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The processing, properties, and applications of calcium aluminate–phenol resin composite[1]

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Abstract

The processing, properties, and a few applications of calcium aluminate–phenol resin composite with very high flexural strength are discussed. This composite contains a very large amount of cement (70 vol%) but shows unusual engineering properties, which have not yet been achieved by traditional cement-based materials. The flexural strength of the composite is found to be 120 to 220 MPa; in addition to durability, thermal properties and stiffness are also appreciable. Three possible applications, such as thermal insulators, structural applications, and our experiences in making a cement shell for a solar-powered car, are discussed. The properties of the calcium aluminate–phenol resin composite that are associated with these applications are reviewed.

Keywords: Calcium aluminate; Flexural strength; Macro Defect Free cement; Phenol resin precursor; Solar-powered car; Thermal insulators

A decade after invention of Macro Defect Free cement by Imperial Chemical Industries Ltd. [1], we introduced a new class of high flexural strength cement-based material that has a flexural strength between 120 and 220 MPa [2–4]. This new composite is made by combining high alumina cement, alcohol-soluble phenol resin precursor, and minor amounts of N-methoxymethyl 6-nylon and glycerol under high shear mixing to produce a viscoelastic cement paste through a twin roll mill. This innovation introduced the concept of making a high-strength cement paste in which no additional free water is added, but utilizing generated water by phenol resin precursor during heat curing to hydrate the surface of cement particles. The chemical characteristics of the composite were discussed in a previous paper [5]. In-depth studies of the durability properties were reported by the authors [6,7]. This paper is mainly concerned with the properties and applications of the composite.

There have been only a few studies of the potential applications of high flexural strength cement-based materials. Alford and Birchall [8] gave four examples of applications for the calcium aluminate–polyvinyl alcohol (PVA) system. They are acoustics, cryogenics, armor, and electromagnetic radiation screening, which generally are not associated with cement-based materials. Ube Industries, Japan, introduced decorative wall cladding and tiling (Mirror Grace) for interior use [9]. Here we discuss a number of different trials with a calcium aluminate–phenol resin system (the "CAPR composite"). One is already on the verge of commercialization (thermal insulators), but for others the potential is not yet clear. Some, at least, will provide opportunities for innovation.

1. Formulation

Table 1 gives the formulation that is widely used in this study. Phenol resin precursor is available in liquid form as a solution in methanol and free phenol. The solvent amount in the mix proportion is calculated by subtracting the amount of nonvolatiles from the total amount of resin. Phenol resin content in the final product can be reduced up to 10 parts for the 100 parts of the cement by weight. Processsing difficulties arise with decreasing polymer cement ratio. In contrast, an increase in polymer cement ratio will cause the material to produce large setting shrinkage during heat curing. Flexural strength dependence with polymer cement ratio is discussed elsewhere [10].

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Table 1
Standard mix proportions

Constituent	Parts by weight	Weight %	Volume %
High alumina cement	100.0	79.8	57.9
Phenol resin	13.06	10.4	18.2
Solvent (methanol and free phenol)	8.24	6.6	18.2
N-methoxymethyl 6-nylon	1.70	1.4	2.6
Total	23.00		
Glycerol	2.30	1.8	3.2

2. Method of processing

2.1. Roll milling

The processing sequence is outlined schematically in Fig. 1, and it is basically equal to the processing steps of the Macro Defect Free (MDF) system [11]. Premixing in a kneader style mixer is the initial step of the processing. A rubbery cement dough can be obtained after premixing. Premixing usually is simple and serves as a partial incorporation [12] of cement into the organic constituents to form a coherent mass. Incorporation may demand a considerable energy and may not be completely finished in the kneader mixing. Premixing in a kneader can be skipped if necessary, because incorporation can be manipulated in the twin roll mill.

