Glass Fiber Reinforced Concrete Products—

Properties and Applications

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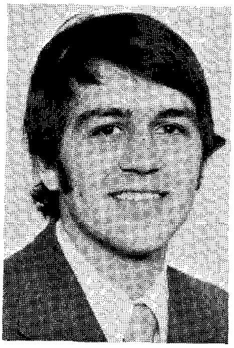

Presents a state-of-the-art report on the production techniques, properties, applications (with design and erection suggestions) and economics of alkali resistant glass fiber reinforced concrete products manufactured by the spray-up process.
The advantages, limitations and cost of the material, especially in regard to producing architectural precast panels, are fully discussed.

Fibers as a reinforcing medium have been used for many centuries. The prime objective of using natural fibers—such as straw in brickmaking—has always been to alter and improve the properties of the brittle matrix.

The largest commercial use of fibers has been in the asbestos cement industry as it has developed for the last 60 years. Asbestos is also a natural fiber and the search for man-made fibers whose properties can be controlled and used for the reinforcement of matrices has been continuing since the beginning of the century.

The potential of using glass fiber reinforced cement (GRC) systems* was recognized in the very early days of glass reinforced plastic development; and, in fact, the Russians started as early as 1941 to develop methods of using glass fiber to reinforce concrete.

The definitive work on Russian experience was published in 1964; this was all based on alumina cements and not portland cement because the fibers then available were not able to withstand the alkalinity generated in the cement paste.

The major breakthrough in the development of GRC systems took place when Dr. A. J. Majumdar of the Building Research Establishment in England conceived a glass composition which gave the fibers a far greater resistance to the alkali attack of portland cements.

Pilkington Brothers Limited of England took a license for this glass and their research and development led to a commercially available glass fiber called Cem-Fil. Processes for producing GRC as well as an understanding of the behavior of the material have been under development now for 8 years.†

References 1 through 12 give the most significant work done so far on GRC and its related products.

As a further step forward in the development of this new material in the United States, the Prestressed Concrete Institute has recently established a special committee whose objective is "to further usage of fiber reinforced precast panels through the development of production information, design criteria and promotional activities."

The purpose of this paper is to present a state-of-the-art report on spray-up GRC products. The discussion is restricted to GRC manufactured by the spray-up process (described later). The paper does not cover the use of glass fibers in more *conventional* concrete mixes or its use in surface bonding materials.

Both these materials are substantially different from spray-up GRC both in properties and the role played by the glass fibers in the composite and their construction is beyond the scope of this particular paper.

What is GRC?

GRC is a composite material made up of a matrix of cement (or cement plus sand) and water, reinforced with glass fibers.

It is important to appreciate that the material is a total composite in that the reinforcing elements are distributed throughout the matrix—unlike reinforced concrete where the reinforcing steel is placed in particular zones.

Manufacture of GRC

Currently, the spray-up process is the most widely used method of producing GRC products. In this paper, it will be assumed that the products described are manufactured using this process.

Nevertheless, at the end of this section brief mention will be made of some other manufacturing techniques.

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*The proprietary term "glass fiber reinforced *cement*" (GRC) has been in long-standing usage. In this article the more generic engineering term "glass fiber reinforced *concrete*" is intended.

†In 1975, Cem-Fil Corporation, a joint venture of Ferro Corporation (USA) and Pilkington Brothers Limited, was formed to market alkali resistant glass fiber and the technology of producing glass fiber reinforced concrete products in the United States.

Pilkington Brothers Limited has granted licenses to produce their patented glass formulations for alkali resistant glass fiber to Ferro Corporation and Owens Corning Fiberglass Corporation in the United States and Asahi Glass Company in Japan.

Spray-up process

In the spray-up process a specially designed hand-held gun is used which sprays a cement slurry onto the given form and at the same time chops a continuous glass roving into predetermined lengths which are sprayed at random in the plane of the surface.

The advantages of this process are that the equipment is relatively inexpensive and products of almost any shape can be produced.

The unit shown in Fig. 1 has been specifically designed for manual spraying of GRC. It comprises a mixer which feeds slurry directly to a pump which in turn transports the slurry to the spray nozzle. Coupled to the nozzle is a glass fiber chopping gun where the continuous roving (Fig. 2) is converted to the required strand length (usually 1½ in.).

Both the slurry delivery rate and the glass delivery rate are adjustable to enable the correct glass fiber content to be achieved which is typically set at 5 percent of the total composite weight.

The spray rate is usually set to deliver between 24 to 30 lbs per minute of wet composite. Much faster rates of spray make it difficult for the operator to control thickness. Actual daily output will vary considerably depending on the product complexity, amount of repetition, and other factors, but for a custom panel operation it should be possible to produce over 4000 lbs of GRC per 8-hour day from one spray-up unit.

For most manual operations one spray-up unit will require a four-man team (comprising one sprayer and three others to handle mix preparation, mold preparation, product demold, etc.) The capital requirement is about $10,000 for a spray unit.

The very minimum factory space needed for correct and efficient production from one spray-up unit is about 10,000 sq ft; this includes areas for spraying, mold preparation and de-molding, product curing, raw material storage, and a quality control section.

Proper curing of GRC is vitally im-

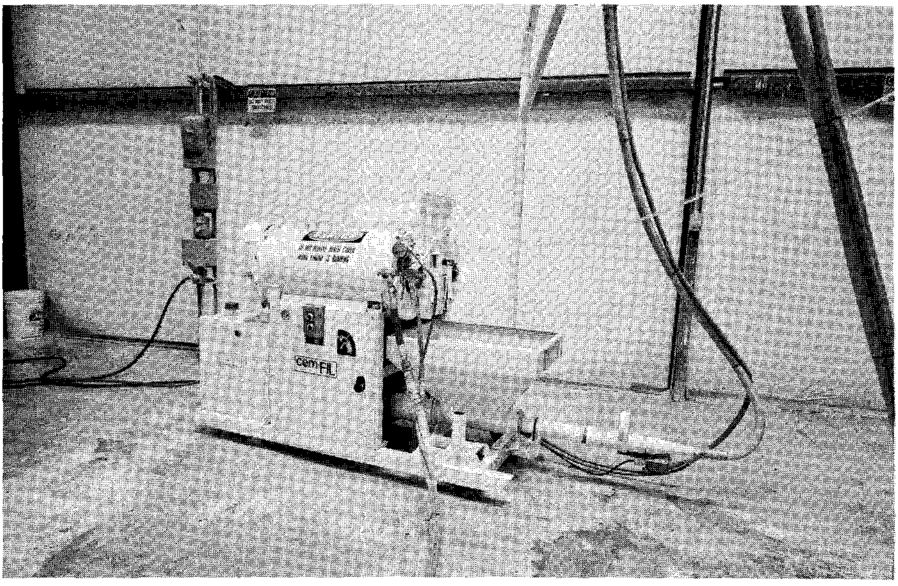


Fig. 1. Spray-up unit for manufacturing GRC.

portant and sufficient space must be available for holding at least 7 days production under high humidity and room temperature conditions.

The use of steam curing is being investigated to reduce this time.

Strict quality control is also essential and usually comprises:

1. Regular checks on material spray rates.
2. Thickness of product is checked during spraying to insure absence of "thin spots."
3. Test boards are made periodically during production from which glass fiber content is checked. Coupons cut from these test boards can be used for strength testing.

Where sufficient product volume and standardization exists it is possible to automate the spray-up process. There are many ways of achieving the desired degree of automation but one well-developed process involves the spray deposition of a flat sheet on to a vacuum dewatering bed. The slurry

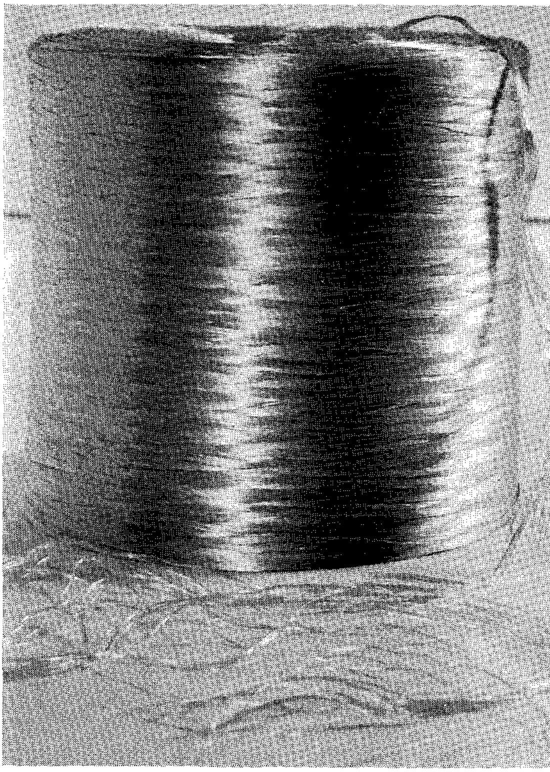


Fig. 2. Glass fiber roving.

