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EVALUATION OF GLASS FIBER REINFORCED CONCRETE PANELS
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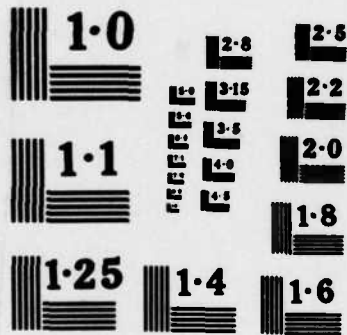
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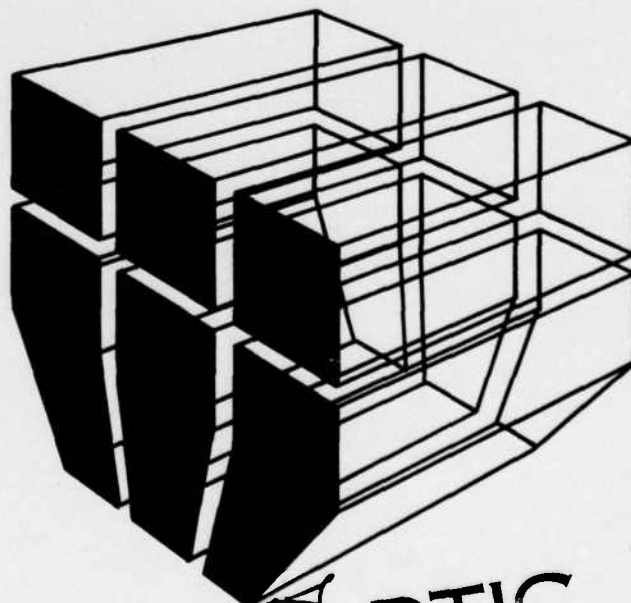
Evaluation of Glass Fiber Reinforced Concrete Panels for Use in Military Construction

by
Gilbert R. Williamson

Glass fiber reinforced concrete (GFRC) materials are investigated for potential use in military construction, especially as exterior building panels. Because GFRC technology is relatively new, long-term durability data are lacking. However, reliable aging tests have been designed that allow the material's performance to be predicted past the 50-year lifetime required for military construction.

Results indicate the GFRC panels are suitable for use in military construction. These materials may, in many cases, provide an economical alternative to conventional construction. The recommendation for their acceptance includes the stipulation that proven methods be used in the panels' design and application (e.g., steel stud frame backup and "L" anchors).

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FOREWORD

This work was performed for the Directorate of Engineering and Construction, Office of the Chief of Engineers, under Funding Authorization Document 2-001773, dated February 1984. The technical monitor was Fred Anderson, DAEN-ECE-D.

The work was done by the U.S. Army Construction Engineering Research Laboratory (USA-CERL), Engineering and Materials Division (EM). Dr. Robert Quattrone is Chief, EM.

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EVALUATION OF GLASS FIBER REINFORCED CONCRETE PANELS FOR USE IN MILITARY CONSTRUCTION

1 INTRODUCTION

Background

Glass fiber reinforced concrete (GFRC) panels have, in the past 10 years, become widely used throughout the world. Several U.S. Army Corps of Engineers Districts and Divisions have received requests from the GFRC industry to consider bids that specify GFRC as an alternative exterior panel material for military construction projects. When the GFRC products have been compared with conventional panels, it has been found that considerable savings could be effected if the GFRC panels were used. However, before permitting general use of this material, the Directorate of Engineering and Construction, Office of the Chief of Engineers, commissioned a study to determine the material's suitability for military construction. Permanent military construction normally is expected to have a 50-year life.

GFRC is a relatively new technology. Many previous attempts had been made to use glass bars as tensile reinforcement in ordinary Portland cement (OPC) concrete but none had been successful. Alkali in the cement causes rapid deterioration of conventional borosilica glass, commonly called "E-glass," rendering the bars ineffective after only a few years. Glass was, however, found to be very effective in reinforcing plastics, and a huge industry offering an enormous number of products resulted from this application. Glass fibers are the primary reinforcement used in these products. Success with this technology renewed the interest in using glass fibers as reinforcement for concrete products, but the prior experience with glass reinforcing bars made it apparent that a way to protect the glass from alkali was necessary.

Three approaches to this problem were to: (1) develop an alkali-resistant glass; (2) use conventional E-glass, but incorporate an additive to protect it; (3) use E-glass with special cements such as alumina cement and gypsum slag. All three approaches produced some degree of success. Work by Dr. A. J. Majumdar and others at the Building Research Establishment (BRE) Watford, England, resulted in a

product marketed under the name "AR" glass and produced by Cem-FIL Corporation and Nippon Electric Company.¹ This is a high-zirconia (minimum 19 percent), alkali-resistant glass that, after some slow deterioration due to the alkali, reaches a point at which no further deterioration takes place. The second approach, developed by Dr. J. Bijen, was to incorporate approximately 15 percent by weight of a polymer marketed under the trade name "FORTON" as the E-glass protective agent.²

Based on these developments, a large GFRC industry developed worldwide. The term "GFRC" applies to products manufactured using a cement/aggregate slurry reinforced throughout with glass fibers. Products include formwork, nonpressure pipe, corrugated and plain sheets, asbestos replacement products, and architectural and industrial panels (cladding) and surface bonding. Paneling is by far the most widely produced of all the products, with surface bonding comprising the second largest market. Because of its versatility and low cost, architects are specifying GFRC paneling at an ever increasing rate. Use of GFRC panels is common in Europe, Japan, the United Kingdom, the United States, and South Africa, as well as in the Middle East, where over 123 projects using GFRC materials have been completed since 1977.

Objective

The objective of this study was to investigate GFRC materials to determine their suitability, from a durability standpoint, for military construction, particularly as paneling for building exteriors.

Approach

The study was conducted by: reviewing the literature; visiting the British Research Establishment and Pilkington Brothers Ltd., the company developing AR-glass and thus founding the GFRC industry; visiting five different GFRC producers in the United States; and consulting with other experts in this field.

¹A. J. Majumdar and J. F. Ryder, "Glass-Fibre Reinforcement of Cement Products," *Glass Technology*, Vol 9, No. 3 (June 1968).

²J. Bijen, "E-Glass Fibre Reinforced Polymer Modified Cement," *Proceedings, International Congress on Glass Fibre Reinforced Cement*, London, Ont., 1979 (Glass Fibre Reinforced Cement Association, 1980).

2 GFRC MATERIALS MANUFACTURE AND PROPERTIES

The most widely used process for producing GFRC panels is the direct spray or spray-up process, which can be done by hand or machine. The process uses a two-nozzle compressed-air-powered gun, with one nozzle fed a continuous strand of glass fibers which is chopped at the nozzle into predetermined lengths of between 25 and 40 mm or 37 and 50 mm. The chopped fibers are randomly combined with a cement-sand slurry from the second nozzle outside the gun after each material has been sprayed (blown at high speed) through its respective nozzle. The material is laid down in thin sections and the required thickness is achieved by making multiple spray passes over this form. The sections are hand-rolled after each pass to consolidate the material and eliminate air pockets. This same procedure (without the rolling) is sometimes followed by a dewatering process that not only increases the material's strength, but also allows for immediate removal from the form and bending into various shapes if desired. Panels and other products

also can be produced by mixing and casting the material as with other precast concrete products. The material is cured in the same way as for other concrete products either by moist curing, membrane curing, or incorporating polymers into the mix.