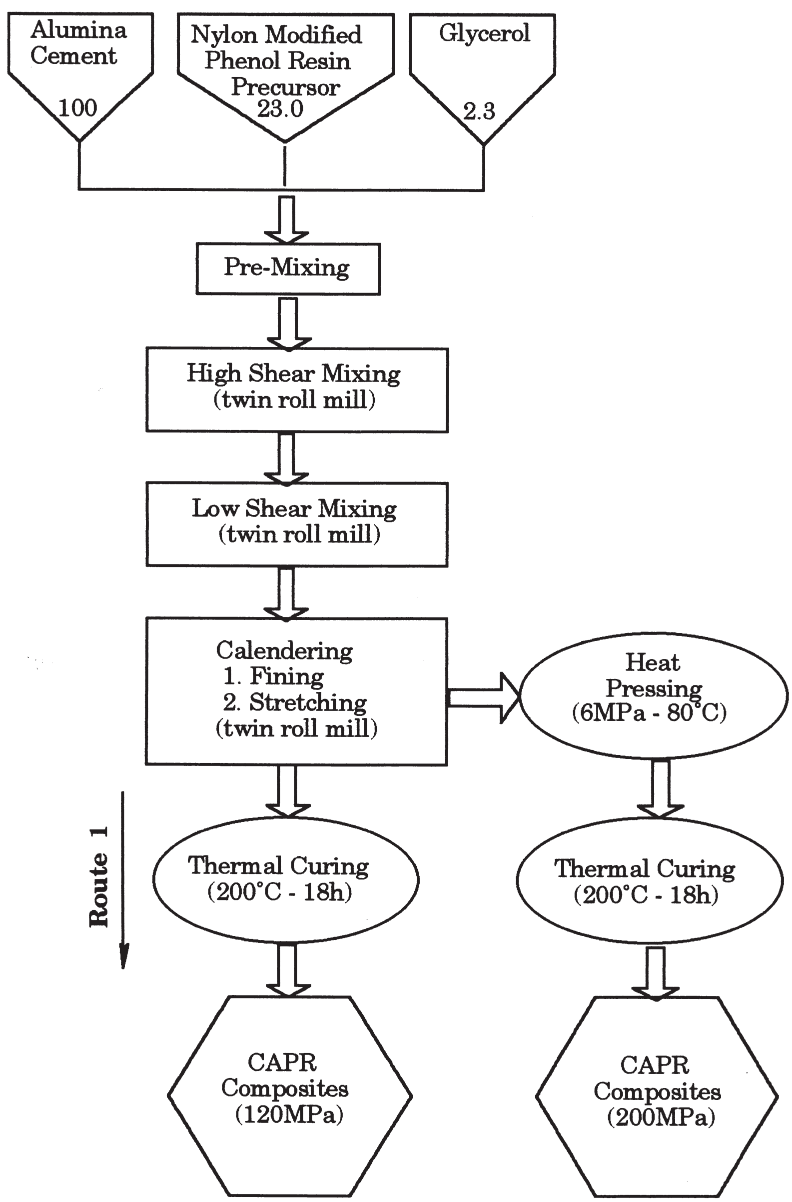


Fig. 1. Flow chart of the two processing routes to the final CAPR composite.

High shear mixing in a twin roll mill is the heart of the process. The premixed cement dough or individual constituents can be fed onto the roll for high shear mixing. In high shear mixing, front and back roller speeds are 250 and 200 mm/s, respectively. During high shear mixing, the solvent evaporates and the cement paste twines around both rollers. After a few minutes of mixing, the paste starts to twine around the faster roller. In low shear mixing, both back and front roller speeds are 200 mm/s. During this regime, the paste starts to peel off from the rollers. The paste then can be scraped away and rerolled several times until it becomes a sheet.

In calendering, both back and front roller speeds are 150 mm/s. Calendering can be divided into two parts, "fining" and "stretching." Fining makes a fine-face homogeneous sheet by diminishing stratified layers. In this step, the sheet is folded and rerolled several times until it becomes a fine-face homogeneous sheet. During "stretching" the sheet is fed onto the rollers several times without folding. Then the sheet stretches and improves the packing of the cement grains.

After roll milling is completed, sheets can be directly cured in an oven at 200°C for 18 h as shown in route 1 in Fig. 1. Alternatively, sheets can be further densified by pressing between the platens of a hydraulic laminating press at 6 MPa and 80°C to remove any lamination defects (route 2). The final strength depends heavily on the processing route selected. In addition, the sheet can be shaped into desired shapes after calendering. The cement paste also can be extruded after high shear mixing. Of the extruded product, the same flexural strength can be obtained with the calendered material.

2.2. Heat pressing

After the calendering, cement sheets can be pressed under 6 MPa at 80°C. To ensure the highest strength, it is necessary to elevate the temperature slowly and keep it at 65°C or higher for more than 30 min under the pressure. When being heated between the platens, the sheet softens due to the increase of the fluidity of the phenol resin at around the boiling point of methanol, flows to heal the defects, and then stiffens partially after the pressing is completed.

3. General properties

3.1. Strength and Weibull modulus

Flexural strength at the 120-MPa level can be achieved by heat curing of a calendered sheet at 200°C for 18 h. Alternatively, the heat pressing step before heat curing increases the strength up to the 200-MPa level. Very uniform heat distribution throughout the steel plates is essential to achieve higher strength. This is a burdensome requirement when being formed into three-dimensional complex shapes; hence, strength achievement without the heat pressing step is more valuable for some commercial applications.