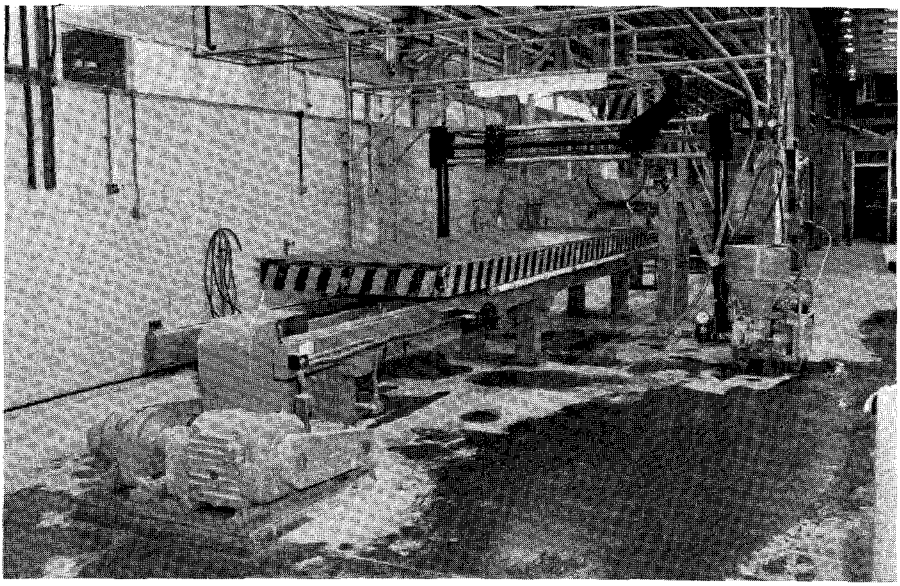


Fig. 3. Semi-automatic spray dewatering plant for flat sheet manufacture.

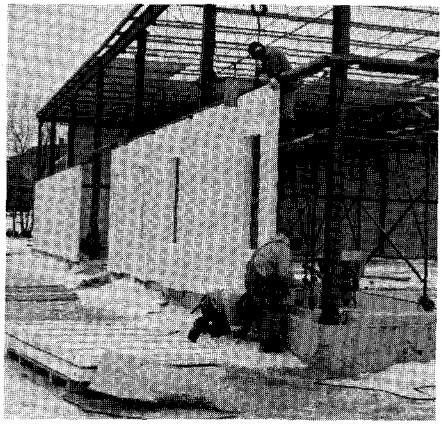


Fig. 4. 5 x 10-ft insulated panels used to construct walls and roof of a manufacturing warehouse and office building in Bridgeport, Connecticut.

used in such a process has an excess water content. The excess water is withdrawn from the deposited flat sheet through the dewatering bed by a suction-vacuum process.

The resulting flat sheet has sufficient integrity to enable it to be molded, while in the "green" state, to produce the required product shape. The automated spray-dewatering process usually provides material with maximum density, the best mechanical properties and the most consistent quality.

The wide range of possibilities for automated spray-up plant makes it impossible to give meaningful representative data on capital cost and output capacity; but the simplest auto spray-dewatering plant, as shown in Fig. 3, would cost around $70,000.

Other manufacturing processes

Although production processes based on the spray method are almost universally used, other methods are under development. It is not possible in this paper to go into any detail because these processes are still under development and as yet some way from being proven, or they are subject to patent applications.

Fig. 5. 30-in. diameter GRC concrete pipes manufactured in England using centrifugal spinning process.

In the United States, Maso-Therm Corp. of Bridgeport, Connecticut, has developed a continuous process for manufacturing GRC panels in which the GRC totally encapsulates a polyurethane core. Fig. 4 shows one of the first projects to use these panels.

Amey Roadstone Corporation in England has developed a centrifugal spinning process for the manufacture of GRC pipes (Fig. 5) which they have just put into production. Initially, their pipes will be confined to low pressure, sewerage and drainage applications; but the process may lend itself in the future to the production of pressure pipes and other tubular products.

Several other companies are investigating processes that use premixed fibers and slurry which can be cast, pressed, extruded or processed on modified asbestos cement machinery.

So far it has not been possible to produce premixed GRC that matches sprayed GRC either in mechanical properties or consistency; but a most promising process, which is based on a modified extrusion concept, is being developed in England by Banbury Buildings Limited.

Undoubtedly, other processes will come into use; but at the moment, almost all commercial application and much of the technical data relates to the spray-up process and the remainder of this paper will deal exclusively with this process.

Mechanical Properties of GRC

All the test data given in this paper has been developed by Pilkington Brothers Limited and the Building Research Establishment in England. It is based on composite material comprising 5 percent by weight of 1½-in. chopped strands of Cem-Fil alkali resistant glass fiber and neat portland cement paste with a water-cement ratio of 0.28 to 0.33. Except where specifically stated the test data relates to material tested at 28 days old.

The test material was manufactured by the spray-dewatering process which produces a composite with fibers that are distributed in a two-dimensional array in the plane of the board. The test specimens were nominally 6 x 2 x ⅜ in.

Some reference, however, will be made to the properties of non-dewatered material and the effect of the addition of sand in the composite.

Stress-strain behavior of GRC

Fig. 6 shows a detailed tensile stress-strain curve giving the four regions that the material passes through before failure. In Region I the material behaves elastically, with Young's

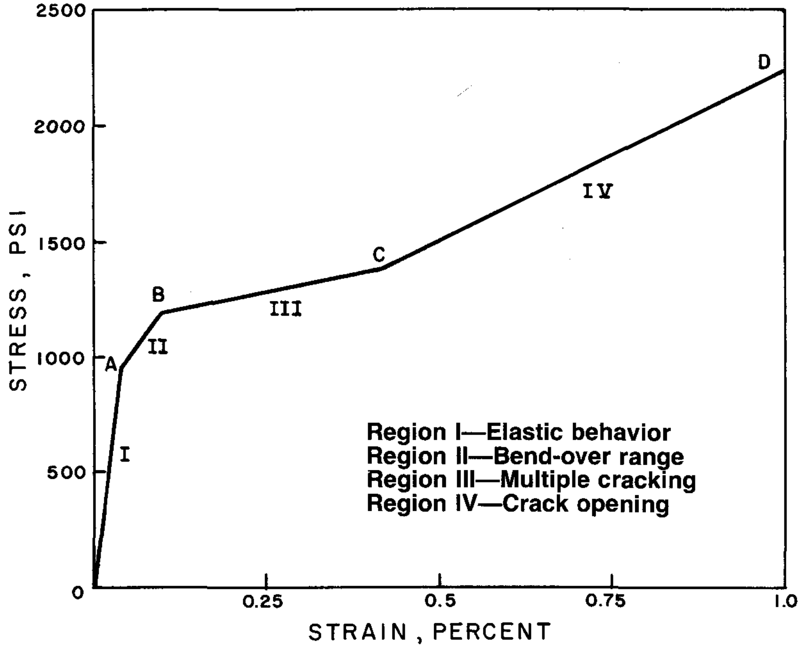


Fig. 6. Stress-strain behavior of GRC in direct tension.

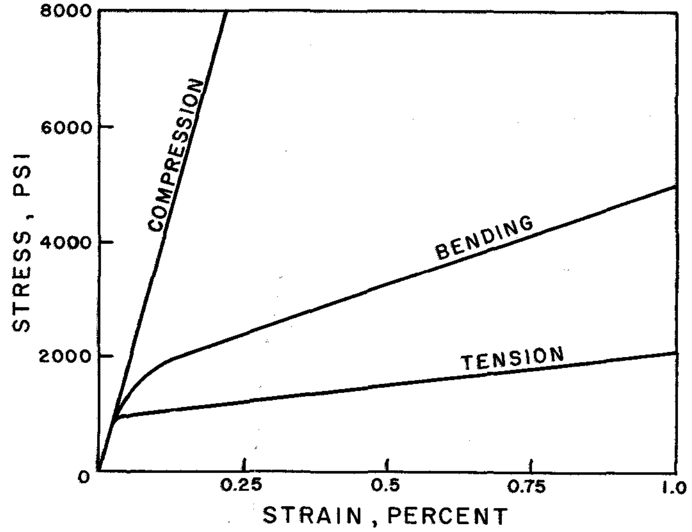


Fig. 7. General stress-strain behavior of GRC subject to compression, bending and tension.

modulus of elasticity given by the mixture law:

$$E_c = E_f V_f + E_m V_m$$

Region II (A-B) is a transition zone where microcracking starts. Point A is usually referred to as the Bend-over Point (BOP). Region III (B-C) is the region in which multiple cracking takes place. At Point C, crack development has been completed and the specimen is covered with fine transverse cracks.

