GRC2011
Istanbul

27 35 year review of the GRC Technology, Equipment and Markets

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Abstract

This paper presents a summary of the research behind the development and successful global use of GRC (GFRC). A review of key research and technology advancements is presented.

Key Words: Glass Fiber Reinforced Concrete (GFRC, GRC), AR Glass Fiber, alkali resistant glass fiber, E glass fiber, polymer modified GFRC (GRC, PGRC), Spray chop, Premix, Type I Portland cement, CSA Cements (calcium sulpho aluminate), pozzolanic materials

Why do this paper?

As I travel the globe talking to old and new GRC producers to promote the use of quality materials to produce GRC products to the international standards of PCI MNL-130-09 Second Edition “Manual for Quality Control for Plants and Production of Glass Fiber Reinforced Concrete Products” and GRCA’s “Specification for the manufacture, curing and testing of GRC Products” Third Edition, March 2010, I am confronted with and realize there is a tremendous amount of mis-information, mis-reading, mis-interpretation and mis-understanding of the original research done by Pilkington, NEG, Owens Corning, Forton BV and other research institutions. This is the data that is the basis of this industry and which makes the architects, engineers, owners and insurance companies feel comfortable using the product.

The goal of this paper is to bring all the key research and test information together in one document, in a time line sequence and with a concise review of this technology so that quality GRC can be produced on a global basis. This will allow these products to be used on buildings without concerns regarding the durability of the GRC as it ages in the various lifecycle environments it experiences around the world.

I believe this to be extremely important in light of all the “low cost”, “same as”, “my friend says it is the same as” products that are flooding the market and being used in GRC in the various geographical markets without the third party, peer review testing required to insure they comply with the specifications referenced above.

I want to produce a single reference that covers all the key industry research so that the producer, architect and engineer (consultant) has a single resource, with correct information and that does not allow any “wiggle room” as to what the proper material specifications and types of materials are. It will also show the ultimate consumers, the architect and building owner, what they can reasonably expect for the life cycle durability of their building facade or products made from GRC using proper materials.

History of glass fiber reinforcement

In the years preceding WW II, the glass maker Owens-Illinois, together with Corning Glass, developed a process to melt glass and pull a very thin continuous strand of glass. This fiber was used to reinforce polyester resin that was fabricated into bomber radomes because the radar beams could pass through and return without distortion. This formulation became known as "E glass" for these dielectric properties. With minor adjustments, this formula is still in use today as the circuit board in your computer or mobile phone, among other applications.

With this glass fiber, the composite industry was born. The concept of composites was to reinforce essentially brittle matrices with a high tensile glass fiber in order to make them thinner and lighter while still maintaining the basic properties of the matrix.

Owens Corning Fiberglas Corp. was formed to produce and commercialize this technology. After the war there was a push to find other matrices to reinforce with this fiber in order to create more applications. Portland cement, a material used in great amounts around the world, was an obvious candidate and research was started to determine the feasibilities. Research conducted in Russia by Biryukovich (father and son) from 1950 to 1965, showed that the alkali in an ordinary Portland cement (OPC) matrix etched and corroded the surface of the E glass fiber strand causing it to lose its tensile strength with a very short exposure period.

In Figure 1, the image on the left shows the result of alkali attack on borosilicate glass (E glass) fibers after a few weeks in OPC in a 50°C, hot water accelerated aging test. You can clearly see the surface of the fibers has been etched and corroded by the alkalis in the OPC matrix.

With these problems well documented, the British Research Establishment (BRE) began research to develop a glass formulation that was more alkali resistant in an OPC matrix than the original borosilicate composition E glass. The Strand in Cement (SIC) test was developed in order to categorize the properties of these fibers after aging in alkali concentrations. The SIC test is defined as embedding a glass filament in a cube of OPC and then submerging the cube in various alkali solutions for a period of time. Then the tensile strength of the aged strand was tested. The tests determined that a glass formula containing a **minimum of 16% zirconia oxide** had superior resistance to the alkalis in the OPC matrix when using the SIC test as the determining factor. Patents on this composition were taken out in 1967 by BRE claiming 16% zircon oxide to be the minimum amount that gave the resistance. The Pilkington Glass Co. soon joined in this program in order to produce and commercialize the formula. Pilkington brought the composition to the market under the Cem-FIL® name in 1970 and patented additional compositions and manufacturing processes. Pilkington chose to manufacture the Cem-FIL® fiber at 16.7% zirconia oxide to insure the alkali resistance indicated by the SIC testing.

The image on the right side of Figure 1 shows that the Cem-FIL® fiber has not suffered any degradation after several years in the OPC matrix.

In 1971 the first commercial products reinforced with Cem-FIL® AR glass fiber were produced. Pilkington licensed the right to produce the AR fiber composition in the USA to Owens Corning Fiberglas in 1975. At the same time, to jump start the market in the USA, they put a plant in Nashville, TN to manufacture architectural panels and other GRC products. In 1980 the Nippon Electric Glass Co. (NEG) began producing an AR glass fiber formula containing 19.5% zirconia oxide and selling their ARG reinforcement products around the world.

Production techniques and product development

While the BRE was doing research on the composition of the fiber they were also doing development work on possible production methodologies that could turn this new material into finished products with viable market applications. They worked on manufacturing techniques such as hand spray-up, adapting the slurry nozzle and glass chopper from the FRP market, premix, vibration casting, where the pre-chopped fibers are already mixed in the slurry, and spray dewatering machines which were for mass produced sheet products so they could be handled in line and quickly for stacking. These production techniques lead to the development of various equipment options…

Figure 2 shows the Face Coat Gun (90 degrees) that sprays the Face Coat into complex molds so that all the detail of the mold is covered evenly with the slurry. This is very important so that thick slurry build up does not occur in corners and mold surface transitions. If it does build up on the mold surface it is very possible that shrinkage cracks and crazing will occur. Other configurations of a Face Coat Gun are available for spraying larger molds.

The Concentric Spray Gun is shown in Figure 3. This gun simultaneously chops the AR glass fibers into the GRC slurry stream as it exits the nozzle to insure good wet out of the glass fiber. It also insures the slurry to fiber ratio is proper regardless of which direction the operator is spraying and distance the gun is from the mold surface. This became extremely important when panels got bigger following the steel stud frame system becoming the industry norm.

The mixing function is extremely important to achieving high quality GRC. Figure 4 shows the High Shear Mixer for slurries and premix that is used. The blade used on this mixer insures good dispersion of materials to make the slurry quickly and it is designed not to harm the AR glass fibers when mixing a premix.

To produce large GRC architectural panels a rotor/stator pump is used in combination with the concentric gun. Figure 5 shows a Rotor/Stator Pump in a production environment.

Figure 6 shows an Industrial plant configuration for standard products produced in high volumes. In many examples this was a spray gun mounted on a reciprocating arm while the peices on a conveyor passed under it.

As the glass fiber suppliers continued to make improvements to the binder chemistry and the fiberization processes in the plant, the equipment suppliers engineered new mixers, pumps and spray guns to optimize these production techniques. Most noteworthy were the ability to spray a 3% chopped strand premix in the mid-90's and continuous mixers to give consistant, high volume output mixes. This output coupled with the fast setting mixes discussed later now give this industry a viable alternative to compete with polyester resin for certain products.

The special nozzle designed to spray premix is shown in Figure 7. Premix containing 3% loading must be sprayed with a specially designed peristaltic pump, an example of which is shown in Figure 8. This unit is designed for both Spray Chop (shown) or Sprayed Premix, when using the Premix Spray Gun shown in Figure 7.

As a general rule, panels 100 sq. ft. ($10m^2$) or larger are produced using the rotor/stator pump and concentric spray gun. Panels 100 sq. ft. ($10m^2$) or less can be produced using the peristaltic pump and sprayed premix as long as the reduced flexural properties of premix are accounted for in composite thickness and design.