The strength properties of CAPR composite are highly reproducible. Fig. 2 shows a Weibull plot of strength. The flexural strength data were obtained by testing 53 specimens that were fabricated through processing route 1; specimens were approximately equal in size. The Weibull modulus (m) given by the slope of the plot is 27, which is considerably high among the brittle materials. It is important to note that as m increases, the material becomes less brittle.

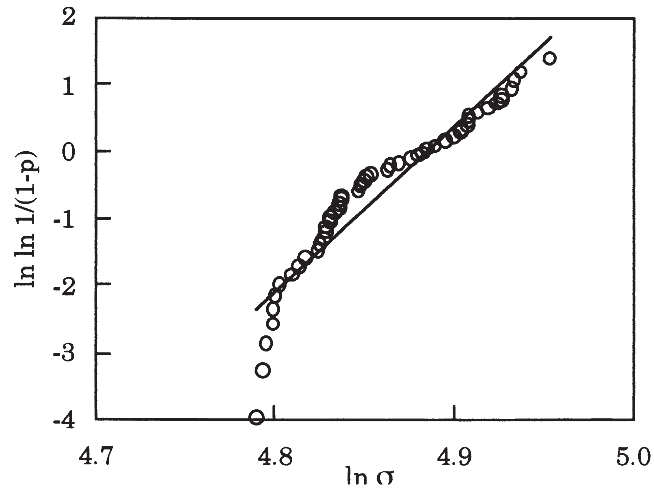


Fig. 2. Weibull plot for CAPR composite. p, failure probability; σ, flexural strength (in MPa).

3.2. Toughness

Measurement of stress intensity factor has been conducted by the single-edge notch beam method in a three-point bending test with the machined cut notch of 0.1-mm notch root radius. This value was found to be 1.8 $MPam^{1/2}$ for the material processed through route 1. Stress intensity factor can be raised up to 3.0 $MPam^{1/2}$ level by heat pressing. Fracture properties and impact strength can be raised greatly by lamination of Aramid triaxial fiber meshes.

3.3. Resistivity to heat

The CAPR composite demonstrates rather high resistivity to high temperatures. Fig. 3 shows flexural strength and weight loss as a function of temperature. Residual flexural strength at each temperature level was measured by heating the specimens at each temperature level in an oven for 6 h. The strength was determined after cooling to room temperature. Weight losses of cured phenol resin and the composite upon heating were monitored by thermogravimetric analysis separately. As shown in Fig. 3, CAPR composite keeps its strength even up to 250°C and begins to decrease above 250°C.

The time dependence of strength at high temperature levels is illustrated in Fig. 4. CAPR specimens were kept at three different temperature levels (100°C, 150°C, and 250°C). The specimens were taken out of the oven at prescribed time intervals, cooled down to ambient temperature,

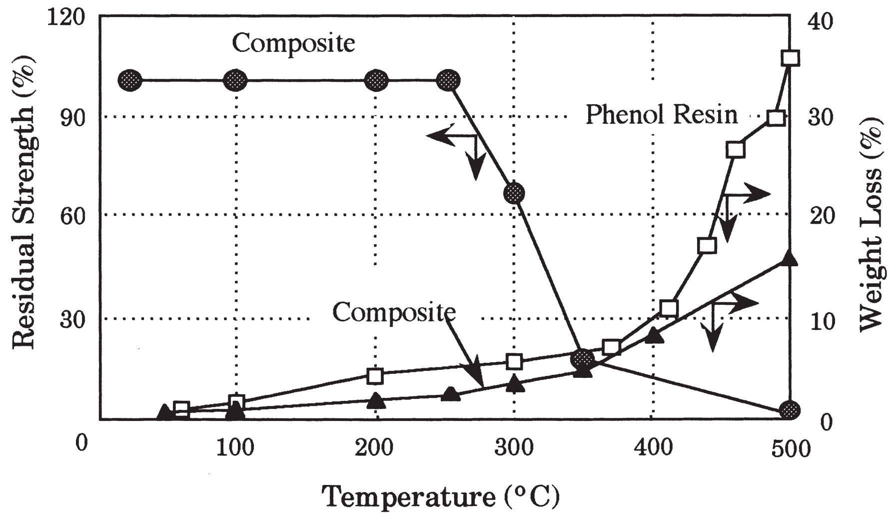


Fig. 3. Flexural strength loss and weight losses vs. temperature.

and tested for flexural strength. In Fig. 4 it can be seen that the CAPR composite loses less than 8% of its original strength when kept at 150°C for 96 h. At 250°C, strength begins to decrease beyond 12 h of heating and more rigorously beyond 36 h of heating.