Composition

GFRC is composed of 1 part cement, 0.2 to 1.0 part sand, and 4 to 6 percent glass fibers by weight, and a water/cement ratio of approximately 0.3. Polymer GFRC (PGFRC) usually is composed of 1 part cement, 0.2 to 1.0 part sand, 4 to 6 percent glass fibers by weight, 10 to 15 percent polymer by volume, and enough water to produce a sprayable slurry. Water-reducing and other admixtures are used as required in these mixes. The cement for both PGFRC and GFRC usually is OPC, type 1, sometimes white; sand usually is fine silica or fine regular type, and the AR-glass fiber is supplied in a roving (made up of strands that contain 204 monofilaments) which is chopped into lengths of 25 to 50 mm during the spraying process. Tables 1 and 2 give typical 28-day physical properties for GFRC and PGFRC, respectively; recommended design properties also are given.

Table 1
GFRC Properties (Recorded at 28 Days)*

Property	Unit	Hand-or Machine-Spray	Recommended Design Value
AR fiber content	% by wt	5	—
Density (normal)	ton/m ³	1.9-2.1	—
Compressive strength	MPa	50-80	12
Tensile strength (UTS)**	MPa	8-11	3
Bend-over point (BOP)	MPa	9-10	—
Bending strength (MOR)***	MPa	21-31	6
Impact strength (Izod)	Nmm/mm ²	10-25	—
Bending elastic limit (LOP)*	MPa	7-11	—
Young's modulus	GPa	10-20	—
Poisson's ratio		0.20-0.25	—
Strain-to-failure	%	0.60-1.2	—
Interlaminar shear strength	MPa	3-5	1
In-plane shear strength	MPa	8-11	—

*Source: Pilkington Brothers, Ltd., *Cem-Fil, GRC Technical Data Bulletin* (St. Helens, Merseyside, England). Used with permission.

**UTS = ultimate tensile strength.

***MOR = modulus of rupture.

*LOP = limit of proportionality.

Table 2
PGFRC Properties*

Property	Unit	Spray (28 Days)	Dry	After 10 Years Under Water	Natural Weather	Recommended Design Value
Bending (MOR)**	MPa	27	21	19	22	8
Bending (LOP)***	MPa	12	15	14	15	—
Elongation at rupture	%	10	2.5	1.5	2.5	—
Tensile strength (UTS)*	MPa	12	13	12	13	4
Bend-over point (BOP)	MPa	8	10	10	10	—
Interlaminar shear	MPa	4	4	5	4	—
Impact strength (charging)	Nmm/mm ²	8	2	2	2	—

*Source: B. V. Forton, *FORTON Polymer-Modified Glass-Fibre-Reinforced Cement: A New Freedom in Building Design* (FORTON). Used with permission.

**MOR = modulus of rupture.

***LOP = limit of proportionality.

*UTS = ultimate tensile strength.

As can be seen, the design values are considerably lower than those recorded at 28 days to compensate for the expected change with aging. OPC GFRC is affected by age, progressing from a ductile material at early ages to a brittle one after a few years. However, by using silica fume, fly ash, or granulated slag in combination with OPC, considerable progress has been made in maintaining the original 28-day ultimate failure strain, even after the material has aged. In one case for which the mix contained 30 percent OPC with 70 percent granulated slag, there was no decrease in ultimate strain at failure after 2 years of natural weathering, or after wet-aging at 50°C for 50 days, which is equivalent to approximately 30 years of natural weathering in a moderate climate. Systems using silica fume, fly ash, or granulated slag are not yet in general use, however.³

Aging

Properties of the cement-sand slurry used in GFRC, including additives, are no different from those of regular mortar mixes and therefore are well understood, especially from the durability aspect. It is when the glass fibers are introduced as reinforcing elements that durability and other properties come into question.

It is well known that silica in the glass reacts with alkalis in the cement and causes the glass to become etched.⁴ The safe design of any product or structure is based on reliable estimates of the components' physical properties and durability over time within a given environment. Thus, it must be taken into consideration that GFRC's properties are known to change with time, and this change is associated with a loss of tensile strength in the fibers. The degree of loss depends on the environment; it is less when GFRC is exposed to low humidity, more with exposure to natural weathering, and greatest when used underwater. At early ages, GFRC can be considered a ductile material with typical stress-strain curves as shown in Figure 1a.⁵ After time, except for use in a dry-air environment, the stress-strain curves become as shown in Figure 1b. These curves typify a brittle material.

Table 3 gives results of 10-year tests on specimens made by the spray-dewatering process and containing 5 percent by weight of 34-mm-long chopped strands of AR-glass fibers—some with matrices of OPC and some with OPC and 10 percent fine sand.⁶ The specimens

³A. J. Majumdar and V. Laws, "Composite Materials Based on Cement Matrices," *Phil. Trans. R. Soc. London*, A310 (1983).

⁴A. B. Poole (Ed.), "The Effect of Alkalis on the Properties of Concrete," *Symposium Proceedings* (Cement and Concrete Association, September 1976).

⁵J. F. A. Moore, *The Use of Glass-Reinforced Cement in Cladding Panels* (Building Research Establishment, Watford, England, 1984).

⁶*Properties of GRC: Ten Year Results* (Building Research Establishment, Watford, England, November 1979).

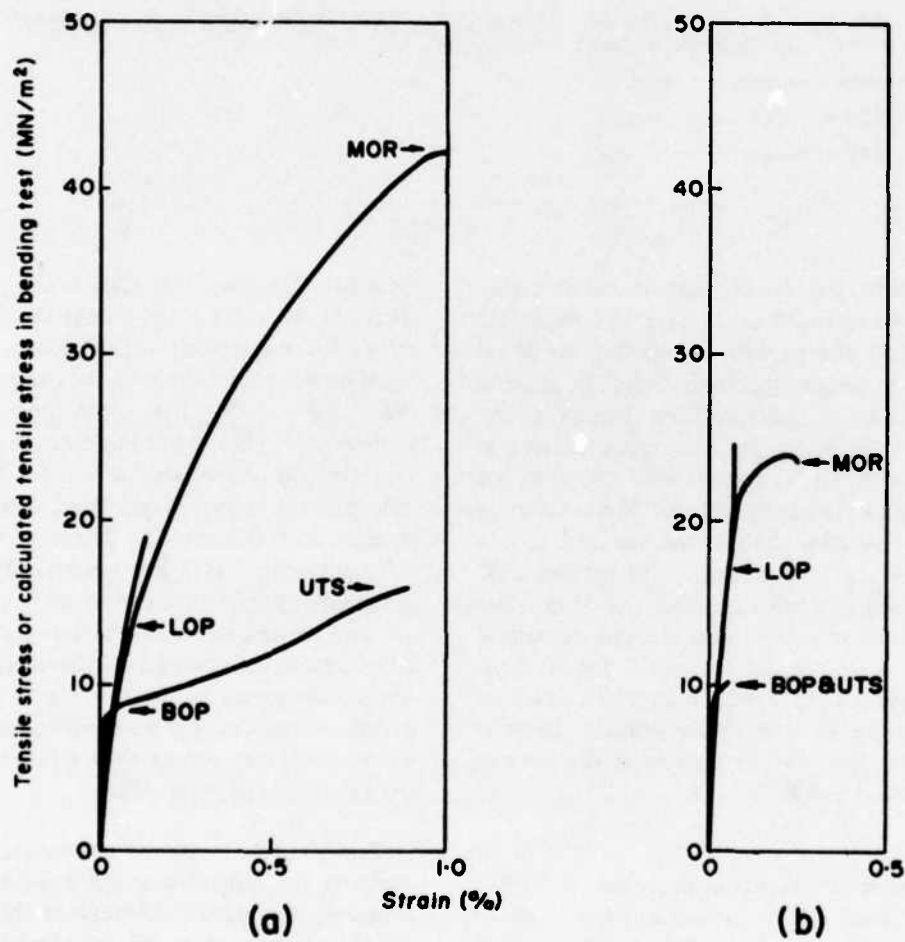


Figure 1. Representative stress-strain curves in tension and bending: (a) after 28 days in water at 18 to 20°C and (b) after 5 years in water at 18 to 20°C. MOR = modulus of rupture; LOP = limit of proportionality; UTS = ultimate tensile strength; BOP = bend-over point. (From J. F. A. Moore, *The Use of Glass Reinforced Cement on Cladding Panels* [Crown copyright: Building Research Establishment, UK, 1984]. Used with permission.)