Finally, Region IV corresponds to crack opening with the fibers bridging the cracks. The final failure is initiated by a combination of fiber pull-out and fiber breakage, the ultimate tensile strength (UTS) being defined by Point D on the curve.

Fig. 7 shows representative stress-strain behavior of GRC in direct tension, bending, and compression.

In bending, the material passes through the same four stages as described above for the tensile test. The principal difference is that departure from linearity, or the limit of proportionality (LOP), and the ultimate failure point, or modulus of rupture (MOR) both occur at higher stress levels than the BOP and UTS in the tensile test. Theory predicts that the MOR should be about two and one-half times UTS and this relation has been verified by the test results.

Shear strength

Because GRC components made by the spray-up method have the fibers randomly distributed in the plane of the section, shear values therefore vary with the type of load application.

(a) *Inter-laminar shear*
The fibers play no part in resisting this shear, the value of shear strength is therefore that of the matrix and is about 300 psi.

(b) *In-plane shear*
Shear is resisted by the matrix and the components of the fibers at right angles to the line of load. The value is about 1200 psi.

(c) *Punch-through shear*
In punch-through shear the fibers are fully utilized and the

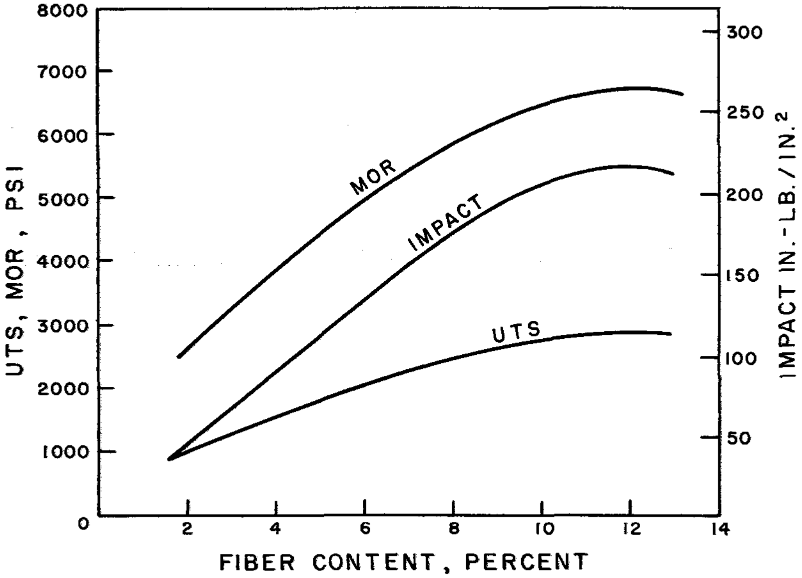


Fig. 8. Effect of fiber content on modulus of rupture (MOR), ultimate tensile strength (UTS), and impact strength of GRC.

value is therefore fiber-controlled. It has been measured at about 5100 psi.

Impact strength

The impact strength of GRC has been measured using the Izod test and values around 120 in.-lb/in.^{2} are typical. As a point of reference, asbestos cement is typically around 25 in.-lb/in.^{2}.

In addition to having much higher impact resistance, GRC has a completely different failure characteristic than either asbestos cement or concrete. Typically, asbestos cement and concrete, being brittle materials, fail in impact by cracking or shattering; GRC on the other hand exhibits a pseudo-ductile characteristic and damage due to impact is usually confined to the area of impact without any evidence of cracks propagating beyond this area.

The high work to failure characteristic of GRC has clear benefits of abuse resistance, particularly where a product may be handled many times before installation.

Effect of various parameters on GRC properties

The principal determinants of the properties of GRC are fiber content, composite density, inert filler content (e.g., sand), fiber orientation, and condition of cure. Other parameters, such as water-cement ratio and degree of compaction, have an indirect effect only because they affect density.

Fiber content primarily affects UTS, MOR, and impact strength; and the relation with these properties is shown in Fig. 8. The leveling off of the strength curves is caused by the fact that the higher fiber contents tend to entrap air into the composite and thus reduce density.

Composite density affects matrix dependent properties such as LOP, BOP, and Young's modulus, the higher the density the higher the property. Fig. 9 shows a typical density effect on Young's modulus. Fiber

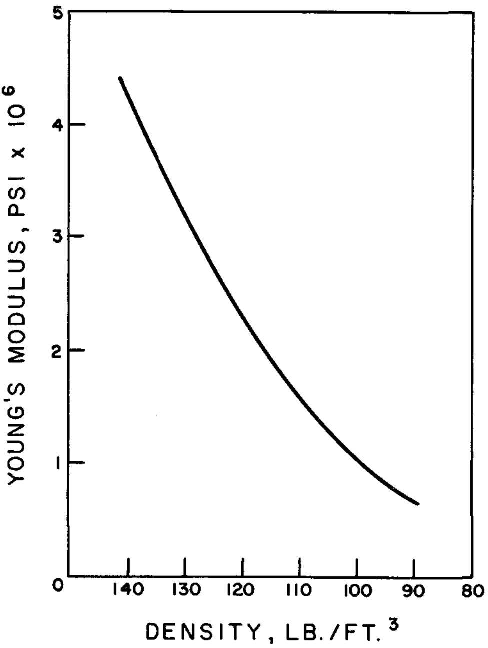


Fig. 9. Effect of density on Young's modulus of elasticity of GRC.

content has little effect on Young's modulus because of the low percentage of fiber used in composites.

Low density also reduces MOR and UTS because at lower densities more air is entrained in the concrete which has the effect of reducing the bond between the fibers and the concrete.

The lower density of non-dewatered material as compared with dewatered material is the primary reason for the difference in the properties of these two composites as shown in Table 1.

Inadequate cure usually means that the concrete is not fully hydrated and so a poor bond develops between the concrete and the fibers. This leads to low MOR, UTS, and impact strength. It will also mean that the matrix dependent properties, such as LOP and Young's modulus, will be low.

GRC based on neat cement paste exhibits fairly high shrinkage. Ultimate initial drying shrinkage can be up to 0.3 percent at 122 F and 30 percent relative humidity. This shrinkage can be reduced by incorporating an inert filler such as silica sand. Fig. 10 shows the relation between sand content and shrinkage.

Although the incorporation of sand benefits shrinkage there is an increasing loss in mechanical properties with increasing sand content as shown in Fig. 11. Point A in Fig. 11 is usually taken as the maximum desirable sand content.

Long-term properties

Many properties of GRC change with time depending on environmental conditions. In the context of this review paper it is not possible to discuss durability in detail. This topic is well covered in Reference 12, and Table 2 summarizes the results of the durability testing program carried out

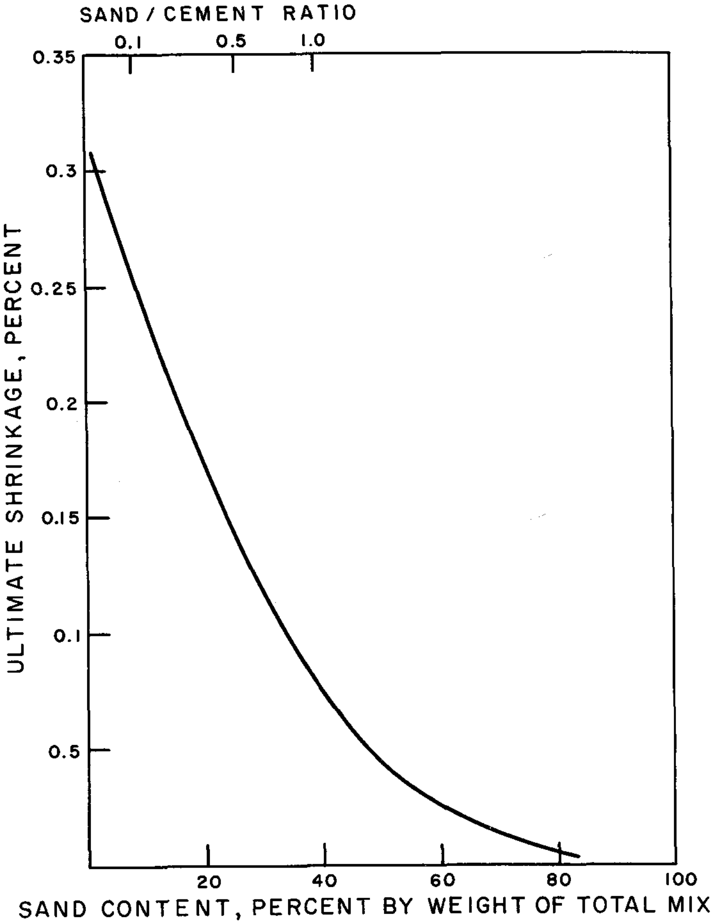


Fig. 10. Ultimate shrinkage at 120 F against sand content for spray-dewatered GRC.