Table 2 lists general properties of CAPR composite. Many properties given in Table 2 were evaluated on the 120-MPa level specimens unless otherwise specified. Flexural strengths at three different temperature levels were tested after keeping the specimens at each temperature level for 30 min and at the appropriate temperature level. The strength of most materials is enhanced at low temperature, and this is true for the CAPR composite as well. Compressive strength was measured by piling up the 2-mm thick specimens according to JIS K 6911 (Testing Methods for Thermosetting Plastics). In addition to mechanical properties, thermal expansion, thermal conductivity, DC resistivity, dielectric strength, and the friction coefficient were measured.

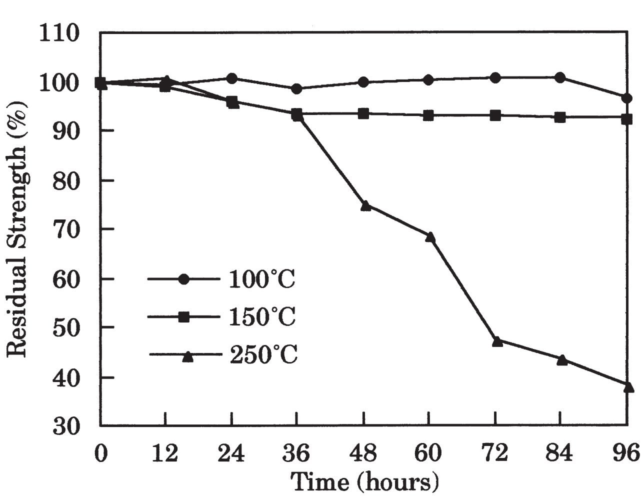


Fig. 4. Time dependence of strength at high temperature levels

4. Applications

High-strength cement-based materials developed recently are being used to explore new applications that have not been occupied hitherto by traditional cement and concrete technology. High flexural strength has not been a fa-

Table 2
Properties of CAPR composite

Property	Values
Flexural strength	
Processing Route 1	
R.T.	120–135 MPa
Processing Route 2	
R.T.	180–200 MPa
77 K	220 MPa
473 K	130 MPa
Bending modulus of elasticity	32–45 GPa
Poisson's ratio	0.24
Compressive strength	300 MPa
Stress intensity factor	
Processing Route 1	
R.T.	1.8 $MPam^{1/2}$
Processing Route 2	
R.T.	2.9 $MPam^{1/2}$
77 K	3.3 $MPam^{1/2}$
473 K	2.0 $MPam^{1/2}$
Specific gravity	2.2–2.3
Weight increases (1 year in water, 2.5 mm thick specimens)	0.82% (Ref. [7])
Thermal expansion (20–300°C)	17.8×10^{-6} °C^{-1}
Thermal conductivity	0.8 W/(m · K)
DC resistivity	10^{13}–10^{14} Ω · cm
Dielectric constant (200 MPa level specimens)	
1 kHz	9
10 kHz	6
Friction coefficient (initial speed) =50 km/h, retardation = 0.3 g)	
100°C	0.584
200°C	0.564
300°C	0.497

miliar property to conventional cement products; thus, there is no established position of cements in modern industries. The relatively high cost of these materials has limited their use in civil and architectural applications that are very common for cements. Searching for new applications in the areas presently dictated by metal, plastics, and ceramics is a challenging task to cement scientists and engineers.

However, a novel processing method of high-strength cement-based materials led to the production of metal-like thin sheets at least 20 times stronger than ordinary cement paste but, unlike metals, they are intrinsically brittle. Metals have high moduli. They are ductile, allowing them to be formed by deformation processes. Plastics are nearly as strong as metals. They are easy to shape; complicated parts performing several functions can be molded from plastics in a single operation. The large elastic deflections allow the design of plastic components that snap together, making assembly fast and cheap. However, plastics are highly dependent on temperature, so that the plastics are tough and flexible at 20°C, but may be brittle at the 4°C of a household refrigerator. They creep even at room temperature, meaning that plastic components are deformed under a load with time [13]. Ceramics are stiff, hard, and abrasion resistant; they retain their strength up to a high temperature but are difficult to machine. Despite this, high-strength polymer–cement composites combine the attractive properties of ceramics and plastics while avoiding some of their drawbacks. They are light and strong, and they can be made tough by introducing fibers. Unlike metals, they are resistant to corrosion. Unlike ceramics, polymer–cement composites can be cured at lower temperatures with great freedom in making desired shapes at room temperature. Unlike plastics, they show a wide range of temperature stability. Beyond this, there are global issues, the social demand to minimize environmental damage to save energy, and to reuse rather than discard.