Table 3

**Measured Mean Strength of Sprayed-Dewatered OPC/GFRC at Various Ages
(5 Percent by Weight Glass Fiber)***

	Total Range for Air and Water Storage Conditions at 28 Days	1 year			5 years			10 years		
		Air**	Water***	Weathering	Air**	Water***	Weathering	Air**	Water***	Weathering
Bending										
MOR* (MPa)	35-50	35-40	22-25	30-36	30-35	21-25	21-23	31-39	17-18	15-19
LOP** (MPa)	14-17	9-13	16-19	14-17	10-12	16-19	15-18	14-16	16-17	13-16
Tensile										
UTS*** (MPa)	14-17	14-16	9-12	11-14	13-15	9-12	7-8	11-15	6-8	7-8
BOP† (MPa)	9-10	7-8	9-11	9-10	7-8	7-9	7-8	9-10	6-8	6-8
Young's modulus (GPa)	20-25	20-25	28-34	20-25	20-25	28-34	25-32	25-33	25-31	27-30
Impact strength (Izod, Nmm/mm ²)	17-31	18-25	8-10	13-16	18-21	4-6	4-7	15-22	2-3	2-6

*Source: *Properties of GRC: Ten Year Results* (Building Research Establishment, 1979). Used with permission.

**At 40% relative humidity and 20°C.

***At 18-20°C.

*MOR = modulus of rupture.

**LOP = limit of proportionality.

***UTS = ultimate tensile strength.

†BOP = bend-over point.

were wet-cured for 7 days and then stored under the conditions indicated in the table. Each value represents the average of five tests.

Since these tests represent the longest-term durability studies of GFRC available, it is important that they be studied in detail. When GFRC is stored in dry air, the bending strength does not change much with time. This is true both for the modulus of rupture (MOR) and limit of proportionality (LOP), and the material remains ductile. For specimens stored under water or exposed to natural weathering, the MOR at 10 years is roughly 50 percent of the 28-day values (brittle material), whereas the LOP values remain virtually constant for 10 years.

The 10-year tensile strength tests on the specimens did not produce as reliable results as some of the other tests due to the difficulty of conducting tensile tests, especially on brittle materials. Essentially, the data

show that, for specimens stored in air, the ultimate tensile strength (UTS) decreased only slightly (16 percent) over the 10-year period and the bend-over point (BOP) remained constant. However, in specimens stored under water or exposed to natural weathering, UTS declined over 50 percent, with the specimens again becoming brittle. The Izod impact strength showed some decrease for all three storage conditions. Samples stored in air were reduced in strength by approximately 24 percent; samples in water storage were 90 percent reduced; and those in natural weather were 84 percent reduced in strength. Only Young's modulus remained constant or increased slightly for all storage conditions over the 10 years.

It can be concluded from this 10-year study that significant changes occur in GFRC's main design properties and that the material progresses from ductile to brittle. The design values selected for GFRC in Table 1 account for the time/environment-associated changes in the material's properties.

Ordinary military construction in the United States is designed for a 50-year useful life. However, since GFRc has been in general use only about 10 years, there was a need for methods to predict the material's long-term properties. Results like the ones shown in Figure 1 had revealed that strain-to-failure declines greatly for GFRc stored in water for 5 years. Similar reductions had resulted from natural weathering (Figure 2), but values for specimens stored in dry air had decreased very little.⁷ The result of a decrease in strain capacity is that the composite takes on strain characteristics of the matrix and becomes brittle, suggesting the material's long-term properties should be assessed carefully.

To compensate for the absence of reliable aging data for GFRc beyond 10 years, techniques have been developed that use accelerated aging procedures to predict the composite material's long-term characteristics. Extrapolation of existing data has provided one way of estimating these properties. For example:⁸

The shape of the strength/time curve suggests two simple empirical relationships that might reasonably describe the experimental data . . .

⁷A Study of the Properties of Cem-FIL/OPC Composites (Building Research Establishment, Watford, England, June 1976).

⁸A Study of the Properties of Cem-FIL/OPC Composites.

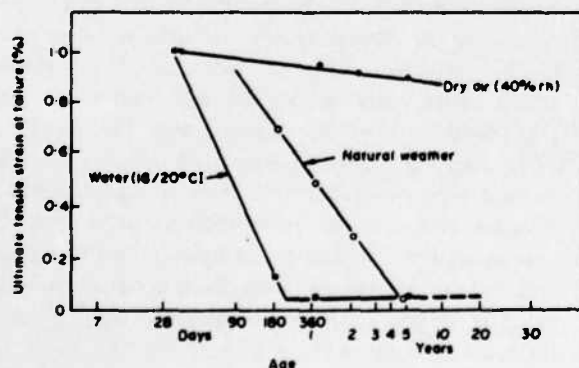


Figure 2. Strain-to-failure in tension for GFRc at various ages in dry air, natural weather, and water storage. (From *A Study of the Properties of Cem-FIL/OPC Composites* [Crown Copyright: Building Research Establishment, UK, June 1976]. Used with permission.)

Empirical curve fitting and extrapolation [were] carried out using these two relationships:

1. A logarithmic relationship, i.e., $S = a - b \log t$
2. An exponential relationship, i.e., $S = a + be^{-ct}$.

These methods have become academic in light of the most recent developments in accelerated aging tests. A newer method of predicting long-term properties for GFRc appears to be much more practical in that it is based on the actual interaction of glass with cement. A test specimen has been developed which consists of a strand of glass fibers embedded in a block of cement paste or a cement/sand mortar. This specimen, called "strand-in-cement" (SIC), is subjected to a test environment, after which it is tested in direct tension. Tensile strength thus becomes a factor influenced by the storage environment, which is actually water at various temperatures. Figure 3 shows the influence of temperature and time on SIC specimen tensile strength. Figure 4 shows similar data for actual composite materials compared with actual weathering data obtained from various places throughout the world.⁹ Material aged in water at 80°C for 5 days is approximately equal to a sample aged 10 years in natural weather.