Table 1. Typical properties of GRC products at 28 days.

Properties	Spray-Up	Spray-Up Dewatered
Limit of Proportionality (psi)	1000-1600	1450-2300
Modulus of Rupture (psi)	3000-4000	4000-6000
Ultimate Tensile Strength (psi)	1150-1600	1450-2500
Impact Strength (in.-lb./in.^{2})	57- 143	85- 170
Compressive Strength (psi)	7300-11400	8700-14500
Young's Modulus (psi)	1.5-3x10^6	2.2-3.6x10^6

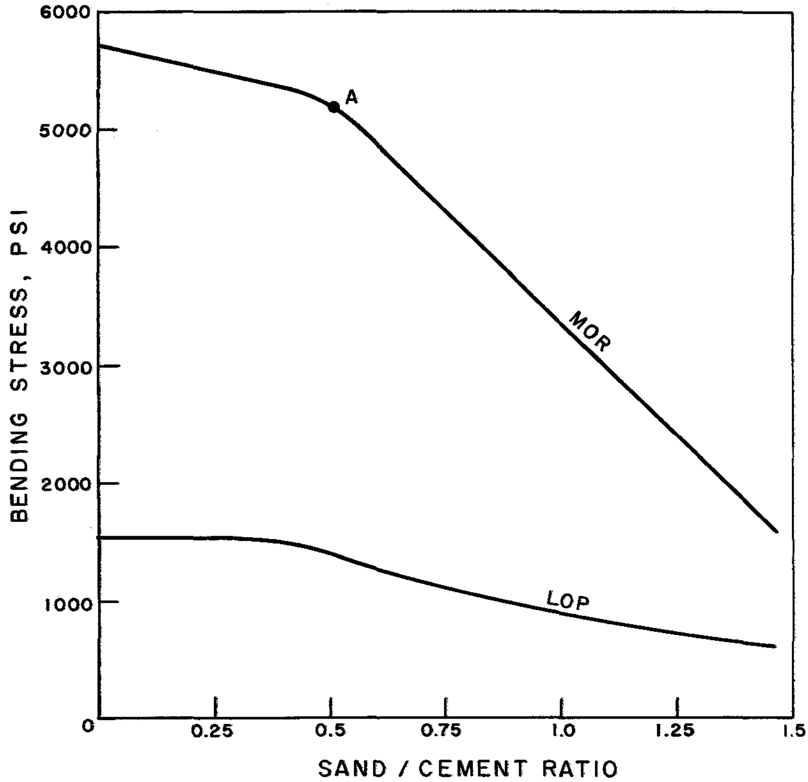


Fig. 11. Effect of sand additions on modulus of rupture (MOR) and limit of proportionality (LOP) on GRC.

Table 2. Strength properties of spray-dewatered GRC at various ages using 5 percent glass fiber (BRE data).

Properties	Total Range for Air and Water Storage Conditions at 28 Days	1 Year			5 Years			20 Years (estimated)	
		Air*	Water**	Weathering	Air*	Water**	Weathering	Air*	Water**
Bending MOR (psi)	5075-7250	5075-5800	3200-3600	4350-5200	4350-5075	3050-3600	3050-3350	3775-4900	2900-3000
LOP (psi)	2000-2550	1300-1900	2300-2800	2000-2500	1450-1750	2300-2800	2175-2610	1200-1450	2300-2610
Tensile UTS (psi)	2000-2550	2000-2300	1300-1750	1600-2000	1900-2175	1300-1750	1000-1200	1750-2175	1200-1600
BOP (psi)	1300-1450	1000-1200	1300-1600	1300-1450	1000-1200	1000-1300	1000-1200	1000-1200	1200-1600
Young's Modulus (psi x 10^6)	2.9-3.6	2.9-3.6	4.0-5.0	2.9-3.6	2.9-3.6	4.0-5.0	3.6-4.6	2.9-3.6	4.0-5.0
Impact Strength (Izod) (in.-lb/in.^{2})	85-155	90-125	40-50	65-80	90-105	20-30	20-35	70-100	20-35

*At 40 percent relative humidity and 68 F.
**At 64 to 68 F.

Notation:
MOR -- Modulus of rupture.
LOP -- Limit of proportionality.
UTS -- Ultimate tensile strength.
BOP -- Bend-over point.

by Pilkington Brothers Limited and the Building Research Establishment over the past 7 years.

The weathering program is continuing in Great Britain; and in addition, weathering sites have been established in several other countries, including Canada, Nigeria, India and Australia, which is providing durability data under a wide variety of different climatic conditions.

Applications of GRC

Although GRC is a relatively new construction material, it has already been used fairly extensively. Many applications of the material are either in existence or are under development.

The predominant initial use of GRC in most countries has been in architectural panels and Figs. 12 and 13 show two of the most ambitious so far. The advantages GRC offers in this type of use include:

(a) Very few restrictions on shape or size of the product (the

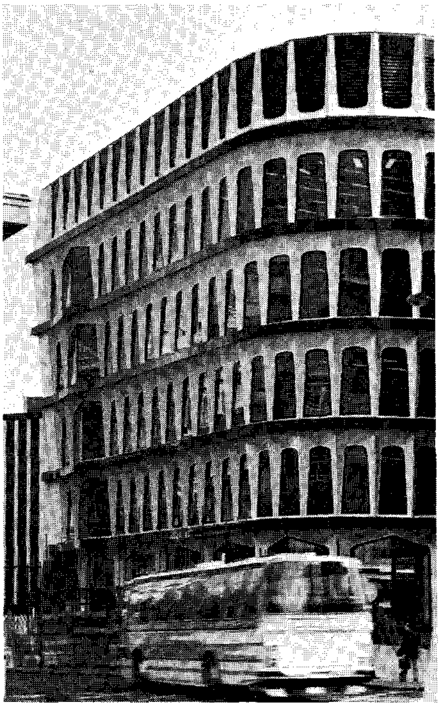


Fig. 12. The new Credit Lyonnais building in London, the first building of its kind in the world is clad internally and externally with sculptured, lightweight GRC.

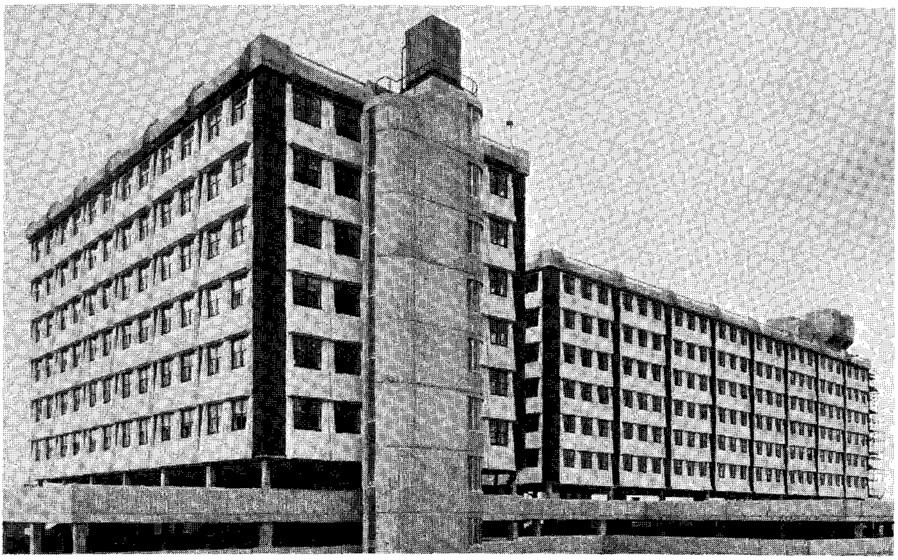


Fig. 13. Double skin window and mullion panels on office block development at Kingston on Thames, England.