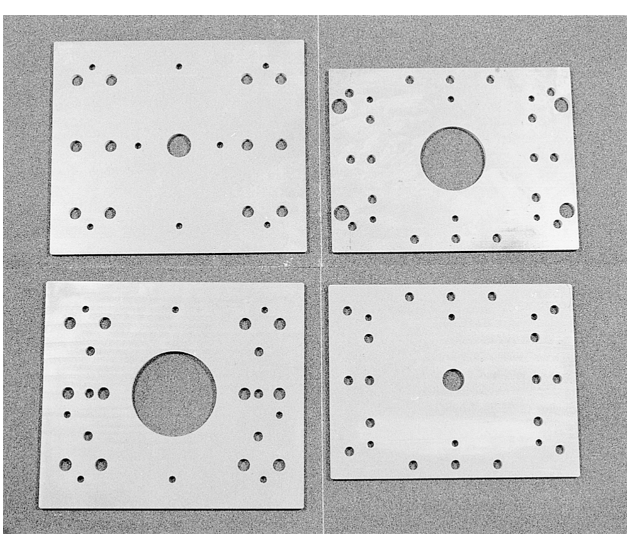


Fig. 5. Four types of thermal insulation plates made by CAPR composite. Holes with various diameters facilitate assembling.

4.1. Thermal insulators

Polymers and ceramics are good thermal insulators because of their low thermal conductivities. Thermal conductivities of ceramic materials at room temperature range between approximately 2 and 50 W/mK. Thermal conductivities of most polymers are on the order of 0.3 W/mK [14]. However, polymers lose their strength and modulus at high temperatures. The CAPR composite is satisfactorily utilized as a thermal insulator because of its considerably low thermal conductivity and wide range of temperature stability.

Fig. 5 shows thermal insulation plates made by the CAPR composite for a hydraulic pressing machine. This machine is utilized for injection molding of plastic parts for earphones, and it is necessary to keep pressing molds at 60°C continuously. Thermal insulation plate is used between the mold and the pressure drum as shown in Fig. 6. The plates were faced with a high degree of precision to fit the clearance between the mold and the pressure drum and were drilled to facilitate assembling. The CAPR plates are relatively easy to face and drill compared to ceramics and thermoplastics. Besides low thermal conductivity, these plates are lower in creep deformation under the elevated temperatures. The property comparison of CAPR insulators with other thermal insulators currently used in this type of application is listed in Table 3.

Fig. 7 shows a cutaway view of a lightweight honeycomb thermal insulation panel for the floor, roof, and wall panels in the building industry. The panel consists of two 1.2- to 1.8-mm thick CAPR composite outer sheets separated by a 25-mm thick layer of less dense aluminum core. Face sheets are stuck to the honeycomb using epoxy-type adhesives. The faces satisfactorily bear in-plane loading and any transverse bending stresses. The load-deflection patterns of honeycomb panels with the CAPR faces and the aluminum faces, both having equal overall thickness, are shown in Fig. 8. The CAPR composite-faced panel is as strong as the aluminum-faced panel, but it is lower in de-

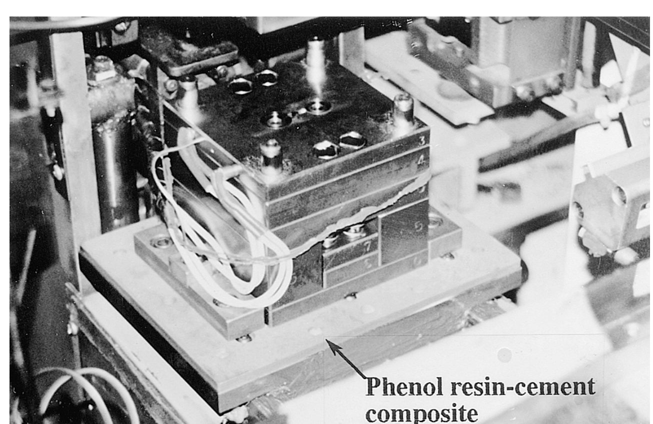


Fig. 6. CAPR composite insulators in operation in an injection molding machine.

Table 3
Property comparison of CAPR insulators with other thermal insulators currently used in this type of application

Property	CAPR composite	Inorganic/glass fiber insulators	FRP insulators	FRP insulators
Specific gravity	2.3	2.0–2.2	1.6	2.1
Flexural strength (MPa)	180	98–147	270	520
Modulus of elasticity (GPa)	35 (in flexure)	—	—	27.5 (in compression)
Flexural strength after heating (MPa)	180 (250°C–3 h)	—	170 (250°C–3 h)	—
Compressive strength (MPa)	300	147–294	>500	600
Water (moisture) absorption; (%)	0.82 (20°C–water–1 year)	1.0–3.0	2.0 (25°C–water–24 h)	0.35 (water–24 h)
Thermal conductivity (W/mK)	0.8	13.9	0.38	0.23

FRP: Fiber-reinforced plastic.

flection and has no permanent deformation under the loading as indicated in Fig. 8 [15]. One interesting result is that the CAPR composite emits far-infrared rays into the atmosphere when heating, which may be an indispensable property of the material for some applications.