When the SIC specimens' reaction time to reach a given strength (Figure 3) is plotted logarithmically against the reciprocal of the temperature (an Arrhenius plot), the results are as shown in Figure 5a.¹⁰ These plots are for actual test data only. Because they are all parallel straight lines, they show that, essentially, only one chemical reaction or corrosion mechanism is controlling the strength changes over the whole experimental temperature range of 20 to 80°C. This result allows good confidence in using accelerated tests to predict strength behavior at low temperatures over longer times. A more convenient way of correlating strength changes in different accelerated test conditions and relating them to changes expected over long periods is to normalize the data of Figure 5a into a single line (Figure 5b) by plotting the logarithm of the time for a given strength loss at some temperature T

⁹B. A. Proctor, D. R. Oakley, and K. L. Litherland, "Developments in the Assessment and Performance of GRC over 10 years," *Composites* (Butterworth and Company, April 1982).

¹⁰K. L. Litherland, D. R. Oakley, and B. A. Proctor, "The Use of Accelerated Aging Procedures to Predict the Long-Term Strength of GRC Composites," *Cement and Concrete Research*, Vol 11 (Pergamon Press, 1981).

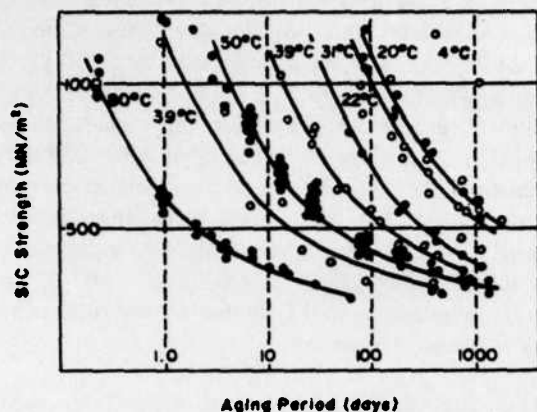


Figure 3. Cem-FIL 2 fiber strengths from SIC tests under accelerated aging conditions (in water at temperature indicated). (From B. A. Proctor, D. R. Oakley, and K. L. Litherland, "Developments in the Assessment and Performance of GRC Over 10 Years," *Composites* [Butterworth and Co., April 1982]. Used with permission.)

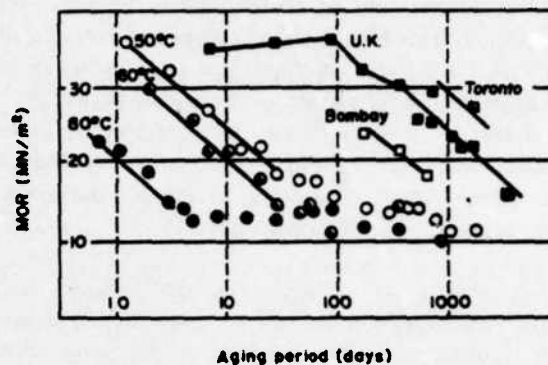
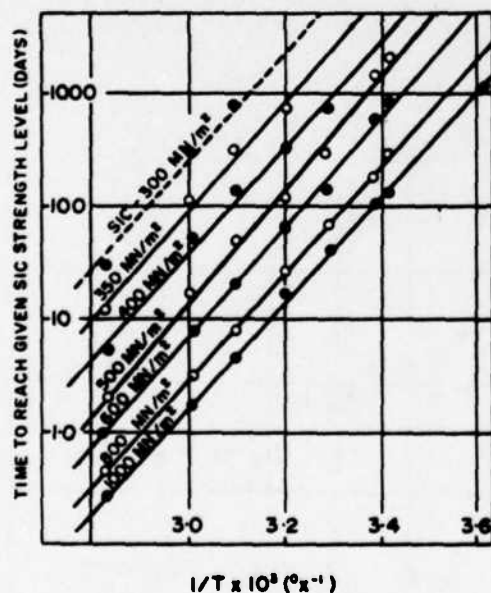
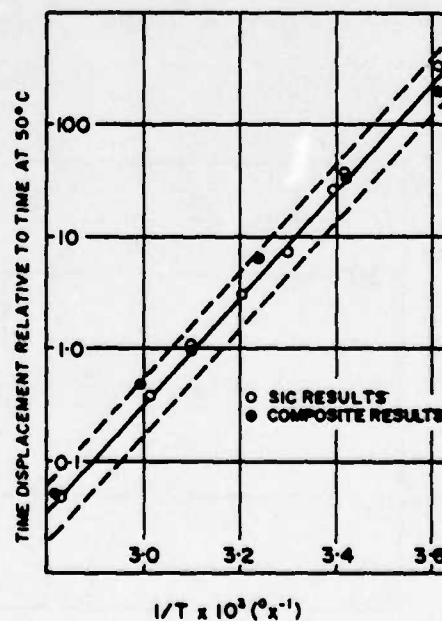


Figure 4. Flexural strengths of GFRG composites after accelerated aging and weathering exposure (5 weight percent Cem-FIL 2 AR-glass fiber). (From B. A. Proctor, D. R. Oakley, and K. L. Litherland, "Development in the Assessment and Performance of GRC Over 10 Years," *Composites* [Butterworth and Co., April 1982]. Used with permission.)



(a)



(b)

Figure 5. SIC specimen reaction time to a given strength. (a) Arrhenius plot; (b) normalized Arrhenius plot. (From K. L. Litherland, D. R. Oakley, and B. A. Proctor, "The Use of Accelerated Aging Procedures to Predict the Long-Term Strength of GRC Composites," *Cement and Concrete Research*, Vol 11 [Pergamon Press, 1981]. Used with permission.)

(relative to the time at some standard temperature) against $1/T$. This effectively combines and averages all the data for different strength levels (given in Figure 5a) into one overall picture of the relative acceleration of strength loss at different temperatures. A more detailed description of this analysis is in "The Use of Accelerated Aging Procedures to Predict the Long-Term Strength of GRC Composites."¹¹

The significance of these tests and analyses is that initially, strength will decrease for a certain period, and then remain essentially constant in the long term. Other experiments have shown that the loss of strength in the falling region was not influenced by cycling between hot and cold, wet and dry, or hot, wet, and freezing conditions, but was governed mostly by time spent at the wet, elevated temperature.¹² Figure 6 shows the change in strength with time for SIC specimens versus actual data for 10 years and the predicted response for 100 years and longer.¹³ The fact that

accelerated aging tests correlate so well with existing natural weathering data provides qualified confidence that GFRC will perform satisfactorily up to 50 years and beyond. It also should be noted that a recent improvement in the AR-glass fiber (now marketed as Cem-FIL 2 and Nippon Electric Glass AR2500H200) has changed the composite's aging characteristics from the standpoint that aging takes place more slowly, although the end results are similar when compared with those of the previous material (Figure 7).¹⁴ These data are from accelerated tests that represent 20 to 30 years of natural weathering.

This discussion has dealt with GFRC; however, the same results may apply to PGFRC. As stated earlier, polymer was added to protect the E-glass from attack by alkali in the cement. However, the long-term results were not as conclusive as originally expected. The U.S. panel manufacturers visited now recommend that AR-glass be used instead of E-glass.

The theory regarding protective mechanisms associated with the addition of a water-dispersed polymer relates to the fact that the space between the fibers in a glass fiber bundle averages about 3 microns, whereas

¹¹ K. L. Litherland, D. R. Oakley, and B. A. Proctor.

¹² A. J. Aindow, D. R. Oakley, and B. A. Proctor, "Comparison of the Weather Behavior of GRC with Predictions Made from Accelerated Aging Tests," *Cement and Concrete Research*, Vol 14, No. 2 (Pergamon Press, March 1984).

¹³ A. J. Aindow, D. R. Oakley, and B. A. Proctor.

