GRC products is very similar to the processes employed within the precast concrete sector. The methods are to be considered by the design engineer to ensure that the finished products are not overstressed beyond their 1 day flexural capacities.

Suitable spreader beams, etc. must always be used to prevent localized stress concentrations.

The use of GRC as rainscreen cladding is becoming more and more popular. With the system the GRC is made as either flat panels or with return legs to form corners or columns. Such panels are manufactured with cast-in or drilled threaded sockets to accept brackets which in turn hook onto vertical rails. The panels rely on their attachment to the structure via the rail system to provide rigidity and, until fitted on site, can easily be stressed beyond their elastic limit causing permanent deflection or, worse, structural cracking.

These panels must not be allowed to be handled in a flat horizontal plane which causes self-deflection. As such they must be demoulded in a landscape orientation and maintained in this position during finishing and delivery. It is normal to deliver such panels in metal stillages.

Returns must be braced, again to prevent imposed stresses through demoulding, handling and delivery causing the units to crack.

FINISHING & APPLIED SEALANTS

GRC elements are finished in the same manner as any other architectural concrete, by acid wash, grit blasting, retarders, etc. It is not recommended to have a smooth as-cast finish due to the high cement content of any mist coats. This can cause surface shrinkage which, although not affecting the unit's integrity, can create crazing, which looks unsightly.

We would always recommend a surface sealant be applied to the finished GRC before it is exposed to the outside environment. Such applications benefit the GRC product in several ways, including minimizing efflorescence and preventing water/dirt ingress into any surface crazing as described above.

Another very important advantage is minimizing the effect that water absorption can have in reducing the reinforcing effect of the alkali resistant fibres. Research over many years(25) has shown that exposure to rainwater causes a decline in the ultimate flexural strength. This is widely considered to reduce to the yield strength over years; however, most such testing was done in the 1970s/1980s and certainly ultra high quality GRC does not display any such aggressive decline. Testing to BS EN 1170-8 (6)(modified) shows a decline over a period equal to 10-15 years as being approximately 15% (26). The tests were carried out without any applied sealant which should assist in reducing the decline even further.

Note – in an open rainscreen GRC system it is beneficial to treat the rear of the cladding panel to prevent rainwater runoff from the rear causing damage to adjacent glazing and powder coated aluminium.

DIMENSIONAL TOLERANCES

There are no specific tolerance standards for GRC products in any of the published British, European or GRCA specifications. This is because these documents relate solely to quality assurance/control processes and associated compliances and not manufactured products.

Many specifiers and manufacturers will thus utilize the tolerances detailed within BS 8297: 2017 [27](Design, manufacture and installation of precast concrete cladding) or BS EN 14992: 2007+A1:2012[28] (Precast concrete products wall elements). Neither of these is fully suitable for stipulating dimensional tolerances as critical information such as facing coat thickness deviations, thickness of structural GRC deviations, angles of moulded returns, and many other important factors are not considered.

The specification for ultra high quality GRC details fully what can be reasonably achieved and should be considered when specifying or procuring GRC cladding products

PACKING AND TRANSPORTATION

The packing of GRC cladding elements is very similar to that of architectural precast concrete cladding. However special attention must be given to the logistics relating to flat, L shaped, U shaped rainscreen GRC elements as detailed above.

FACTORY QUALITY CONTROL TESTING

The wash-out test is carried out in accordance with BS EN 1170-2 [10], of which the sample preparation is detailed in the section entitled "Sample Board Preparation". The test is an essential part of GRC production to verify that the correct quantity of fibres is contained within the finished composite.

As this test must be carried out on the GRC whilst it is still in the wet state it must be at the factory in a purpose-provided laboratory equipped with a suitably compliant drying oven and accurate scale or balance. This and LDM 1203 are the only tests not carried out by accredited laboratories under the specification.

The test is carried out daily with the results compiled to provide characteristic values. These can then be used in conjunction with the flexural bending strength tests to optimize mix designs but more importantly to assist in producing manufactured products with consistent material properties. The results of the test should be also compared to that of the pre-start calibration described earlier. It would be expected to have some fibre loss through overspray etc. and regular data analysis helps manufacturers again ensure consistency.