Figures 9 and 10 show a continuous mixer processing a GRC premix formulated with a fast setting cement, directly into molds on a roller conveyor system. These are panels that will be part of a permanet formwork system that will replicate limestone. This formula had a 2 hour demolding time.

Recently, continuous mixers have been developed to process preblends of fast setting cements (as short as 1 hour demolding) containing AR chopped strands while maintaining the color control required for the architectural market.

The mix design for these first research/production equipment tests was Type I Portland cement, water and 5% by weight of Cem-FIL® AR fiber sprayed into a mold to make a 12mm GRC composite. It was quickly determined this mix design had too much shrinkage when it cured. Mix formulas were changed to 3 cement and 1 sand (3:1) and then to 2 cement and 1 sand (2:1) in order to reduce shrinkage during the curing process. The concern about changing the cement to sand ratio was a reduction in physical properties so each change was thoroughly tested for performance before being given to the market.

Because these composites were so thin (10 to 12mm) there was a major concern about evaporation and having the available water for hydration in the matrix. The basic premise to design and use GRC was to have the highest matrix strength possible. It was determined that a 7 day wet cure at 100% RH was mandatory.

During the mid 1980's, the mix design changed to 100 parts Type I Portland and 100 parts 30 mesh silica sand (1:1) to further reduce shrinkage and lower the cost per square foot without a major reduction in physical properties. The 1:1 mix design, or something very close to it, is the standard mix design today.

Quality Control and Accelerated aging tests to predict durability

Since the goal of GRC was to fabricate thin, lightweight Portland cement based products used in non-load bearing applications, a full understanding of the physical properties, such as tensile, flexural and inter-laminar shear, of the GRC composite over time became very important in addition to the typical 28 day properties associated with concrete products. Since GRC products were not load bearing, compressive strength was not a controlling factor in design. It was, however, tested for informational purposes.

Ideally, a research and quality control program would have been based on the tensile properties of the composite, but performing a tensile test on GRC was difficult and not very feasible for a plant Quality Assurance program. So a flexural test protocol and ultimately specifications ASTM C-947 and EN 1170 Part 5, were developed based on Roark's stress-strain formulas. A flexural test was easier for plants to perform, especially as more focus was placed on determining Limit of Proportionality (LOP) to comply with design requirements.

Figure 11shows a representation of the typical chart recording the load deflection curve in the above referenced flexural test.

The matrix of GRC is essentially brittle without glass fiber reinforcement. It is considered an unreinforced mortar. Any test procedure used for design purposes needed to first define the matrix strength (LOP) and then quantify the contribution of the glass fibers (MOR). The testing program giving these flexural properties was critical to determine basic properties of the composite so that engineers could use these values in their design equations. First, and of utmost importance was to determine the LOP, under which is the region where the GRC composite can absorb the applied load without cracking. When the applied load on the composite reaches and exceeds the LOP, the matrix cracks. So for safety, the design of GRC products includes a safety factor applied to tested values to keep performance loads below the LOP.

By designing with a value under the LOP, or first crack strength, the importance of how thorough and complete the matrix is cured becomes very important. To insure the matrix was fully cured and the matrix strength was as high as it could possibly be the researchers and fiber suppliers required that GRC products be cured at 100% Relative Humidity (RH) for 7 days.

In testing after the LOP has been exceeded, the applied load continues and is transferred to the AR glass fibers in the matrix. The high tensile strength AR glass fibers continue to carry the load by bridging the crack and pulling out from the matrix until they no longer can carry the load. This is called the Modulus of Rupture (MOR).

The Limit of Proportionality (LOP) and Modulus of Rupture (MOR) have subsequently been re-named Flexural Yield (FY) and Flexural Ultimate (FU), respectively.

The distance under the FY and FU on the chart is calculated to be the "strain to failure", or the degree of ductility of the composite when loaded to failure. GRC at 28 day shows a high strain to failure, or ductility, because the fibers are free to bridge the crack and to pull out from the matrix.

This data became the basis of the design equation for GRC panels. The assumption being that the Aged Flexural Ultimate (AFU) never drops below the Aged Flexural Yield (AFY). This premise, along with a safety factor insures that designs loads stay under the cracking strength of the matrix. This concept is seen in Figure 12.

Figure 13 shows the young properties of 3 mixes and the typical allowable loads to use when designing a product or application.

Since GRC was a new, cement based product, the potential users, engineers, architects and building owners wanted to know what the long term properties of this product were and if there was any change from the 28 day values. If there was a change over time, what influence did environmental conditions have? The traditional method to accelerate the ageing behavior of cement based materials was to soak them in hot water (50 or 60ºC) for set periods of time and run comparable tests against the 28 days tests.

The FY values of GRC, an indication of matrix strength, increase in these tests due to the more thorough cure achieved by soaking in hot water.

The tested FU values of GRC coupons after being put through the accelerated ageing programs dropped significantly from the 28 day values, as again shown in Figure 12. This was a concern and not really predicted based on the BRE research because it implied that the alkali resistance of the glass fiber was not the controlling factor to maintain durability in the context of flexural properties.

However, once analyzed and understood, this information prompted additional corporate and academic research programs. Remember, one of the goals at this time was to find a replacement for asbestos fiber in cement asbestos products. The research question became, "if alkali resistant glass was used and the flexural properties still dropped, what else is going on in the composite?"

Several approaches were undertaken to understand what was causing this change and what could be done to deal with it. In general terms, the research was divided into 2 philosophies. One was to apply a coating on the glass fiber filaments (either E or AR glass fiber) to protect it against any possible degradation and the other was to modify the OPC matrix so that it was a more hospitable environment for the fiber.

All glass fiber filaments have a binder, or sizing, that is applied almost immediately after the filament is formed from the molten glass at the bushing. This binder is chemically formulated to protect the fiber filaments from abrasion by adjacent filaments, but more importantly it also controls reinforcement performance in whatever matrix the filaments are put into. Pilkington made additional improvements to the binder on the original Cem-FIL® fiber and called it Cem-FIL® II. It showed improved long term flexural properties in hot water aging tests. However, the amount of this new binder on the filaments made it difficult to process in the spray-up process and to compact after spraying.

Other companies not wanting to make the investment of licensing the AR formula from Pilkington chose to try various coatings on E glass filaments. This approach required using textile yarns, weaving them into a mesh or scrim type product and then applying a heavy coating of a flexible resin or polymer. This approach became the basis of the scrim for the EIFS (Exterior Insulation Finishing System) market. These coatings were acrylic, epoxy, PVC or PVA based to give the protection against the alkalis. As an example, fiber glass insect screening came out of these programs.

The matrix modification concept was presented at the GRCA Conference in London in 1979, where Dr. Bijen, of DSM Research presented the 7 year results of a research program he conducted. To summarize his research to that point in time, he presented data that compared the properties of GRC with AR fiber and no other modifications to that of a system that incorporated a high amount of an acrylic co-polymer (12 to 15% polymer solids by volume) and E glass fibers as its reinforcement. This system was introduced to the market as Forton PGRC.

While immediately controversial, especially in regards to which fiber was used, Dr. Bijen's research brought some very interesting technical and practical points of the matrix to the fore. His theory is explained in Figure 14 where you can see the relation of a typical cement particle to the filament spacing in a glass fiber bundle. When GRC was in the young condition, this space between the filaments was left open since the cement particle, as well as the sand particle, were so much larger they could not penetrate it. The effect of this is documented in the higher ductility of young GRC in the flexural tests. However, as GRC ages, a product of hydration, calcium hydroxide, grows into these spaces as seen in Figure 15. The calcium hydroxide fills up those spaces as a hard crystalline material, effectively bonding those high tensile filaments into a brittle straight jacket.