¹⁴ B. A. Proctor, D. R. Oakley, and K. L. Litherland.

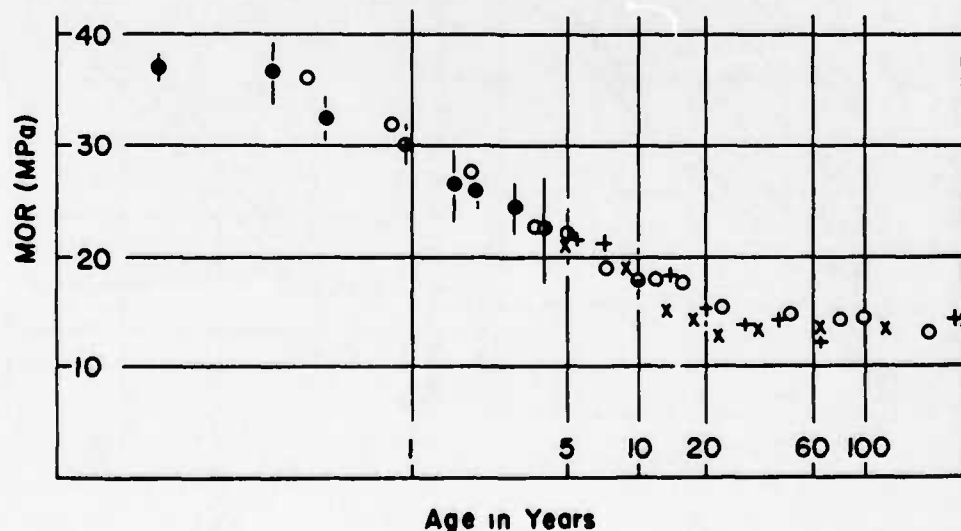


Figure 6. Cem-FIL 2 GFRC strength retention in natural weather, United Kingdom (●), compared with predictions from accelerated-aging tests at 50°C (○), 60°C (+), and 80°C (x). (From A. J. Aindow, D. R. Oakley, and B. A. Proctor, "Comparison of the Weather Behavior of GRC with Predictions Made from Accelerated Aging Tests," *Cement and Concrete Research*, Vol 14, No. 2 [Pergamon Press, March 1984]. Used with permission.)

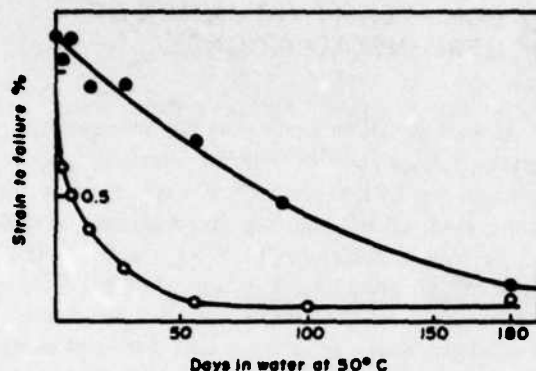


Figure 7. Retention of strain-to-failure in bending for Cem-FIL 1 and Cem-FIL 2 GRC composites (5 weight percent) in accelerated tests of 50°C (○ = Cem-FIL 1 fiber; ● = Cem-FIL 2 fiber). Note: 180 days is equal to about 150 years of natural aging. (From B. A. Proctor, D. R. Oakley, and K. L. Litherland, "Developments in the Assessment and Performance of GRC Over 10 Years," *Composites* [Butterworth and Co., April 1982]. Used with permission.)

the smallest cement particles average about 30 microns.¹⁵ Therefore, the space between the fibers does not fill with cementitious material. Eventually, this space becomes filled with cement hydration products (e.g., calcium hydroxide) which, though not as hard as glass, are suspected of notching the fiber's surface when placed under load. If this happens, the glass, which is very notch-sensitive, would lose considerable tensile strength; this would, in turn, reduce the composite strength. However, when polymer is added to the mix, the particles, being only 0.1 to 1.5 microns in diameter, can fill the interstices between filaments in a glass fiber bundle. This not only prevents the formation of hydration products, but also provides a matrix between the fibers that is soft enough to preclude mechanical degradation under load, assist in the load transfer between fibers, and help protect the fibers from alkali attack. Figure 8 shows results of accelerated-aging bending tests on E-glass GFRG with and without polymer.¹⁶

Figure 9 compares the effect on bending strength of specimens containing E-glass and 15 percent poly-

¹⁵ M. J. N. Jacobs, *FORTON PGRC—A Many-Sided Material* (Department of Material Application Development DSM-Control Laboratory, Geleen, The Netherlands, October 1981).

¹⁶ M. J. N. Jacobs.

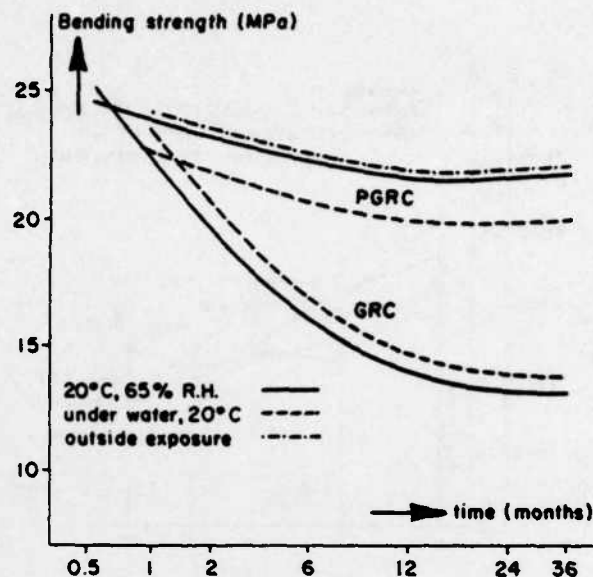


Figure 8. Results of accelerated aging bending test on E-glass mixes with and without polymer. (From M. J. N. Jacobs, *FORTON PGRC—A Many-Sided Material* [Department of Material Application Development DSM-Control Laboratory, Geleen, The Netherlands, October 1981]. Used with permission.)

mer (FORTON) with AR-glass mixes containing no polymer. Whether PGFRC's better performance is a result of the polymer protecting the E-glass or just an improvement in the matrix properties due to the polymer is still a subject of debate. Similar results were obtained for accelerated aged tensile strength and strain at UTS.¹⁷

Other benefits attributed to the use of a polymer include lower water absorption, reduced drying shrinkage and thus less cracking and crazing, higher 28-day MOR, and better overall performance in the aged state. Perhaps the most practical benefit claimed for the PGFRC is the absence of curing requirements.¹⁸

¹⁷ J. Bijen, "Durability of Some Glass Fiber Reinforced Cement Composites," *ACI Journal*, Paper title No. 80-30 (American Concrete Inst., July-August 1983).

¹⁸ J. I. Daniel and M. E. Pecoraro, *Effect of FORTON Polymers on Curing Requirements of AR-Glass Fiber Reinforced Cement Composites* (Construction Technology Laboratories, Portland Cement Association, Skokie, IL, October, 1982); H. P. Ball, Jr., *The Effect of FORTON Compound on GFRG Curing Requirements* (Ball Consulting Ltd., Ambridge, PA).