LABORATORY QUALITY CONTROL TESTING

There are many issues surrounding testing within the global and especially the British/European GRC industry. GRC is a hand-made product which requires high levels of skill, knowledge and experience. GRC cladding is increasingly used on very large construction projects and is probably the fastest growing sector in the construction supply chain.

Given its history of early in-service failures it is therefore surprising that very low levels of accredited testing are carried out, certainly in the UK and more widely across Europe. In an effort to encourage manufacturers to carry out testing, the complex tests required under both BS/EN and ASTM for the primary material property (flexural strength) have been largely replaced by the GRCA Method of Testing Part 3(23). This requires only 4 specimens from a test board with no predetermined stipulation of the location of such samples within the board. There is no requirement for controlled conditioning which of course can cause inconsistent test data. Both BS EN 1170-5(22) and ASTM C947(29) address these issues within the drafting. The GRCA test is the most widely used in the UK and its relative simplicity does encourage more manufacturers to at least carry out some testing.

The QC/QA testing within the general industry is nearly all done by either the manufacturer or the fibre supplier. Neither can be considered impartial or independent. It is also very easy to provide incorrect test results by simply entering a different specimen dimension than that measured. There is of course no traceability with such testing. For example, entering a thickness 10% less than that measured either by incorrect measuring, inaccurate measuring equipment or malicious data input to the software, can increase estimated flexural strength by up to 20%.

It is a sad reflection on the GRC industry that currently there is only one accredited test facility in the UK to carry out either GRCA Method of Testing Part 3(23) or BS EN 1170-5(22). From our research there are no accredited facilities for the GRCA test anywhere in Europe and less than 5 accredited to test to BS EN 1170-5(22). Virtually all the large GRC projects completed in the last 5 years, including UK Government infrastructure public funded works, have not had any accredited testing carried out.

Compare that to the concrete industry as a wider body where virtually all cube testing is carried out using suitably accredited test facilities.

Under the specification for ultra high quality GRC, all testing, other than wet testing, has to be carried out by a laboratory accredited to the requirements of ISO/IEC 17025:2017(2) with a schedule of accreditation appropriate to the tests being undertaken.

Anchor pull-out testing is also worthy of mention within this paper. Such testing is not a requirement of any other published UK or European specification or standard and yet it is so very important in the manufacture of GRC cladding elements. It is this anchor which generally provides the fixing point to the structure or secondary steelwork. Any failure of an anchor will transfer increased stresses to adjacent fixings and, indeed, finite element analysis shows that these anchors are often sited where the highest stress concentration occur.

Results of tests carried out on anchors used in normal precast concrete cannot be considered for GRC cladding. Whilst most precast is made using highly viscous concrete, spray process GRC is not. This means that rather than simply flowing around any embedded anchors the composite must be hand packed around the fixing. The use of longer fibres within the matrix makes this not only quite difficult but also time consuming within the production operations. As part of the specification for ultra high quality GRC, weekly anchor pull-out testing should therefore be carried out as part of the QA process.

It is critical that all test results are used in a statistical analysis to determine any given material property characteristic. The values must at all times meet or exceed those used within the design engineering.

LABORATORY VALIDATION TESTING

As has been described, all testing within the GRC industry is of purpose-made test boards. This is understandable given the high value of some manufactured products. However, it is important to conduct some testing on finished goods to ensure that at least the flexural strength of products is the same, or at least within an allowable and considered safety factor used in the engineering design (ɣb factor).

This is not normal practice and is not required under either the GRCA specification or BS EN 1169(5).

Within the specification any units rejected for purely aesthetic reasons are to be put aside for sample extraction and testing to BS EN 1170-5(22). This must represent a minimum of 2.5% of the manufactured population. In the event that this number is not reached through visual rejects, then elements which would otherwise be supplied to the customer must be tested. Such units are to be selected by a party independent from the manufacturing team.

RECORDS, DOCUMENTS, NON-CONFORMITIES AND CORRECTIVE ACTIONS

As the above forms part of the mandatory ISO 9001:2015(1) Quality Management System required under the specification, full traceability is provided.

Specifically, there is a requirement for all records to be retained for 10 years and critically tested specimens be retained for two years. The latter allows for verification of the critical dimensional inputs used during the testing process.