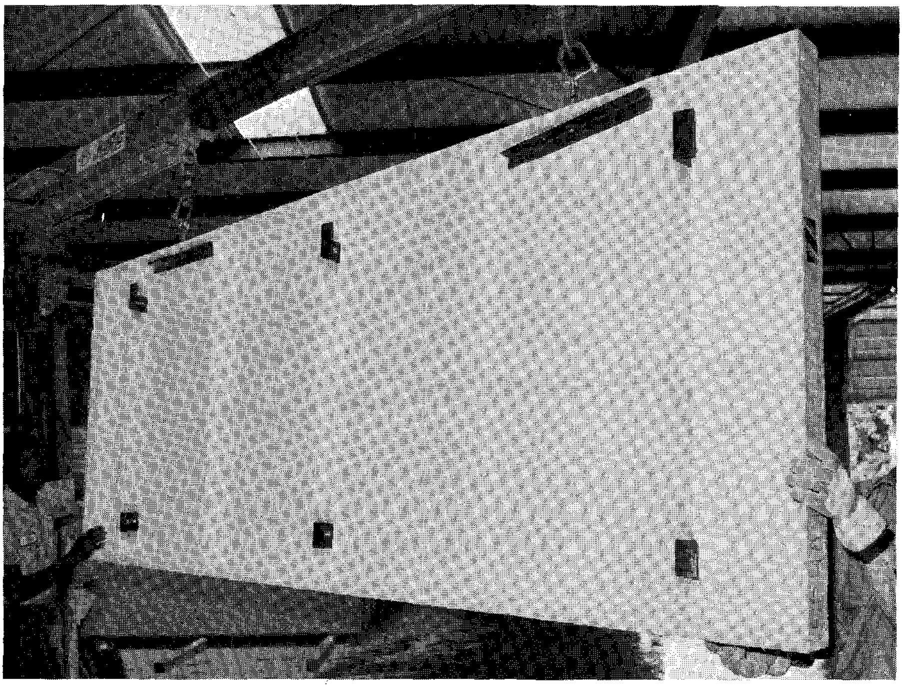


Fig. 14. Ribbing detail for 10 x 4-ft panel shown in Fig. 20.

largest panels manufactured so far are the ground floor units on the Credit Lyonnais building, measuring approximately 24 x 10 ft).

(b) The product's high impact strength provides resistance to damage during handling and erection.

(c) The product being non-combustible, it does not contribute to the fire load of the building and further it is possible to design panels with over 2 hours fire resistance.

(d) The panels are relatively lightweight, particularly when compared with concrete (typically between one-quarter to one-tenth the weight).

(e) A wide range of surface finishes are possible, including as-molded exposed aggregate, and as-molded cement color with plain, textured, or featured finishes.

Two basic approaches are possible in the design of GRC panels, namely, single skin and sandwich construction. Typically, single skin panels are nominally ⅜ in. thick, but design considerations may require extra thickness or the incorporation of stiffening ribs in the panel. These are usually manufactured by over-spraying lost rib formers located in the appropriate places on the back of the panel while it is still "green."

Fig. 14 shows the ribbing on the back of a 10 x 4-ft fascia panel in which the horizontal rib was formed by over-spraying a strip of polystyrene foam. The vertical ribs were formed by spraying against removable steel formers which were fastened to the edges of the mold.

Sandwich panels usually comprise two skins of GRC, ¼ or ⅜ in. thick,

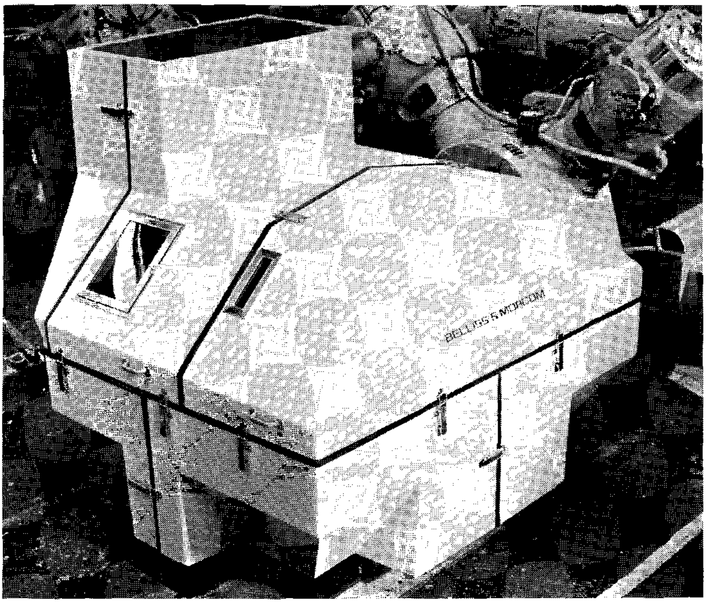


Fig. 15. Acoustic enclosure for compressors. Units measure 6 x 4 x 6 ft and are constructed in ⅜ in. GRC with lining of 1 in. of mineral wool.

separated by a lightweight core. By the appropriate choice of core material and its thickness, almost any desired U-value and fire rating can be achieved. Core materials used in such panels require a minimum shear strength of 35 psi in order to be capable of resisting the transverse shear forces which can be developed in such panels. Suitable core materials are foams of polystyrene and polyurethane and lightweight concretes, particularly polystyrene bead concrete.

Where a sandwich panel is designed with an impermeable finish (e.g., polyurethane paint) under certain conditions, particularly low external temperatures and high humidity inside the building, there is a danger of water vapor condensing in the core material. Because of the impermeable finish the core cannot dry out and water build-up can occur. The possible likelihood of this occurring should be checked and if an impermeable finish cannot be avoided, then a vapor check should be applied to the inside surface.

The fastening of GRC panels presents no unusual features and many of the cast-in fasteners used with concrete panels are suitable for use with GRC panels. As well as cast-in fasteners, bolts through flanges in the panel or through the face of the panel can be used; particularly these methods are often used with single skin panels.

The main considerations required of the design of the fastening of GRC panels are that (1) the main support should be at the bottom of panel so that the panel is put into compression under its own weight and (2) the fastening system must allow movement of the panels and the main structure without causing localized over-stressing.

Such movements can be caused by changes in moisture and temperature, and settling of the structural frame; and they are usually allowed for by using slotted and/or oversize holes in fixing brackets and other fixtures.

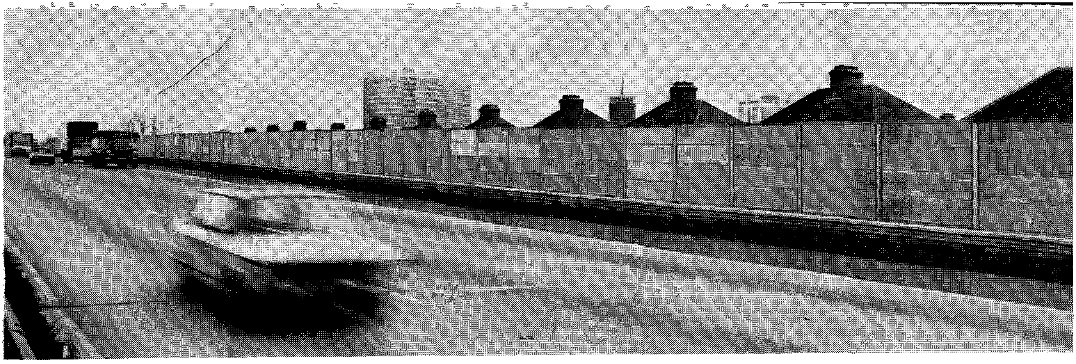


Fig. 16. Highway noise barrier constructed on M4 highway, London, England. System comprises steel posts and ⅜ in. thick GRC panels 2 x 8 ft.

Localized crushing of the GRC by the fasteners should also be avoided by use of large washers or compressible washers.

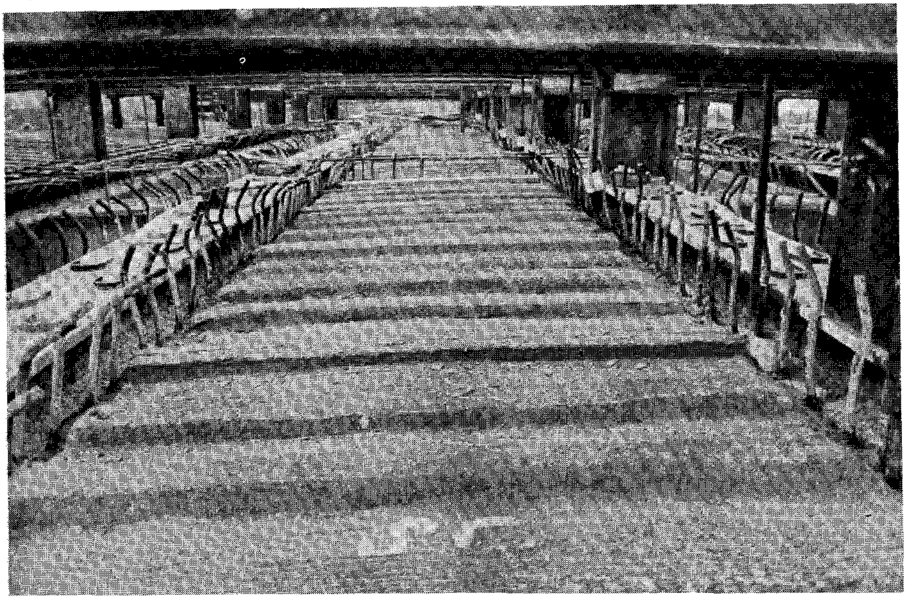
Jointing between panels also presents no unusual features in that butt joints with caulking, gaskets, and drain joints are all possible, and the principles observed with precast concrete are applicable to GRC.