3 LONG-TERM EVALUATION OF GFRC INSTALLATIONS

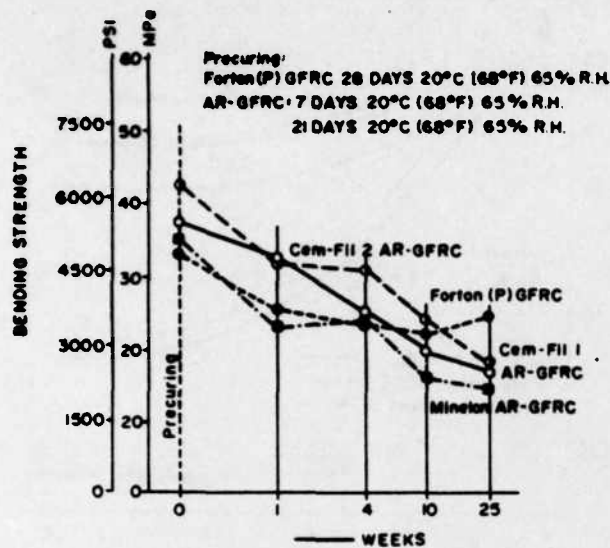


Figure 9. Bending strength development under accelerated aging at 50°C under water. (From J. Bijen, "Durability of Some Glass Fiber Reinforced Cement Composites," *ACI Journal*, Paper Title No. 80-20 [American Concrete Inst., July-August 1983]. Used with permission.)

GFRC design is based on the assumption that the aged MOR does not drop below the 28-day LOP. To obtain this property, it usually is recommended that the material be wet-cured for 7 days. However, tests have shown that by adding 5 volume percent polymer, the requirement can be met without wet-curing. Figure 10 shows the results of curing tests conducted by the Portland Cement Association on AR-glass specimens.¹⁹

The data show that composites containing at least 5.0 percent solids by volume develop 28-day LOP strengths equal to or slightly greater than similar composites containing no polymer and subjected to 7-day moist cure. This result indicates that, for LOP development, the recommended 7-day moist-curing period for AR-GFRC panels can be avoided by adding at least 5.0 percent FORTON polymer solids by volume.

¹⁹ J. I. Daniel and M. E. Pecoraro; H. P. Ball, Jr.

As part of an ongoing program to assess the in-service performance of building materials and components, the BRE studied, from a structural performance aspect, GFRC paneling that had been in service in the United Kingdom for 5 to 7 years.²⁰ The inspections included visual examination to determine the incidence of cracking, movement, water penetration, displacement of sealants, and color and compass orientation of panels. Thirty-five major sites together with 25 smaller sites, some with single-skin cladding, were inspected. Seven housing sites in Scotland with 95,000 m² of single-skin cladding also were inspected. It should be pointed out that none of these installations used the metal stud backup with the highly flexible "L" anchor used in the United States (see Chapter 4). The results showed:²¹

There were no signs of cracking at 10 of the major sites. Of the remainder, there was incipient cracking at two sites, there was cracking of some panels at 10 sites, minor repair of cracking had been carried out at seven sites, major repair or partial replacement had been carried out at five sites, and all the cladding had been replaced at one site.

More cracks in cladding on individual buildings were observed on south- and west-facing panels than on other aspects . . . In some cases joint sealants were partially detached. Bowing of large and small panels was observed at a few sites.

Cracks were observed in single-skin cladding panels at two sites in England, at one of which the panels were located internally. No cracks were observed in single-skin panels in Scotland.

The cracking represented a potential safety hazard at only one site; here remedial action was taken to prevent detachment of cracked parts. Reports were received on practice and experience from Holland, Japan, South Africa and the United States of America, which provide a range of climatic conditions different from those of the United Kingdom.

²⁰ J. F. A. Moore.

²¹ J. F. A. Moore.

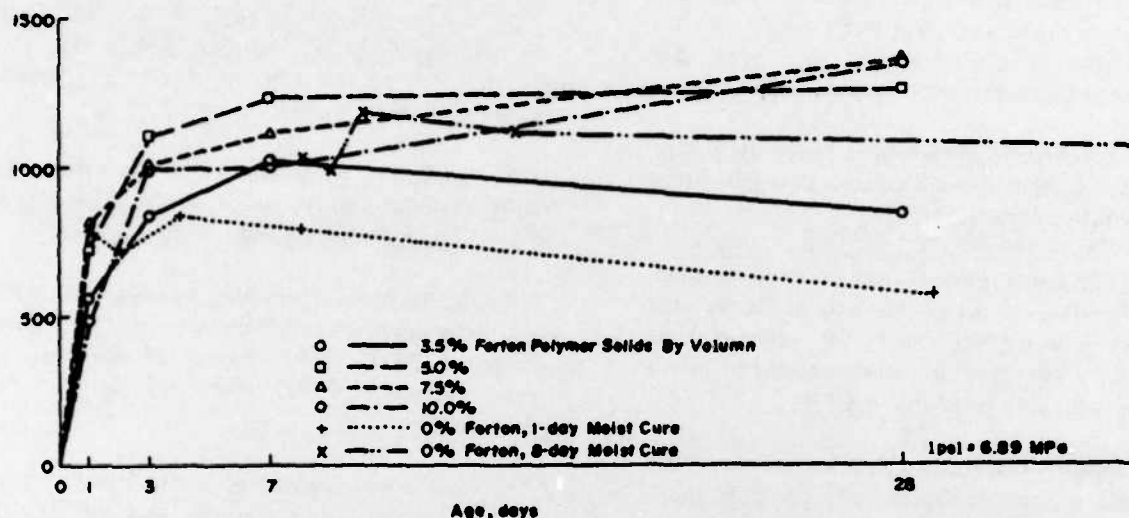


Figure 10. Results of curing tests on AR-glass specimens—LOP versus age. (From J. I. Daniel and M. E. Pecoraro, *Effect of FORTON Polymers on Curing Requirements of AR-Glass Fiber Reinforced Cement Composites* [Construction Technology Laboratories, Portland Cement Association, Skokie, IL, October 1982]. Used with permission.)

In Japan and the United States of America, single-skin cladding predominates. Experience is limited to about 8 years, with no reports of significant cracking. The experience with sandwich panels in Holland and South Africa appears to be similar.

Practice in the design, construction and use of sandwich panels in South Africa appears to be broadly similar to that in the United Kingdom, although skin thicknesses and glass fibre contents may be marginally lower, overall thicknesses seldom exceed 100 mm and panels are generally flat, of limited area and produced by mechanical methods.

Experience of large flat sandwich panels in Holland appears to have been satisfactory. The cement is likely to have properties different from those of the ordinary Portland cement usually used in the United Kingdom.

GFRC cladding panels in service in the United Kingdom show that an unacceptably high proportion of buildings inspected had some cracked panels. Investigations revealed that design procedures have not always adequately taken account of all the relevant factors and uncertainties, and that deficiencies in manufacture and installation have contributed in some cases to poor performance. In particular, the contribution which moisture and thermal effects, and internal

and external restraints, may make to inducing tensile strains in the GFRC have not been recognized sufficiently in relation to its ability to resist cracking.

Some calculations for certain types of plain sandwich panels suggest that allowance for the worst combinations of wind loads, thermal and moisture movements, and internal restraints can only just be accommodated with a suitably factored long-term tensile strength capacity.

The additional considerations posed by a long-term reduction in strain capacity have not always been fully appreciated.

Any additional restraint from connections could easily erode the margin not only in the factored strain capacity but also in the ultimate strain capacity and therefore cause cracking in panels containing even good-quality GFRC.

It appears that cracking in recently installed panels can be explained only by gross shortcomings in restraint or quality of manufacture.