SUMMARY

The Specification for ultra high quality GRC has been developed by GRC Synergies Ltd to ensure that all recognized good practices developed by various bodies over the last 40 years are incorporated in the design, manufacture and testing of GRC products.

Other than the modified EN 1170-7 (12) and EN 1170-8 (6) tests and the Laboratory Developed Method for testing embedded anchors, all other tests and procedures are part of either the GRCA Specification, BS EN 15191(30) or PCI MNL-130(3). The latter being probably, prior to the introduction of the UHQGRC on by most American architects.

Currently UHQGRC is only produced by one manufacturer, Syntec GRC which is part of the PBS Synergies Group, however we have made the publication available in the public domain(31) in order that others, committed as we are to lifting quality standards across the industry, will follow our lead and ultimately benefit the entire construction industry.

REFERENCES

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2 BS EN ISO/IEC 17021-1:2015 – TC Tracked Changes. Conformity assessment. Requirements for bodies providing audit and certification of management systems. Requirement

3 PCI MNL-130-09: 2009 Manual for quality control for plants and production of Glass Fibre Reinforced Concrete Products

4 ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories

5 BS EN 1169:1999 Precast concrete products. General rules for factory production control of glass-fibre reinforced cement, BSI, London

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7 ASTM 1560-3 ASTM C1560 - 03(2016) Standard Test Method for Hot Water Accelerated Aging of Glass-Fiber Reinforced Cement-Based Composites, ASTM International, West Conshohocken, PA, 20168

8 Developed in House Method SOP 13 based on EN 1170-8. GRC synergies Ltd, Sheffield UK

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10 BS EN 1170-2:1998 Precast concrete products. Test method for glass-fibre reinforced cement. Measuring the fibre content in fresh GRC, 'Wash out test', BSI, London

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13 BS EN 1170-7:1998 Precast concrete products. Test method for glass-fibre reinforced cement. Measurement of extremes of dimensional variations due to moisture content, BSI, London

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28 BS EN 14992:2007+A1:2012 Precast concrete products. Wall elements

29 ASTM C947-03 (2016), Standard Test Method for Flexural Properties of Thin-Section Glass-Fiber-Reinforced Concrete (Using Simple Beam With Third-Point Loading), ASTM International, West Conshohocken, PA, 2016

30 BS EN 15191:2009 Precast concrete products. Classification of glass fibre reinforced concrete performance, BSI, London

31 Reference to be added Specification for the design and manufacture of Ultra High Quality Glassfibre Reinforced Concrete cladding elements. Rev 13 2020. GRC Synergies Ltd Sheffield UK

Table 1 Test methods, frequency and testing body

Test	Method	Frequency	Testing Body
Aggregates and sand loss on ignition	EN 1097-5:2008	Each consignment	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Sieve analysis sands and aggregates	EN 993-1: 2012	Each consignment	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Compressive Strength – Facing Mixes	EN 12390-3: 2019	Each new facing mix - proof test	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Differential movement	GRC Synergies LDM 1203	Each new facing mix – proof test	Factory
Equipment calibration	EN 1170-3: 1998 (simplified permitted)	Once per day each spray machine and	Factory

		after any work interruptions or breakdowns	
Slump test	EN 1170-1: 1998	Every mix	Factory
Wash out test	EN 1170-2:1998	Once per day each spray machine	Factory
Flexural test – 1 day old	EN 1170-5:1998	Once per day each spray machine	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Flexural test – 7 days old	EN 1170-5:1998	Once per day each spray machine	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Flexural test – 28 days old	EN 1170-5:1998	Once per day each spray machine	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Density and water absorption	EN 1170-6:1998	Once per week each spray machine	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Anchor pull out	GRC Synergies LDM 1201	Once per week each spray machine	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Volumetric movement	GRC Synergies DIHM SOP 12 based on EN 1170-7: 1998	Every new facing/GRC combination and thereafter annually	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Ageing	GRC Synergies DIHM SOP 13 based on EN 1170-8: 2008	Every new GRC mix and thereafter annually	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Fire Classification	EN 1305:2007+A1:2009	Every new GRC mix and thereafter 5 years	Accredited ISO/IEC 17025:2017 laboratory (CAB)
Product Testing	EN 1170-5:1998	1 element per 100 produced	Accredited ISO/IEC 17025:2017 laboratory (CAB)