Although architectural panels is the predominant application at the moment, GRC has many other uses. Figs. 15 and 16 show two applications where GRC has been used for acoustic control. GRC follows the accepted mass law for sound reduction and so its relatively high density (125 lbs per cu ft) offers good attenuation characteristics.

A ⅜-in. sheet of GRC at 4 lbs per sq ft yields a sound reduction index of 22dB at 350 Hz rising to 39 dB at 4000 Hz.

The use of GRC formwork for concrete is an application to which the material is well suited. Being cement based it is compatible with the concrete and because it is strong in thin section, non-rotting, and can be pro-

Fig. 17. Permanent GRC bridge deck formwork for road bridge.



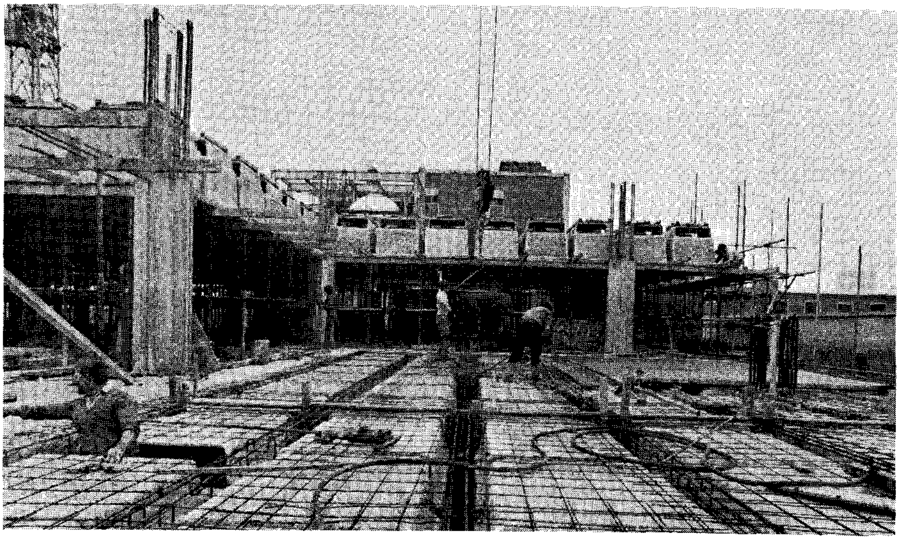


Fig. 18. Permanent GRC forms for waffle floors in Trumans Brewery, London, England.

duced in a variety of shapes and textures, it is most often used as lost or permanent formwork, although with a suitable surface sealant and mold release agent it has been used for reusable formwork.

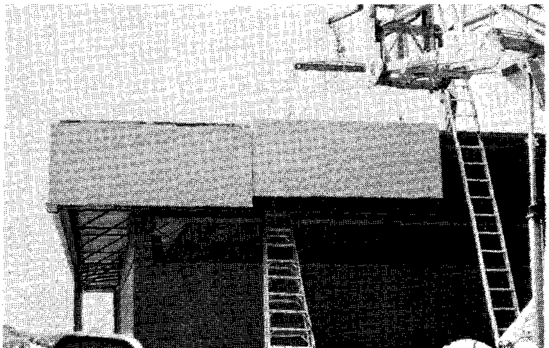
An added benefit of GRC permanent forms is that they can substantially upgrade the fire performance of the concrete structure. Tests in England on GRC column forms showed that a column cast in a permanent GRC form had fire rating almost one hour longer than a column of exactly similar overall dimensions and cover to the reinforcement steel but cast in a removable timber form.

Fig. 17 shows GRC panels being installed as permanent formwork for a road bridge deck. The bridge spanned a river which made it difficult to provide support for removable formwork and permanent GRC formwork proved to be the most cost effective solution. The unsupported span was 4 ft 6 in., the load due to wet concrete and live loads was taken as being 140 lbs per sq ft and the deflection limitation was $\frac{1}{75}$ times the span. The GRC panel used was $\frac{3}{8}$ in. thick with 2 x 3-in. ribs at 18-in. centers.

Fig. 18 shows GRC waffle pans which were used to form the five floors of a brewery building in London. Each of the 5500 units required for the job was 4.75 x 4.75 x 3.75 ft with $\frac{1}{2}$-in. wall thickness and weighed 396 lbs.

Most of the commercial applications of GRC shown up to now have occurred in Great Britain. However, in the last few years some noteworthy structures have been built in the United States using GRC panels (see Figs. 19 through 28).

Fig. 19. Single skin aggregate faced panels on Marshall Street Educational Center, Hagerstown, Maryland. (Courtesy: Cem-Fil Corporation.)



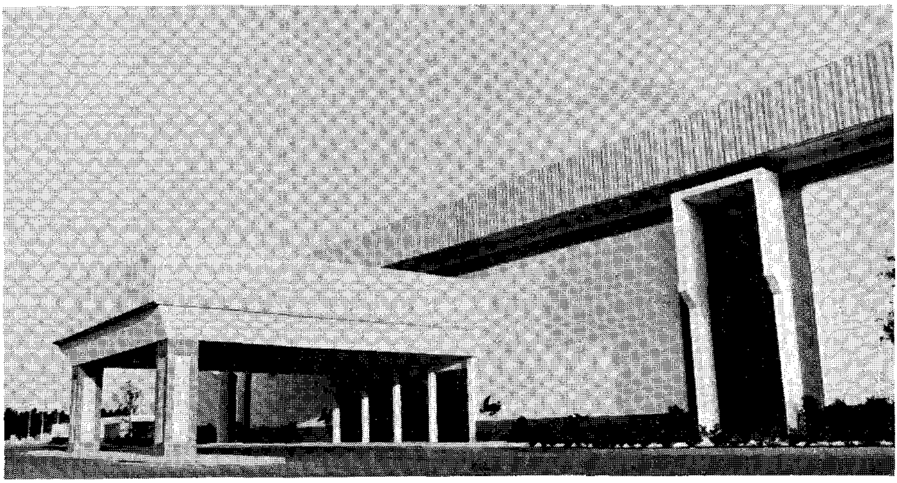


Fig. 20. Single skin panels in buff concrete on Ivey's Store, Volusia Mall, Daytona, Florida. (Courtesy: Lake Manufacturing Company.)

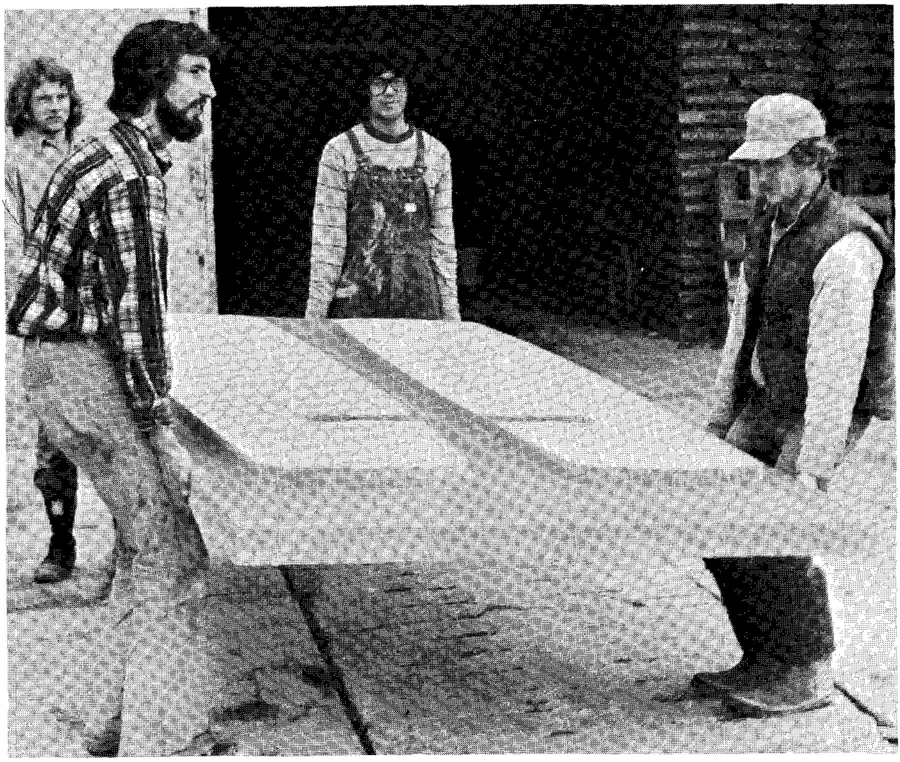


Fig. 21. A fascia panel used at the U.S. Post Office, Ketchikan, Alaska, weighs only 450 lb. (Courtesy: Olympian Stone Company.)