A wide variability in susceptibility of individual panels to cracking would be expected for panels of any age, even if of uniform quality, because the loading and exposure conditions will differ, the restraint imposed by any imperfect fixing is unpredictable and the actual strain capacity, even of good-quality material, is variable and will differ from that assumed in design by an indeterminate amount.

The BRE study has shown that the greatest contributing factor to U.K. failures apparently has been the connections' inability to accommodate the large panel movements due to temperature variations and moisture absorption. The use of sandwich panels together with their shape and size also appears to contribute. Designers apparently underestimated and failed to provide for the magnitude of movement. As described in the next chapter, present U.S. practice avoids this problem.

A similar study of GFRC panels in the United Kingdom and other European countries was carried out by Pilkington Brothers and Fiberglass Limited.²² The investigation involved: the incidence of GFRC architectural cladding in Europe; the causes of these

problems; the analysis of stresses in sandwich panels; and material properties and weathering behavior of GFRC. The study concluded that:

1. Nearly all cracking was caused by the restraint of drying shrinkage of GFRC—possibly accentuated by thermal strain differentials.

2. Most problems resulted from the use of rigid, overtightened, and/or multipoint fixings—or from restraint due to the inherent rigidity of particular shapes of sandwich panels.

3. Significant contributory factors were poor GFRC material quality, poor manufacturing practice, and damage in demolding and handling.

4. The incidence of cracking was significantly higher for large sandwich panels that consist of the sequence composite PBAC (polystyrene bead aggregate concrete)—polystyrene-PBAC cores and also for dark-colored panels.

5. Careful reassessment of previous and new data from actual weathering confirms that the long-term strength behavior of GFRC is closely in line with previously published data. There is no suggestion that cracking was due to unexpected material deterioration or that the strength values recommended for design were incorrect.

The seven U.S. installations visited for this study had no cracks, though one had a considerable amount of minor crazing. All were single-skin panels, primarily with steel stud framing backup. Three failures have been reported (by word of mouth) in the United States; two appeared to be due to faulty manufacturing procedures and the other to building attachments that did not accommodate enough movement by the panels from temperature and moisture migration.

Information from the sources cited in Chapters 2 and 3 was used to develop design criteria that could apply to GFRC used in military construction. These criteria are explained in the appendix.

4 PANEL PRODUCTION AND PRACTICE IN THE UNITED STATES

Five panel manufacturers and a GFRC consultant were visited. Two operate in the northwest, two in

²²*Cem-FH, Information Bulletin, No. 44 (July 1983).*

Central United States, and one in the south central part of the country. All five manufacture panels using AR-glass fibers and two use 5 to 7 volume percent polymer (FORTON). Both silica sand and fine ordinary sand are used in combination with either white or ordinary Portland cement. Manufacturers who do not use a polymer use a sand/cement ratio of 0.20:0.30; those adding a polymer use as high as a 1:1 ratio. The most widely used mix design is reported to be a 0.5 sand/cement ratio with 5 volume percent polymer.

Panels are designed for self-loading only, with no other superimposed structural loads permitted. Wind loads are accounted for, but these are relatively minor when the steel stud frame is used (Figure 11). Studs usually are spaced at 0.61 m. The "L"-shaped connector shown in Figure 12 and described below accommodates the large panel movement due to temperature and moisture absorption. The steel stud frame and "L" connectors have simplified panel design considerably.

All five plants had similar production processes, using what could be called "standard" procedures. All had excellent production facilities, with two able to produce over 322 m² sq ft of panel per work day. All were operated by persons experienced in producing GFRC (5 to 10 years) in particular and concrete in general. All understood the importance of quality control, and each plant had a small laboratory for conducting bending tests, fiber-count tests, and others on a regular schedule. All of the plants are producing panels with the steel stud backing, rather than using built-up ribs (Figure 13) as was the original procedure.

An important recent development, in addition to the use of steel stud framing as backup, was the introduction of the "L"-shaped anchor for attaching the panel to the steel frame. The anchor is a 10-mm round rod, bent into the shape of an "L." One leg is attached to the panel with GFRC before the panel has set up. A bond breaker is used on the rod so the connection can accommodate large movement. The other leg is welded to the steel stud frame using only about 25 mm at the very end of the leg, thus avoiding a rigid attachment and allowing for large movement if necessary. The frame is then attached to the building structural frame, but the panel has been more or less isolated from movement by the building and is free to move on its own.

The hand spray-up method is the predominant one used in manufacturing panels; however, several companies can machine-spray flat and corrugated

sheets. Minor premixing and casting are done when necessary. Each plant has well equipped metal-fabrication and wood-framing shops. Production in all five plants consists of single-skin panels 10 to 13 mm thick with approximately 5 weight percent fiber. Sandwich panels are not a routine production item, being made only for special applications. In general, panels smaller than those ordinarily used in the United Kingdom are used in the United States. Seldom do the U.S. panels exceed 18.6 m² in size. When they are made, sandwich panels are kept flat and less than 5.6 m².

As already stated, two plants cure their panels by adding 5 to 7 volume percent polymer to the mix. The other plants use wet-curing, but only when it is necessary to do so. Otherwise, panels usually are cured by storing outside before shipping. Membrane-curing also is used at times. Because the panels are very lightweight, running 29 to 73 kg/m², shipping costs are low and all of the manufacturers said they could compete by shipping up to 1609 km.

The manufacture of GFRC panels by the companies visited is a very sophisticated operation, comparable to any good precast concrete plant. These manufacturers have developed basic techniques into production procedures that result in a consistently uniform product, high in quality and using to the fullest the great versatility of the material. Figures 14 through 16 are typical examples of GFRC projects in the United States.

5 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on information obtained from the literature, visits to installation sites and manufacturing plants, and interviews with the developers and producers of GFRC.

1. GFRC panels and other products have been widely used throughout the world since 1974.

2. Failures of GFRC panels have occurred mainly in the United Kingdom. The main cause of the failures is attributed to the panel connections' inability to accommodate the large movement associated with temperature and moisture, especially in large profiled sandwich panels.

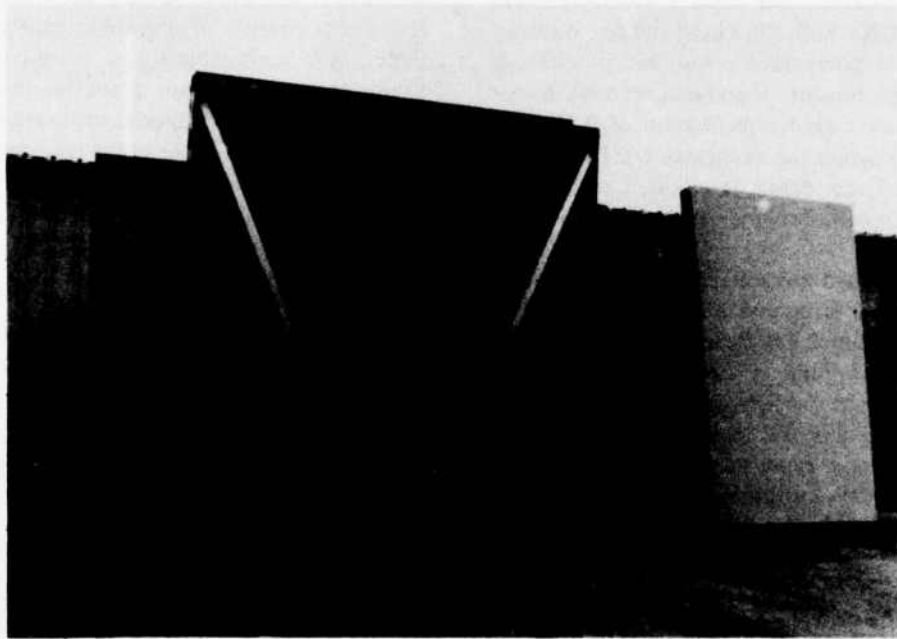


Figure 11. Typical steel stud framing used in the United States.