Figure 16 shows what happens to the filaments in the cement matrix under load. The stress concentration on the fiber at the point of loading is dramatically increased when the filaments are tightly bonded to, and by, the calcium hydroxide crystals. This reduces or eliminates the filaments ability to bend or pull out of the matrix to the same degree it did at 28 days. It strips the fibers ability to carry the load.

Dr. Bijen's concept was to design a water based polymer whose particle size, molecular weight and other properties would allow it to migrate into the inter filament spaces by way of capillary action during production to deny that space for the calcium hydroxide crystals to grow into. Thus, by filling these spaces early with the soft polymer particles, the tensile strength of the fiber to carry the applied load when stressed in the aged condition was maintained.

Figure 17 shows no polymer particles within the filaments. Figure 18 shows the polymer particles between the filaments. Figure 19 is another view of the polymer particles in the composite. In this case the cement and sand have been washed away with acid.

Because this system used E glass fiber as the reinforcement, major concerns regarding the long term durability of the system were raised.

While trying to address those durability concerns in both the European and North American market, the North American market was also quickly changing from the box rib or standing rib approach of producing architectural panels to the use of a steel stud/truss frame concept where the GRC skin was bonded to the steel truss frame by means of flex anchors made from a smooth steel rod. The spacing and orientation of the leg of the flex anchor was such that it allowed for shrinkage and thermal movements without over stressing the GRC skin.

This was a major advancement to the acceptance of GRC architectural panels in the market because it allowed for larger panels and gave the architect great freedom to design panels with unique profiles without the weight penalty normally associated with precast concrete, especially in area with seismic design codes.

The acceptance of using E glass and a high polymer loading was going nowhere in the market. However, a review of certain properties of the system now in the context of the steel stud frame system took on new interest with the manufacturers.

Data indicating that GRC with a polymer loading above 10% by volume did not have to be wet cured and reduced moisture absorption and thermal movement properties of the composite versus non-modified products were of particular interest to producers. Later it was discovered that the drying shrinkage rate of the sprayed panel and absolute shrinkage were also much less in the polymer modified matrix.

The new steel stud frame system, the panel size and design flexibility it provided was now preferred by architects and the GRC producers. However, it conflicted with the demands of fiber producers to wet cure GRC, due to the potential for accelerating the rusting of the steel frames. Also, the large size of these panels made handling in a wet curing environment more of an issue. The space required for a "wet room" to hold the panels for 7 days, coupled with the handling, became a huge cost burden to the producer.

Two key questions were asked by the producers about the polymer modified system at this point. The answers would prove pivotal to the growth of the industry. Given the industry was so vested in using AR fiber; they were not going to embrace any system using E glass fiber reinforcement. So the question was, "would the polymer modified system work with AR fiber and what was the minimum amount of polymer that would eliminate the wet curing regime required by the fiber suppliers?"

The answer to the first question was easy. Dr. Bijen had begun his research initially using AR fiber and the acrylic polymer now known as Forton polymer compound. The young and aged physical, mechanical and durability results of the composite were dramatically increased. But someone decided that the combination of AR fiber and high polymer loading would make the system too expensive for the market, so they switched the test program to using E glass fiber, which was a lower cost product. In hindsight, what a strategic error that was.

But how much polymer was needed to eliminate the wet cure was not so easy to determine. The industry and researchers knew that 0% required a wet cure and that 10% solids by volume did not. I decided to conduct a third party research program to establish what amount of the Forton Polymer compound was required to eliminate the wet cure. That testing program was under taken by the Construction Technologies Laboratory of the Portland Cement Association in Skokie, IL. I presented the results of that test program at the 1983 GRCA meeting in Stratford, UK. The results from that report are shown below.

The graphs shown in Figure 20 indicate that 5% polymer solids by volume gave an "equal to, or greater than LOP (now FY) to GRC samples cured 7 days at 100% RH at 28 days when using 5% AR glass fiber". This was exactly what the market wanted and the "5 – 5" market was born.

However, the CTL data was barely on the table when the next obvious question was asked by producers, "what does the combination of AR fiber and polymers do to long term durability?"

The remainder of the 1980's and 1990's saw additional testing programs being conducted on the 5-5 as well as additional matrix modifications using available pozzolans, with and without polymer.

Parallel programs using the hot water accelerated aging tests to predict durability ran alongside natural weathering tests. The natural weathering conditions exposed the coupons to rain, sun, hot/ cold and freezing conditions at a test site in the south of Holland. The hot water aging tests of the 5-5 mix showed noticeably increased properties and especially the strain to failure value in the standard time frames. However, the naturally aged results did not correlate with the predicted values at 5 years. The surprise was the naturally aged results were much better. It was determined the hot water aging test tests were not a valid predictor of aged properties of polymer modified matrices.

I should also interject that based on additional research done by CTL during this time frame; it was determined that a truer, more conservative approach to doing the flexural test would be to soak the coupons for 24 hours before testing. All the various test reports run by the companies and academic institutions showed a drop in their values in 1985/86 and thereafter, which if not explained by this change in test protocol, can be a cause of concern when you see an unexpected drop in flexural properties in their reports.

As the industry gained more experience in the field and with more test data to correlate with field experience, other very important properties of the 5-5 mix became apparent. Figure 21 shows that polymer modification has little influence on thermal expansion.

The influence of the various polymer loadings becomes apparent in water vapor permeability, water absorption and rate of expansion due to water absorption as a function of time. These are all very important factors in the life cycle performance of GRC products in use. Water vapor permeability as a function of various polymer loadings is shown in Figure 22.

Two key points: absolute absorption is lower as shown in Figure 23 and the rate of absorption as a function of time, as shown in Figure 24, is much slower. Figure 25 shows the rate of absorption over time as a function of polymer content. Thus the GRC containing polymer is not subjected to the same degree of internal stress build up that GRC without polymer is. DSM did a test that showed that the thermal cycling stresses in GRC can exceed the strain to failure of non-polymer modified aged GRC. This is why it could crack.

With large GRC skins on steel stud frames, the thermal behavior in the context of aged strain capacity became a very important factor for the successful life-cycle behavior of GRC panels on high rise buildings.

In addition to the improvement in all the physical properties of GRC, there were improvements in many production and practical points when using the Forton polymer compound. The key practical improvements are:

- Better workability of the slurry and the ability to spray vertical surfaces without sag lines
- Better compaction, which results in better density and flexural properties
- Elimination of micro cracks and crazing on the surfaces of panels

- And most importantly, when pigment is used, color uniformity from batch to batch and panel to panel when the panels are installed on the building. This means happy architects and building owners. It also reduces color fading over time.

Industry Specifications and Recommended Practices

Starting in 1978 and continuing to this day, 3 associations were instrumental in developing and implementing the specifications for GRC in the USA building industry. Each association had a particular mandate from the industry and yet they needed to work together as the industry evolved, because the success of one was based on the success of the other. The Associations are:

The Precast/Prestressed Concrete Institute (PCI) accepted the role of being the primary association of GRC producers and the responsibility of writing and promoting Recommended Practices and Quality Control Manuals.

The first edition of the “Recommended Practice for GFRC Architectural Panels”, MNL 128 was published in 1981. Subsequent revisions have brought the Fourth Edition published in 2003.

“The Manual for Quality Control for Plants and Production of Glass Fiber Reinforced Concrete Panels”, MNL 130 was first published in 1991. The Second Edition (2009) is now available online at www.pci.org. With MNL 130 in place it was now possible to have certified plants producing GRC. The most current publication of the document is the controlling reference.

Critical to the success of generating these documents was the continuing research data supplied by Cem-FIL®, NEG, Forton BV and academic institutions showing various properties of the GRC composite and mix designs.