Fig. 22. Fascia panels are lifted into place on to wood framing at U.S. Post Office construction site. (Courtesy: Olympian Stone Company.)

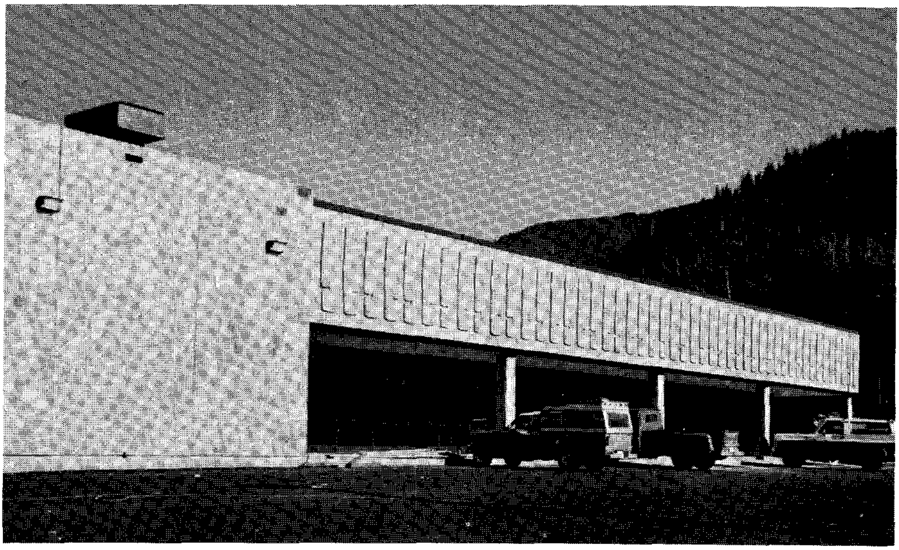


Fig. 23. Single skin Cem-Lite panels with raised aggregate finish on completed Ketchikan Post Office. (Courtesy: Olympian Stone Company.)

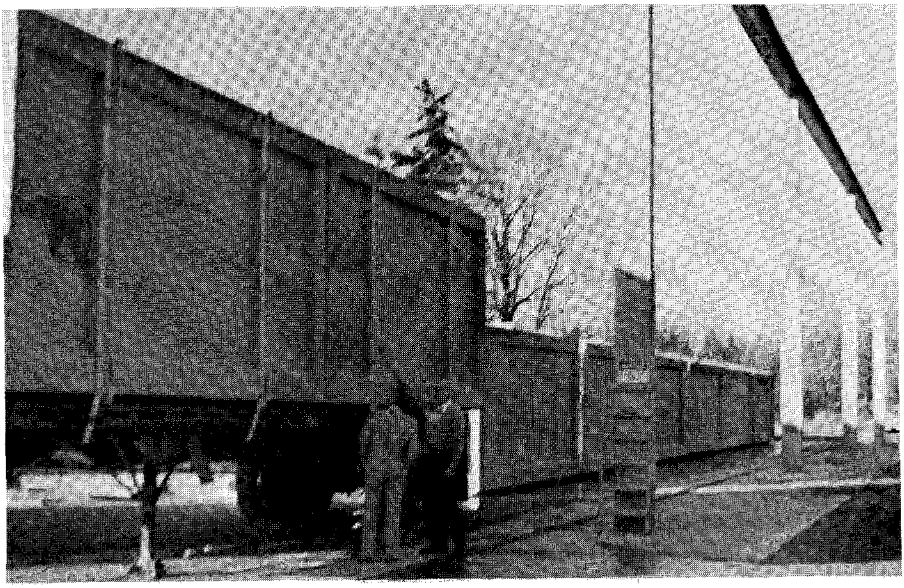


Fig. 24. Finished panels are located on a truck ready for shipment to the RCA Alascom Headquarters Building in Anchorage, Alaska, by roll-on-roll-off ship. (Courtesy: Olympian Stone Company.)

Fig. 25. Panels at RCA job site being readied for placement on building. Panels were insulated at producer's plant for a "U" factor of 0.05. Typical panels are 20 ft x 9 ft 6 in. x 2 ft deep and weigh 2800 lbs. (Courtesy: Olympian Stone Company.)

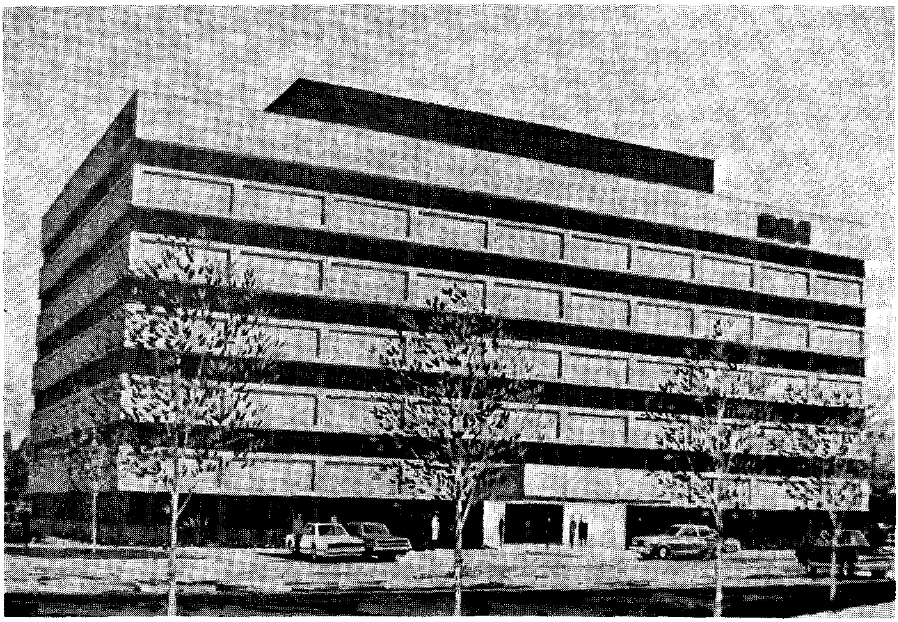


Fig. 26. Large spandrel panels with 2-ft returns top and bottom provide setback for windows in energy saving design at Alascom Headquarters Building. (Courtesy: Olympian Stone Company.)

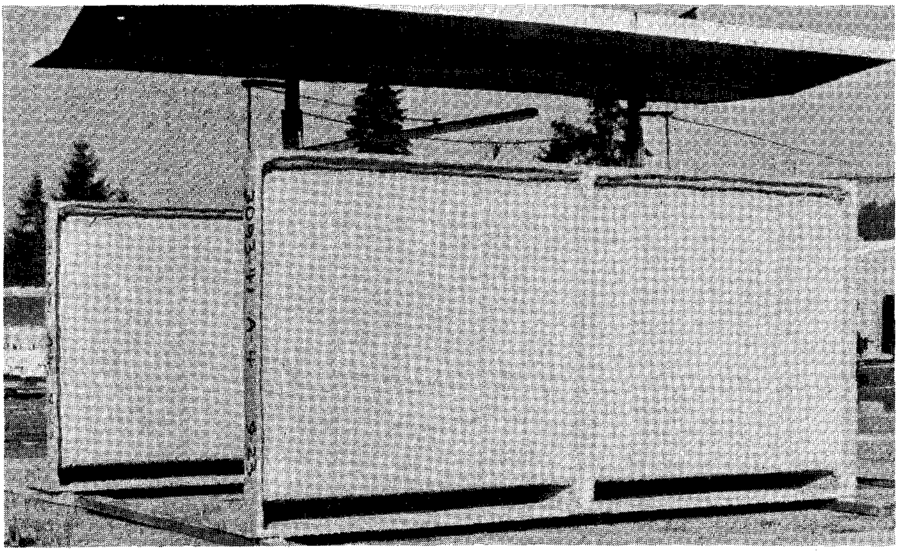


Fig. 27. Typical sunshade stored in producer's yard for University of Washington Health Science Modification, Seattle, Washington. One inch of styrofoam insulation was applied to the back of these panels prior to shipping to the job site. Typical panel size was 13 ft x 4 ft 1 in. with sunshade projection of 1 ft 4 in. (Courtesy: Olympian Stone Company.)