Figure 12. "L"-shaped anchor used to secure panels to the steel frame.
One leg of the "L" is buried in the panel.

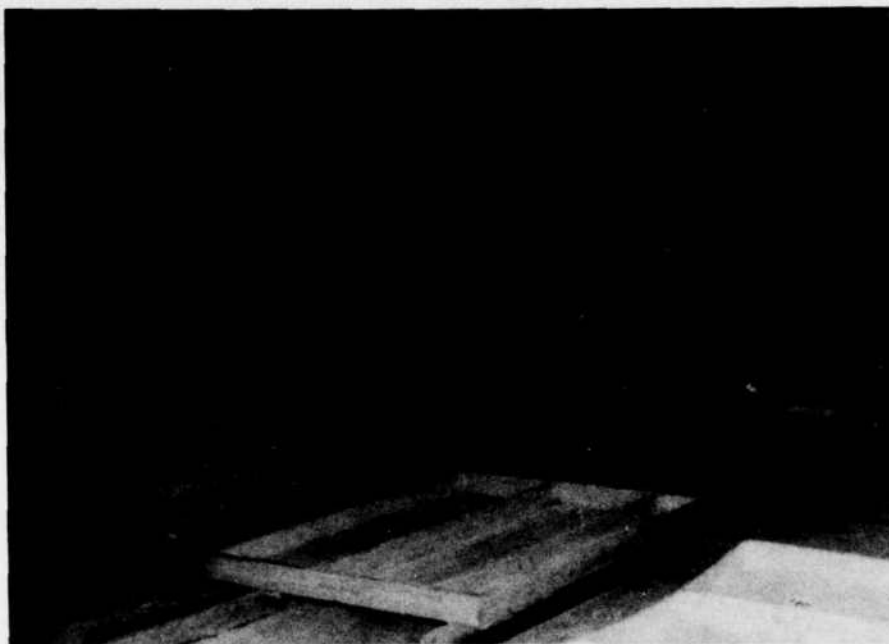


Figure 13. Panels with built-up ribs as stiffeners.



Figure 14. GFRC use on a bank building in Dallas, TX.



Figure 15. Hotel facade in Seattle, WA.



Figure 16. Office building in Nashville, TN.

3. Two AR-glass fibers are available in the United States—the Nippon Electric Glass Company, Ltd., fibers and the Pilkington Brothers, Ltd., fibers. The Pilkington second-generation AR-glass (Cem-FIL 2) has replaced Cem-FIL 1 throughout the United States.

4. Failures due to the material made with Cem-FIL 2 are relatively few and reportedly are a result of poor manufacturing procedures, not inherent material deficiencies. All other failed panels discussed in this report used Cem-FIL 1 fibers.

5. The GFRC panel industry in the United States is thriving and capable of providing a continuous supply at any location in the country.

6. Design and manufacturing procedures are relatively standard throughout the United States.

7. The use of the steel stud frame and "L"-shaped anchors in the United States has overcome the deficiencies in design and construction that contributed to failures in the United Kingdom.

8. The addition of 5 percent or more of a polymer to the GFRC mix eliminates the need for other forms of curing.

9. A reliable accelerated-aging test procedure has been developed to predict long-term durability of GFRC. The procedure has been verified by comparison with existing data.

Based on these conclusions, it is recommended that GFRC panels be used in military construction. Since the material itself is simply a reinforced Portland cement mortar, for which long-term durability and properties are well understood, there should be no problems from a materials standpoint when panels are designed to take into account the long-term properties. Also, it now appears that factors which have contributed to failures are well understood and accounted for in present design and construction practices; the vast number of successful projects worldwide attest to this.

Criteria for using this material are given in the appendix.

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APPENDIX:

RECOMMENDED CRITERIA FOR THE DESIGN, MANUFACTURE, AND ERECTION OF GLASS FIBER REINFORCED CONCRETE (GFRC) PANELS

This information has been compiled based on the durability data examined in this report.

Design

All design, manufacture, testing, storage, transportation, and erection of GFRC panels shall be in accordance with the following two publications of the Prestressed Concrete Institute (PCI), unless specifically waived by the contracting agency: "Recommended Practice for Glass Fiber Reinforced Concrete Panels," *Journal of the Prestressed Concrete Institute*, Vol 26, No. 1 (January-February 1981); and *Guide Specifications for Glass Fiber Reinforced Concrete Panels*, SPC-120-82 (Prestressed Concrete Institute). Local codes will govern when requirements are more stringent than the criteria given by PCI. In any case, the following minimum design criteria must be incorporated.

1. Designs are to consider the dead load of the panel itself (no other loads are to be placed on the panel), wind loads, seismic loads if applicable, loads at connecting points, strains resulting from variations in temperature and moisture content, and strains resulting from curves and returns in the panel.

2. Panels are to be designed primarily as single-skin with minimum thickness 10 mm, maximum size 18 m², and no dimension greater than 6 m. Sandwich panels are to be used only when necessary (e.g., when exterior panels must provide insulation) and shall have a minimum skin thickness of 10 mm and be no larger than 6 m².

3. Panels shall be designed with light-gauge metal stud frame backup. Panels shall be connected to the

metal studs and frame by the "L" anchor or other approved anchor that permits complete movement of the panel independent of the frame. The frame shall be attached to the building structural system following recommended practice. Built-up ribs may be used with special approval.

4. The modulus of rupture value to be used in design shall not exceed the 28-day value of the limit of proportionality. Stresses in the material shall be kept at a level that provides a factor of safety of 2.5 against cracking. Connections of the GFRC panel to the steel stud frame, or if connected directly to the building frame, must account for irreversible strain due to drying shrinkage of 0.05 percent, and for reversible strain of 0.15 percent due to moisture movement in and out of the material. In the absence of other data, the ultimate tensile strain capacity of the material can be assumed to be no less than 300×10^{-6} . Higher values are to be substantiated by test data. In design, a minimum safety factor of 1.8 shall be used with the ultimate strain capacity. Also, in the absence of other data, Young's modulus can be assumed to be approximately 20,000 MPa.

Materials

All concrete materials such as cement, sand, water, coloring, admixtures, sealants, coatings, curing compounds, metals, fabrication, and welding shall be in accordance with Corps of Engineers specifications as given in the *Handbook of Concrete and Cement* (U.S. Army Waterways Experiment Station, 1949), or ASTM specifications if not covered in the handbook. Glass fibers must be made of high-zirconia glass with alkali-resistant properties equal to or greater than Cem-FIL 2 AR-fibers. In general practice, to reduce shrinkage, moisture movement, and creep, panels should be made with a maximum amount of fine aggregate, but in any case the sand/cement ratio is to be no less than 0.25 nor greater than 1.0. All panels are to receive 7 days of moist-curing following production. Membrane-curing or use of a minimum of 5 percent polymer in the mix may be used instead of moist-curing.

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