4.2. Structural applications

The mechanical strength of cement materials may be improved by reinforcement methods such as embedding steel rods or wires and adding metallic or polymeric fibers. It is also possible to strengthen the cementitious structures in flexure by high flexural polymer–cement composites by:

- Embedding it into the cementitious structure,
- Glueing into the soffit of the cementitious structure, and
- Placing together with the cementitious structure.

Table 4 shows the effect of lamination on strength development in silica fume mortar and lightweight perlite mortar. To prepare, 2-mm thick 120-MPa flexural strength level CAPR sheets are placed in 15-mm thick wooden molds and fresh mortar is poured into the mold so that they harden together to make a united body. This strengthening method can be satisfactorily applied when making thin and lightweight cement membranes instead of steel or fiber-reinforced plastic (FRP) embedments, which make handling difficult. Fig. 9 shows a cutaway view of a 15-mm thick, lightweight double-deck floor panel that corresponds to the last example in Table 4.

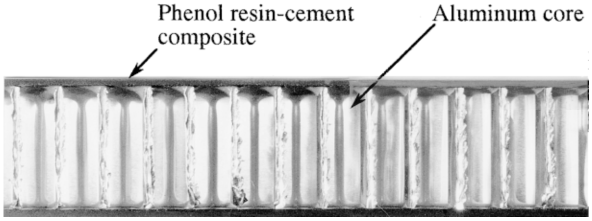


Fig. 7. Cutaway view of a lightweight honeycomb thermal insulation panel. Facing plates were made by the CAPR composite.

4.3. Applications with shape

The roll milling process and the ability to make thin sheets and their flexibility have created new opportunities for these high-strength materials in areas conventionally appropriate only for metals or fiber-reinforced plastics. Here we describe an attempt to make the body of a solar-powered car. The property requirements of a vehicle body depend on the type of the vehicle and industrial standards, but in general terms the following factors are important from the viewpoint of material science:

- Ability to withstand the loads that cause bending, twisting, buckling, or collision; and
- The body must be as light as possible.

Fiber-reinforced CAPR composite fulfills these two requirements to a certain extent.

A solar car with a 3600 × 700 × 900-mm body was made, and a trial run was given in a solar car rally to study the feasibility of utilizing cements in the transportation industry. A side view of the solar car is shown in Fig. 10.

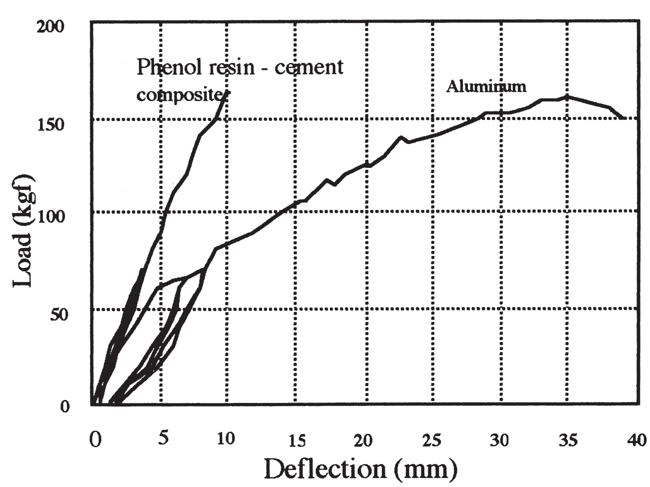


Fig. 8. The load-deflection response of honeycomb panels with the cement faces and the aluminum faces.

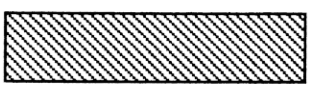
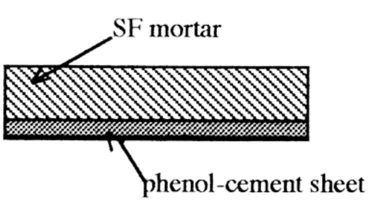
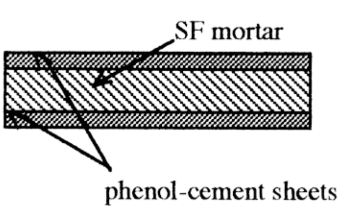
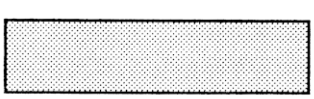
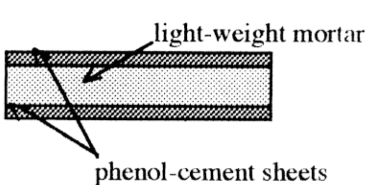
Considering the facilities available, this was made in four parts. Mix proportion and method of processing were the same as described previously, except for using an industrial scale roller with twin rolls 1800 mm long and 600 mm in diameter. The circulation of cement dough or sheet around the rollers was done by two conveyor belts. Fig. 11a shows the 2.6-mm thick roller milled sheet. Sculpting was started 6 h after formation to avoid shrinkage cracks. First, the sheet was moved onto a previously made concrete mold and manipulated into the desired shape (Fig. 11b). The sheet was still in good working condition with leathery consistency and was tear resistive. The excess that hung off the mold was cut off with a scissor, and the sheet was adhered to the concrete mold using double-faced adhesive tape (Fig. 11c). The sculpted sheet and the mold were put in an oven as they were. One rigorous challenge was reducing or eliminating cracks due to setting shrinkage.