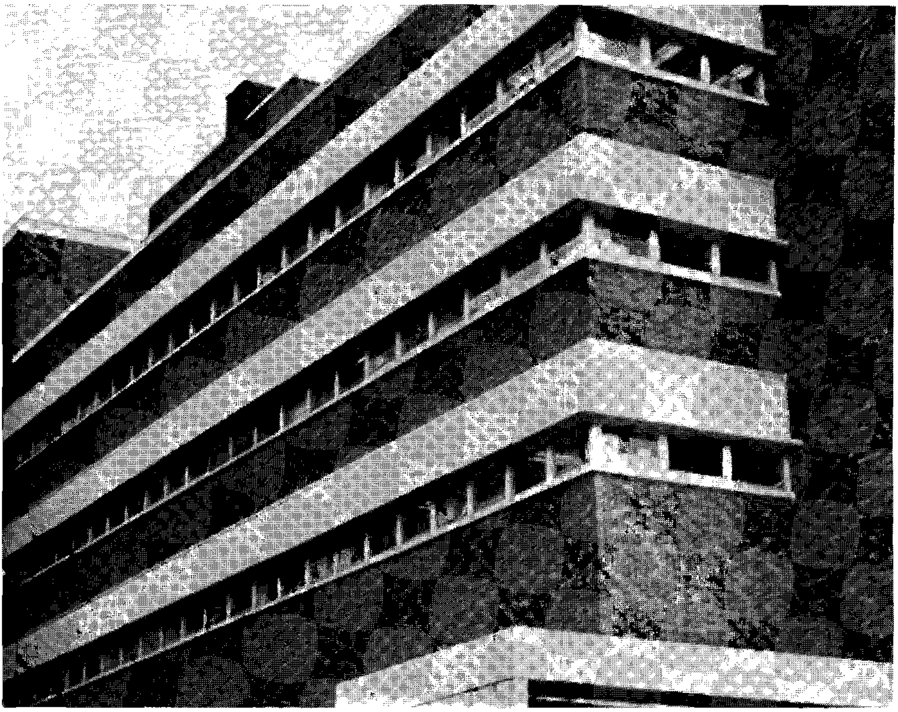


Fig. 28. Cem-Lite sunshades were designed to cover glass block window area to cut down heat loss and gain at the University of Washington project. A projecting lip was designed to provide a sunshade for the remaining window. Over 600 sunshades were required. (Courtesy: Olympian Stone Company.)

These are only some of the applications where GRC is in commercial use. Others include, light-duty manhole covers, exterior panels for wood-framed houses, drainage canal bank support, street furniture, roof tiles, and utility service boxes. The list is far from exhaustive and as new processes for manufacturing GRC are developed, the cost effectiveness of GRC will be improved which will then make many further applications viable.

Technical Limitations and Potential Problems

At the moment the applications for GRC are restricted to non-structural or semi-structural products such as those shown in the photographs. This limitation on the use of GRC is largely a result of the conservative approach which is being adopted by the principal firms involved in its development.

Further experience will be required in the design and performance of GRC in non-structural applications before fully structural or more critical uses will be considered.

Also, further long-term durability data are required particularly as regards the behavior of GRC under prolonged stress conditions. Also, more needs to be understood about creep and fatigue of GRC before structural applications can be developed with absolute confidence. The continuing weathering program, and monitoring of existing installations and certain prototype structures is providing valuable information. However, it will be several years before fully structural GRC uses will be advocated.

Many of the problems that have been encountered with GRC were associated with the relatively high drying shrinkage of GRC based on neat cement slurry. The incorporation of sand, as is now standard practice, has reduced the amount of shrinkage; but nonetheless, it is still significantly greater than that exhibited by precast concrete because of the much higher cement content of GRC.

Shrinkage derived problems manifest themselves in the usual ways of bowing and distortion. Although this can usually be kept to within a tolerance of less than 1/360 the span, designers should be mindful that stiffening ribs or some other method of restraint may be necessary. A particular case is where the product is to be faced with a material which shrinks significantly less than GRC, such as exposed aggregate mix, or which prevents the GRC drying out through the face of the product, such as tiles or impermeable paints.

Shrinkage cracking should not be a problem with GRC, even where the composite does not contain sand; but it can occur where there is a low fiber content or fiber orientation. Cracks can run in the direction of the orientation because there are not enough fibers to resist the propagation of the crack.

The temptation to use steel reinforcement in GRC should be avoided because the higher shrinkage of GRC can cause severe distortion and probably cracking. The use of molded-in steel in GRC products should be confined to the fastening devices and any supporting steel should be kept external to the GRC.

Like all materials GRC has to be produced according to recommended procedures; and, if it is not, suspect or faulty products will be produced. GRC produced by the manual spray process has the added feature that material quality is dependent on the operator. This means that GRC producers must operate strict quality control procedures to insure maintenance of material quality and specifiers of GRC products should check that the GRC manufacturers they purchase from are operating a satisfactory quality control program.

Economics of GRC Architectural Panels

GRC hand spray is a labor intensive process and alkali resistant glass fiber is a relatively expensive raw material, both of which mean that GRC cannot be considered to be a cheap building material. The precise economics will depend substantially on the manufacturer's labor utilization and material wastage, particularly from overspray and unnecessary over-thickness.

Well-trained spray operators are essential to control material usage efficiency and careful planning and experience is necessary to insure that plant layout and work organization maximizes labor utilization.

Economically priced GRC can only be produced by manufacturers with well-trained operators and who have well organized plants. Where these requirements are not met, GRC can only be produced at competitive prices by skimping on quality and material thickness.

The basic raw material cost for GRC composites depends largely on the type of cement and the glass content but typically it will be around 35 to 40 cents per sq. ft. for a composite containing 5 percent glass fiber and $\frac{3}{8}$ in. thick and not allowing for material wasted.

The finished product price will obviously depend on the type of product, labor force, production volume, mold cost, type of manufacture, treatment of overhead, and other factors. However, by way of example, the price of architectural custom-made architectural GRC panels ranges from $2.50 to $8.00 per sq. ft.

In the case of architectural panels the factory or delivered price should not be looked at in isolation but rather GRC often provides cost savings when the effect on the total cost of a project is considered.

These corollary savings can derive from:

(a) Panels are relatively lightweight, particularly when compared to concrete or masonry walls (typically less than one-quarter the weight of an equivalent concrete panel) which can provide cost savings in transportation, site handling, and a lighter structural frame.

(b) When constructed in sandwich panel form, high insulation values can be obtained with thin wall panels (e.g., a wall of 6 in. overall thickness will have a "U" better than 0.06), which provides developers with more usable floor space for the given total ground area covered by the building.

(c) Being "non-combustible" and being able to design GRC panels which meet most required full fire resistance ratings GRC does not contribute to the fire load of a building. Therefore, special fire protection measures are not necessary.

(d) There is very little restriction on shape or size of panels which, in particular, offers the opportunity to achieve savings in installation costs.

(e) Its good impact strength provides resistance to damage during handling and erection, but even where damage may occur it is often repairable on site.

(f) A wide range of surface finishes are possible, many of which are maintenance free.

In many other product areas the same is true, namely, that the economic justification for its use is not necessarily in the factory cost of the GRC product but rather it can stem from technical advantages and cost savings which GRC offers elsewhere.

Conclusion

GRC is just at the start of its development in North America, but the extent of its use in Europe after only 6 years of commercial development leaves little doubt that similar growth in its use will be seen here and other parts of the world.

Its good impact strength and flexural strength together with its good fire properties, flexibility in shape and size, maintenance-free surface finishes, and relative lightweight compared to concrete makes it an eminently suitable material for the construction industry.

Although these characteristics are well utilized in building panels, its use is not confined to this application, but rather it is anticipated that many other applications will become just as important.

Further, they will not be confined to the construction industry as GRC has benefits to offer other areas, particularly products used for public works, (e.g., pipes and products at present made in cast iron), in noise abatement and control. The product also offers a ready solution to those situations where a replacement for asbestos cement is being sought to overcome the health hazard problem of handling asbestos-containing products.

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Discussion of this paper is invited. Please forward your discussion to PCI Headquarters by November 1, 1977.