The American Concrete Institute (ACI) is primarily an academic oriented group that researches products and processes related to concrete based materials and issues standards or state of the art reports on materials based on the work of committees specializing in those areas. GRC is currently represented in Committee 549- Thin Reinforced Cementitious Products and Ferrocement, which recently issued “549.3R-09 Report on Glass Fiber-Reinforced Concrete Premix”. Polymer products for cement and concrete modification are covered in Committee 548- Polymers and Adhesives for Concrete which has issued “548.1R-09 Guide for the Use of Polymers in Concrete” that categorizes the various polymer chemistries used for cement modification and their properties to determine where they should be used.

The American Society for Testing Materials (ASTM) is a group that develops and maintains test specifications for materials and processes for industry and code bodies. In the early years, they were called upon to develop specific test procedures for GRC, specifically, the flexural test, C947-03 and the absorption test, C948-81. C947-03 became the key test around which the quality control program for GRC was built, thus insuring the designers and engineers that GRC panels would meet the required design loads. C1228-96, C1229-94, C1230-96 and C1560-03 are additional test specifications covering GRC.

In Europe, the associations responsible for GRC growth and development were:

The Glass Reinforced Cement Association (International) (GRCA) has developed technical reports covering GRC using specifications first developed in conjunction with British Standards. Now this function has been taken over by European Standards. The GRCA has developed the “Specification for the manufacture, curing and testing of GRC Products”, Third Edition

British Standards (BS) and European Standards (EN) covering GRC are BS EN 1169, BS EN 1170, DD EN 1176, BS EN 14649 and EN 15422.In Germany, DIN standards were developed that were unique to that market.

In the GRC standards developed by both the PCI and GRCA are two material specifications critical to the successful production and long term performance of GRC architectural panels. These are the specifications referenced in the PCI MNL 130 (2009) as Appendix F the AR fibers and Appendix G for the polymer curing admixtures. They are shown as Figures 26 and 27, respectively.

You can see that Appendix F defines the specific requirements for an AR glass fiber reinforcement product to be used in GRC. Both Cem-FIL® and NEG produce their fibers above the minimums required by the standards. It clearly states that a minimum of 16% zirconia oxide is the requirement to achieve long term durability. Any fiber containing less than 16% zirconia oxide must be tested for long term durability in a GRC composite by a third party testing company.

Appendix G for the Polymer Curing Admixture is very specific as to the proper requirements of a product satisfying this specification. It should be:

- Acrylic based
- High molecular weight
- Ultraviolet resistant
- Alkali resistant
- Consistent particle size range from batch to batch

For a polymer to be acceptable, documentation must be supplied from an independent testing laboratory that verifies:

- Properties of polymer modified GRC are verified to be equal or greater than wet cured GRC
- Long term durability of the product verified by aging tests.
- Cured density greater than 120 pounds a cubic foot (1930 g/cm3)
- Durability, UV stability, oxidation resistance and stability in highly alkaline environments

The report from the ACI Committee 548, “Guide for the Use of Polymers in Concrete” (548.1R-09), is also very specific as to what polymers are acceptable for use in architectural grade cement based products.

- acrylic copolymers should be used because they have the superior UV resistance and permeability required in architectural applications. (Section 5.2.1.3)
    - Styrene-Butadiene copolymers (S-B) should not be used because they degrade and discolor. (Section 5.2.1.4)
        - That means Styrene Butadiene (SBR) polymers should NOT be used
    - PVA copolymers should NOT be used because they are known to deteriorate with exposure to moisture. (Section 5.2.1.1)

Additional qualities specific to the GRC manufacturing require that:

- They must have the proper amount and type of defoamer to withstand the rigors of the high shear mixing and spraying so that the specified density is achieved
- The pH for acrylic copolymers is 8 to 10 (PCI Appendix G)
- The batch to batch particle size is very important for architectural applications to maintain color uniformity thorough out the project.
- The MMFT are very important for production

Other systems

CGC Cement – Japan: specialty formulated cement that requires a stringent and complicated curing regime. It has a low alkalinity but not low enough to use E glass fiber reinforcement. Long term durability was very good as well as very low shrinkage which allowed it to be used as a backing material for tile faced panels.

Durapact – Germany: system incorporating Type I Portland cement, slag cement and microsilica that gives improved durability to the GRC when aged.

CemStar® - Spain: the use of a specific grade of metakaolin as a Type I Portland cement replacement to give a pozzolanic reaction to tie up the calcium hydroxide and reduce efflorescence. Also used with the Forton polymer to produce GRC parts with excellent surfaces. The system can have some processing issues at higher loadings because it is clay based.

Zircrete – USA: cement based on calcium sulphoaluminate (no Portland cement) reinforced with NEG AR fibers. It contained about 5% of a pozzolan. It required a combination of accelerator and retarder to control working times and set times. Set times could be varied from 20 minutes to 1 hour. Accelerated aging tests showed excellent long term properties with no drop in MOR and strain to failure. However, there were not enough examples to give good statistical results to justify its use. The cement had low alkalinity but not low enough to justify the use of E glass. Fast demolding times were interesting for high volume, mass produced products. It offered low shrinkage properties so it could be used with tile and brick faced products.

CSA Cements - Europe, USA, and China: the use of CSA cements in combination with Type I Portland to achieve faster mold turnovers. Rockfast, Ultimax, Rapid Set are products where CSA and Type I Portland are hot blended at the kiln level in their respective ratios. They are also compatible with polymer. They are not to be confused with high alumina cements which are not recommended.

Fast Stone® - USA: Cold blends of Type I Portland (white or grey), CSA and VCAS that achieve various demolding times, replace Type I Portland cement with a recycled, white, pozzolan to control efflorescence and produce a product with excellent surface density. By replacing Type I Portland cement and using a recycled glass material with pozzolanic properties a green product is obtained.

16 Years of natural weathering durability comparing GRC without polymer and with 6% polymer solids of Forton polymer compound.

As mentioned earlier in the paper the ability of the hot water accelerated aging tests were not predictive of how the material was aging in a natural environment. The Forton polymer addition gave all indications that it was minimizing the effects of aging in the GRC composite. However, the scientists involved in the program were reluctant to make any hard predictions until results from longer natural aging programs became available. Finally, flexural tests were performed on coupons naturally aged 16 years and SEM photos were taken of the fracture interface. The results of those tests and the SEM's are shown in Figure 28.

The flexural tests show the aged strain to failure is .02% for the GRC without polymer and 1.0% for the GRC with 6% polymer solids to the weight of cement. While these values are impressive, the SEM's of the fractures are even more impressive.

The SEM of the 0% polymer example shows a "straight line" break with few fibers and fiber bundles shown as being pulled out. It also shows calcium hydroxide crystals visible around the fibers.

The SEM of the GRC example containing the Forton polymer shows a distinctly jagged fracture (center to right) and many intact, longer fiber bundles, as well as almost no calcium hydroxide crystlas around the fiber bundles. These fiber bundles absorbed the load, pulled out and resulted in the higher strain to failure, or ductility value.

This is shown graphically in Figure 29 where the data from the tests of no polymer and with VF-774 naturally aged is shown side by side. The use of the Forton VF-774 clearly shows improved properties, especially the strain to failure, or ductility, when loaded to failure.

Summary

In the competitive real world, it is very easy to be tricked by all this information when it is in the hands of nonexperienced people. The data presented in this paper is the only published third party data available supporting the use of a specific arcylic polymer to BOTH eliminate the wet curing regime and maintain the long term durability, especially the strain to failure, of a GRC composite. Companies might be making claims based on in house programs, but that is not the same as published, third party, peer reviewed documentation such as the information I have presented on the research work done by Forton BV and others.

ACI 548 report on polymers in concrete confirms that acylic polymers only should be used where the finished parts are to be used in architectural situations. (Section 5.2.1.3)

In conclusion, nowhere can all of this information be more dramatically shown than in two photos I recently took in Saudi Arabia at the Princess Nora University project.