CAPR composite shrinks by 2.5% in length during the heat curing. Linear contraction and residual weight as a function of time during the heat curing and before heat curing are shown in Fig. 12. A very high linear contraction appears within the first 6 h just after being formed; the contraction is explained in terms of preliminary relaxation of the sheet, which is heavily subjected to shear stresses during roll milling. To avoid this contraction, sculpting was started 6 h after being formed, as mentioned previously.

Several precautions were taken to reduce shrinkage cracks during heat curing. First, the temperature elevating rates were chosen so that dimensional changes associated with setting did not result in internal stresses sufficient to cause severe cracking. Second, the work was removed from the mold after being cured at 100°C for 4 h; the resulting work was cured alone at 200°C for 18 h, which allowed it to shrink freely without causing cracking. It should be noted that, after curing at 100°C, the CAPR composite attained one third of its final strength; thus, removal from the mold did not cause any damages. The final product is shown in Fig. 11d.

We have drawn the following merits and demerits in utilizing the CAPR composite for the transportation industry, through the experience gained by making the outer shell of the solar powered car.

Table 4
Effect of lamination of CAPR sheets on strength development in silica fume mortar and lightweight perlite mortar

Illustration	Description	Flexural strength (MPa)	Significance
	Silica fume mortar	13	—
	Silica fume mortar and a 2-mm thick CAPR sheet on bottom	41	Flexural strength is 3.2 times higher than silica fume mortar
	Silica fume mortar and 2-mm thick CAPR sheets on top and bottom	45	Flexural strength is 3.5 times higher than silica fume mortar
	Polytethylene fiber-reinforced lightweight perlite mortar	5	Specific gravity 1.39
	Polyethylene fiber-reinforced lightweight perlite mortar and 2-mm thick CAPR sheets on top and bottom	47	Specific gravity 1.63. Flexural strength is 9.4 times higher than fiber-reinforced lightweight perlite mortar

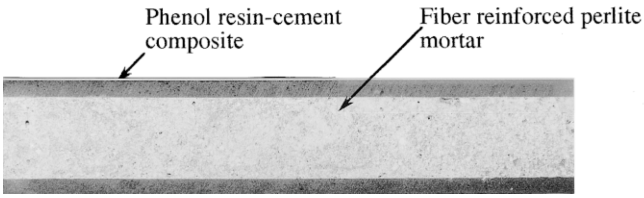


Fig. 9. Cutaway view of a lightweight double-deck floor panel. Two-millimeter thick CAPR sheets are used in the top and bottom for reinforcement.

Merits:

- Shaping can be performed using a single mold (male or female).
- Pressing is not necessary to form the desired shape.
- Cutting is easily done by a scissor before hardening and by a diamond cutter after hardening.
- No stickiness even before hardening, thus easy to handle.
- High stiffness could not be achieved by the same weight metallic shell.

Demerits:

- Shaping is not possible after hardening.
- Dimensional accuracy is less than metals.
- Impossible to make thinner sheets like metal.

5. Discussion

Practical use of high flexural strength cement materials in the fields generally not associated with cements poses some practical problems because of lack of experiences in these fields. The major drawbacks include machineability, which may be compensated by selecting suitable drilling tools and setting shrinkage by appropriate mold designing. In the beginning these are laborious, but the interest of specialists may be increasing with the growing market demand.

Cost performance is one of the essential demands of users, as to be expected. Market price of a product has several determining factors. Mainly they are the cost of the raw material from which the composite is made and the cost of processing, but there is also the cost of the research and development that went into its innovation. In the case of these new cementitious products, the cost of processing is the overriding factor, in contrast to the conventional cement products. The practical processing cost of the CAPR composite is 10 times higher than its cost for raw materials. The higher processing cost is mainly due to the batch-type roll milling currently being used during formation. Required time for mixing and calendering cannot be easily pre-evaluated, and they are heavily dependent on the temperature of the rollers. Careful observation is essential throughout the whole process, and the surface texture of the cement sheet is improved by folding and feeding it several times into the twin roll.