Figure 30 is a close up of the surface of a panel approixmately 3 months old before it was erected. This panel was not produced by the prime contractor for the project. This panel contained SBR polymer at a very questionable loading. At 3 months you can very easily see the crazing on the surface. You have to ask about the overall durability and integrety of this GRC panel, especially the face mix and how it will perform in thermal cycling.

On the other hand, Figure 31 shows the surface of a panel produced in the same region using the proper amount of Forton VF-774. You can see that it is tight, dense and uniform in color.

Completing a review of all the research and testing over the years since the beginning of the glass fiber reinforced concrete industry, it really comes down to 4 visual images in my mind; the 2 SEM’s showing the interface of the break of 16 year old naturally weathered composites (Figure 28) and Figures 30 and 31 showing the surface of a panel using the wrong product and the surface of a panel using the proper product.

I think the evidence is very clear what direction you must go, if producing a quality GRC product is the goal.

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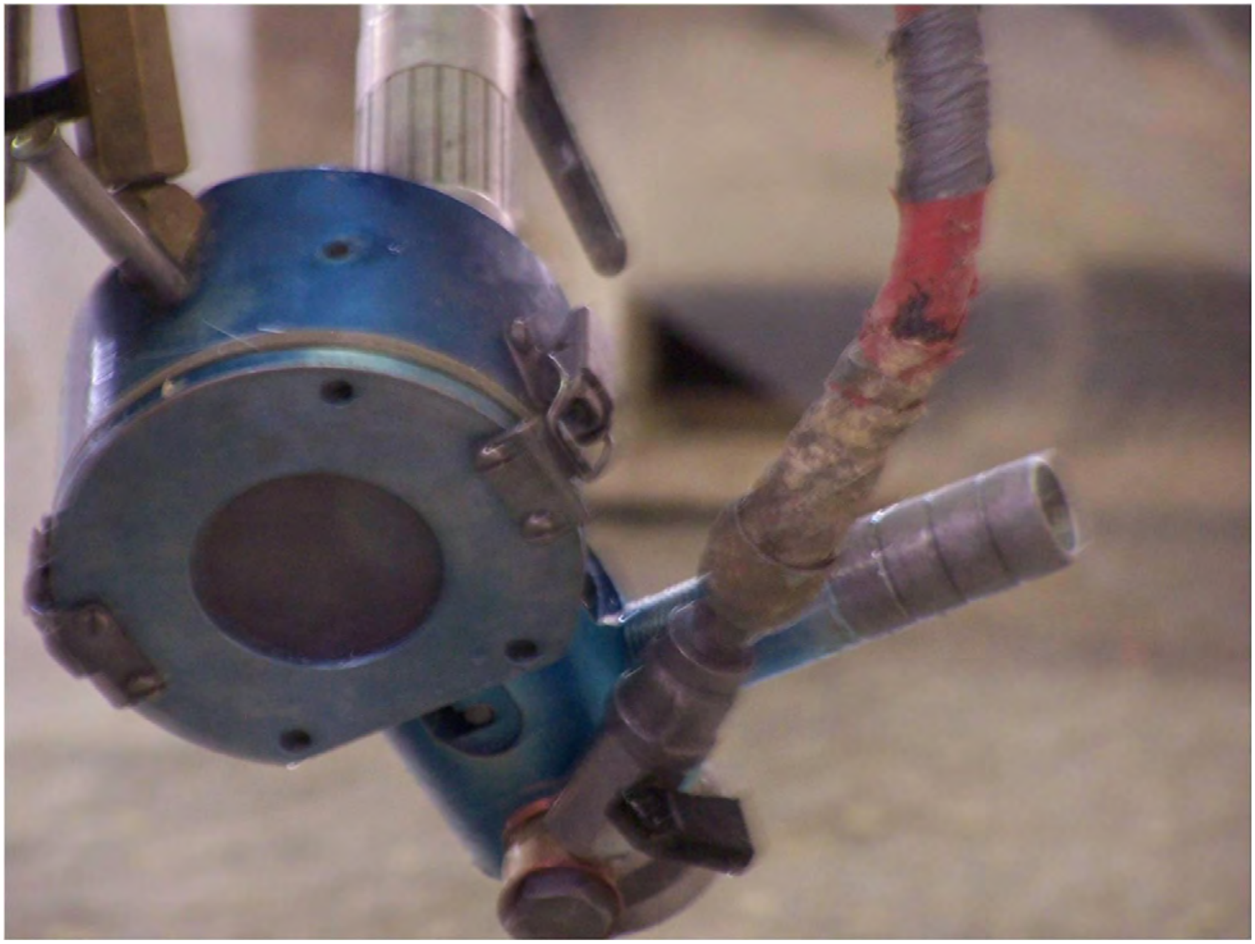
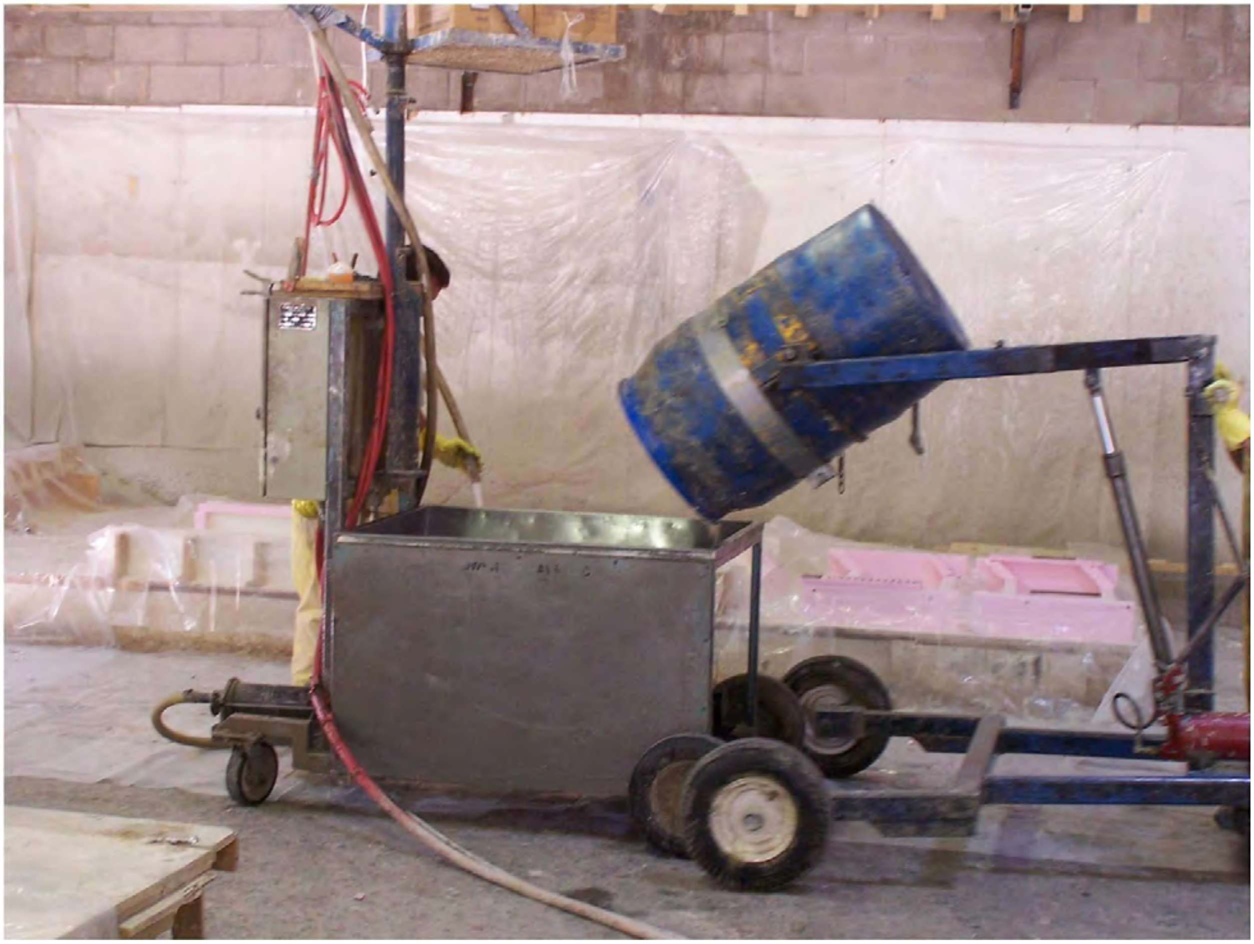



POWER-SPRAYS
POWER-SPRAYS
DANGER High voltage
Eye protection must be worn
EMERGENCY STOP




RIMCASTER

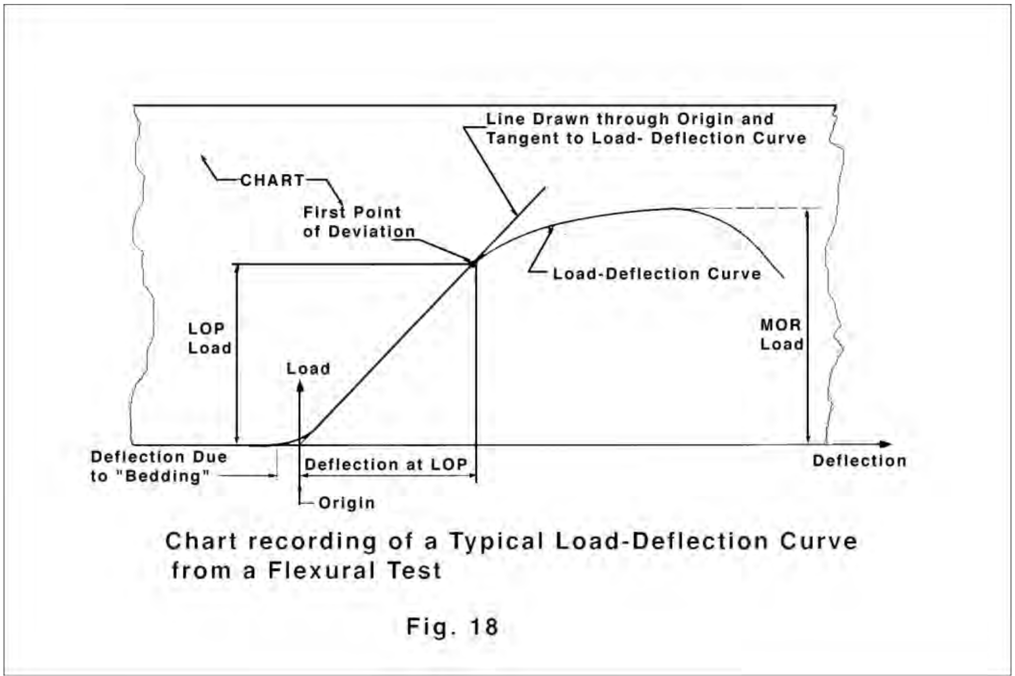
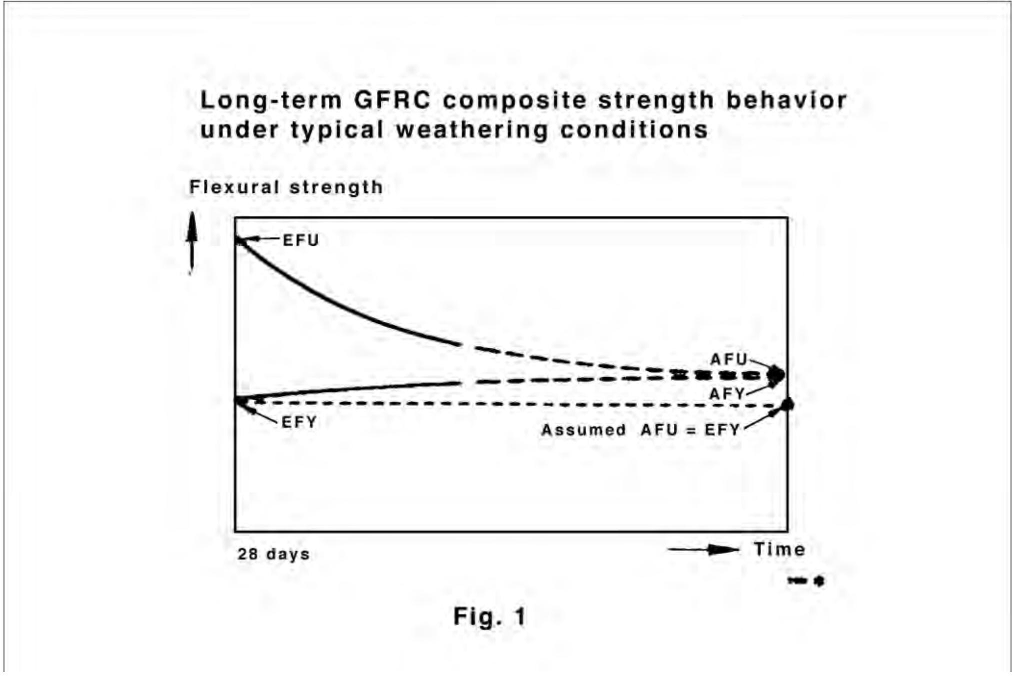


Chart recording of a Typical Load-Deflection Curve from a Flexural Test

Fig. 18



Long-term GFRC composite strength behavior under typical weathering conditions

Fig. 1

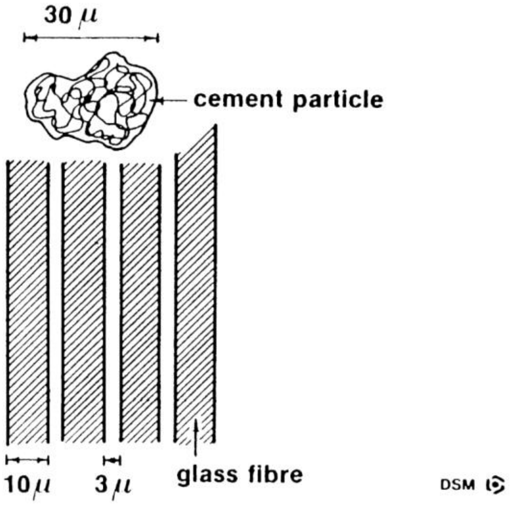


Fig.6

Glass fibre in aged grc-matrix
12 months under water

magnification 1800x

Fig. 4

Stress concentration in glass fibre caused by sharp bend

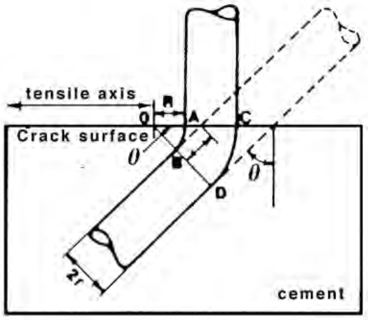
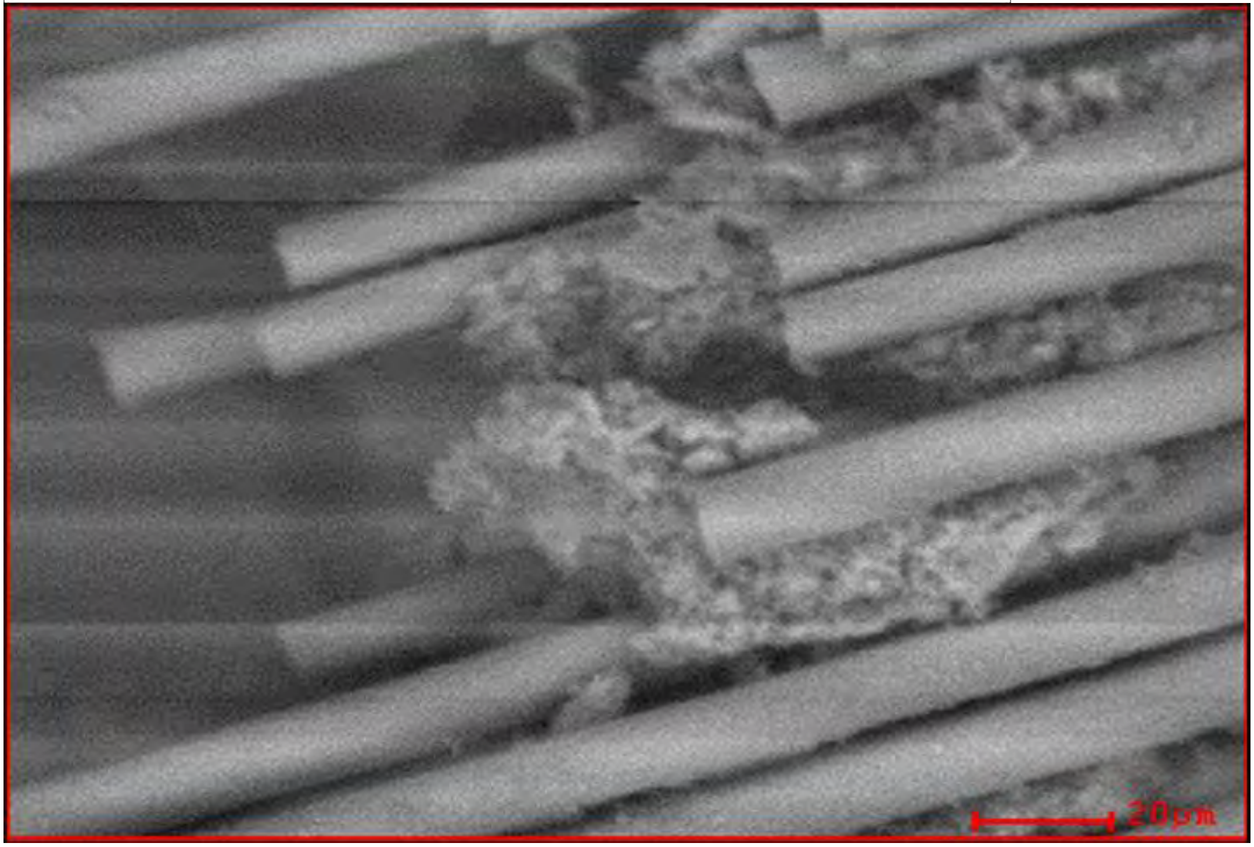


Fig. 5



Polymer particles between glass fibres

magnification 5500x

Fig. 7

Polymer film on glass fibres magnification 1800x

Fig. 8

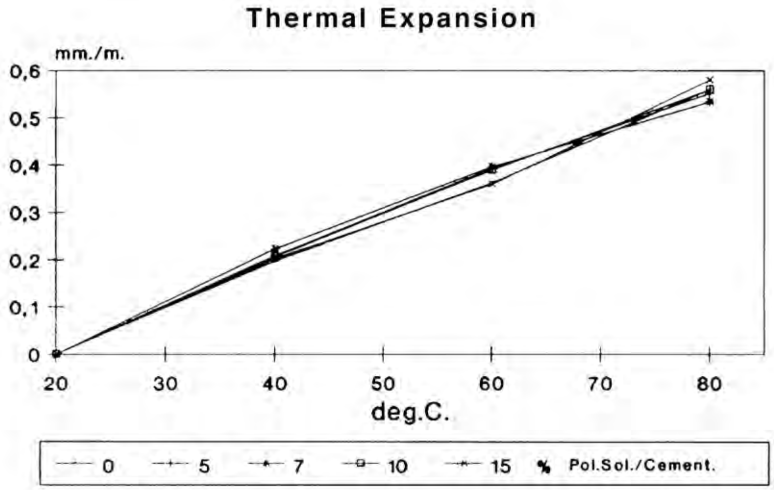

Thermal Expansion
mm./m.
0,6
0,5
0,4
0,3
0,2
0,1
0
20
30
40
50
60
70
80
deg.C.
0
5
7
10
15
% Pol.Sol./Cement.

Fig. 43

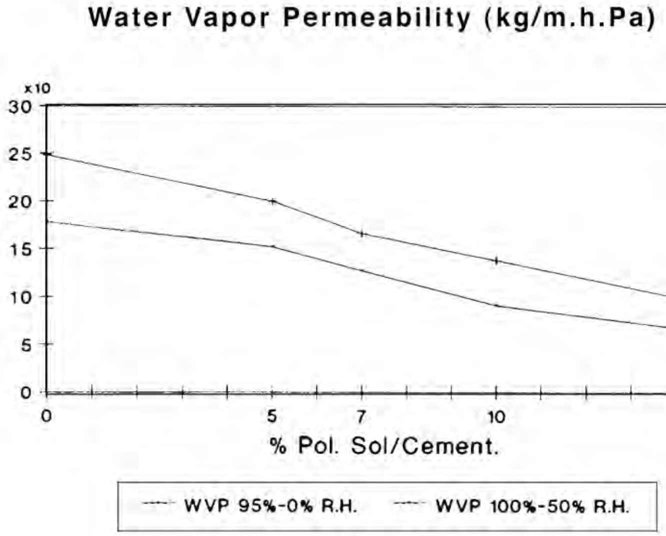

Water Vapor Permeability (kg/m.h.Pa)
x10
30
25
20
15
10
5
0
0
5
7
10
15
% Pol. Sol/Cement.
WVP 95%-0% R.H.
WVP 100%-50% R.H.

Fig. 44

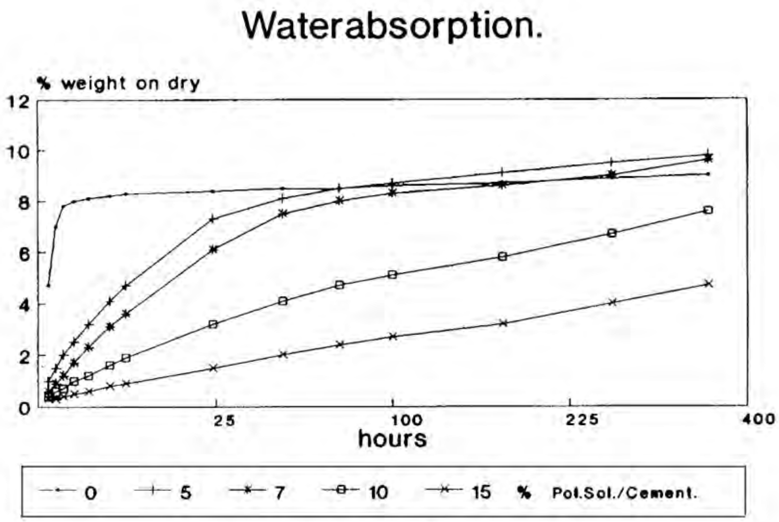

Waterabsorption.
% weight on dry
12
10
8
6
4
2
0
25
100
225
400
hours
0
5
7
10
15
% Pol.Sol./Cement.

Fig. 45

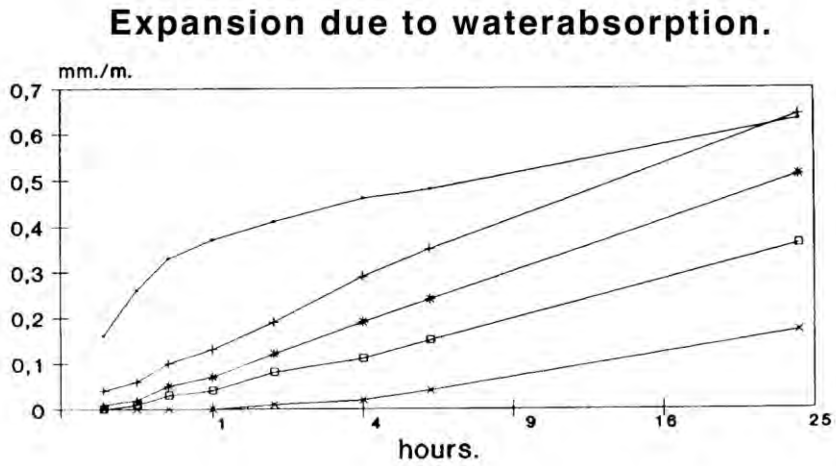

Expansion due to waterabsorption.
mm./m.
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1
4
9
16
25
hours.

Fig. 46

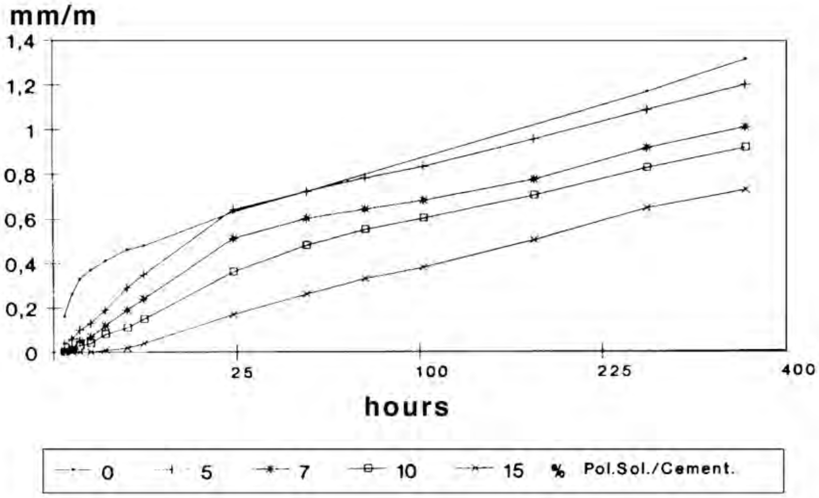
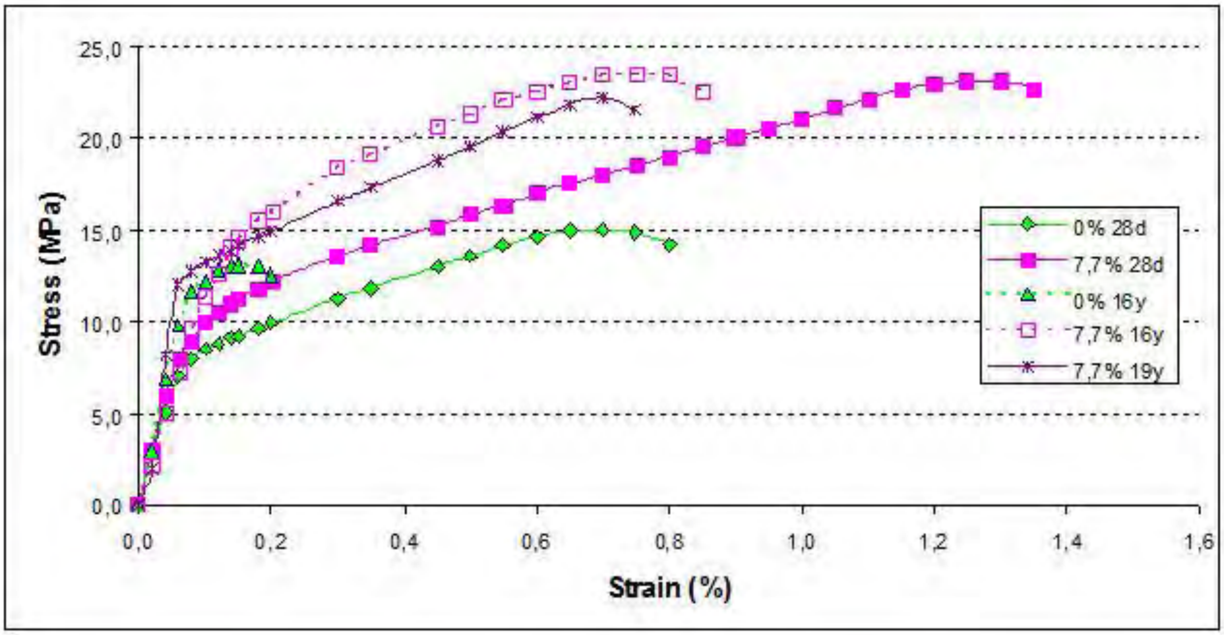
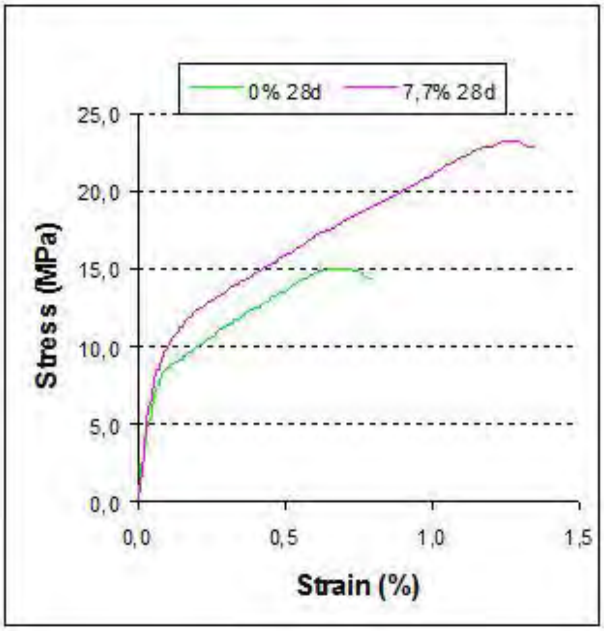
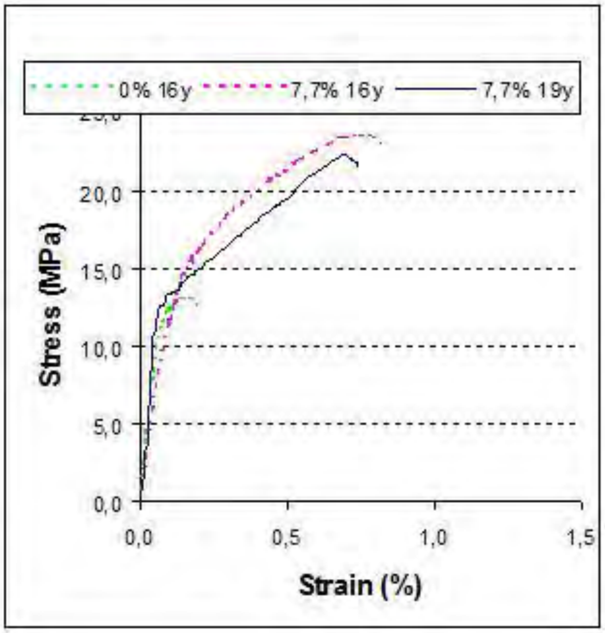

mm/m
1,4
1,2
1
0,8
0,6
0,4
0,2
0
25
100
225
400
hours
0
5
7
10
15
% Pol.Sol./Cement.

Fig. 47


Stress (MPa)
25,0
20,0
15,0
10,0
5,0
0,0
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
Strain (%)
0% 28d
7,7% 28d
0% 16y
7,7% 16y
7,7% 19y


0% 28d
7,7% 28d
Stress (MPa)
25,0
20,0
15,0
10,0
5,0
0,0
0,0
0,5
1,0
1,5
Strain (%)


0% 16y
7,7% 16y
7,7% 19y
Stress (MPa)
20,0
15,0
10,0
5,0
0,0
0,0
0,5
1,0
1,5
Strain (%)