As we have seen, it is not worthwhile to produce architectural facing materials such as decorative wall cladding and tiling because of the high processing cost and availability of more appropriate and less expensive building materials. However, applications given by Alford and Birchall [8] seemed a tenable proposition. The properties of the calcium aluminate–PVA system that were shown to be beneficial for the armors are the same for the CAPR composite. The technology utilized in making a cement shell of a solar-powered car also can be easily applied to form armors. MDF cement-based loudspeaker cabinets also were introduced [8]. Generally a material higher in damping (tan δ), Young modulus, and specific gravity is known to show good acoustic properties [16]. CAPR composite processed by route 1 is lower in Young modulus and specific gravity than data given in Alford and Birchall [8]. Although these two properties can be increased by adding alumina and then by heat pressing, there are several other suitable candidates, such as DSP cement, for this kind of application. In addition, DSP is more aesthetically pleasing after facing and polishing than MDF cements because of its heterogeneous granular structure [17].

Fig. 10. View of the solar-powered car in which the body is made by the CAPR composite.

The other unforgettable performance of cements is their environmental friendliness compared to metal and plastics. There is a growing interest in reducing and reversing environmental damages caused by years of technical progress. This requires materials that are easier to recycle and dispose. In particular, fiber-reinforced plastics now face a knotty problem of how to be recycled or disposed. The CAPR composite can be easily recycled or disposed without environmental damage.

Fig. 13 schematically represents our suggestions for methods of recycling. One method is to reuse the CAPR

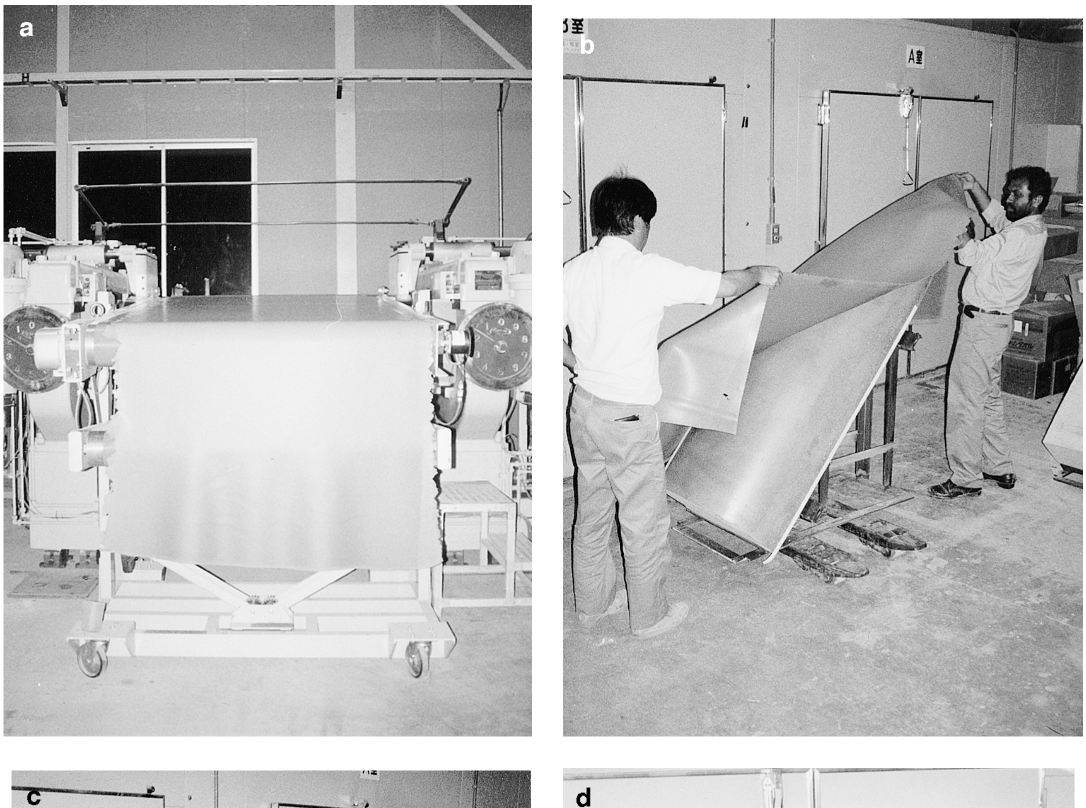


Fig. 11. Various steps in making a cement shell. (a) A roller milled sheet positioned on a conveyor belt. (b) Shaping using a previously made concrete mold. (c) The sheet adhered to the concrete mold. (d) The final product.

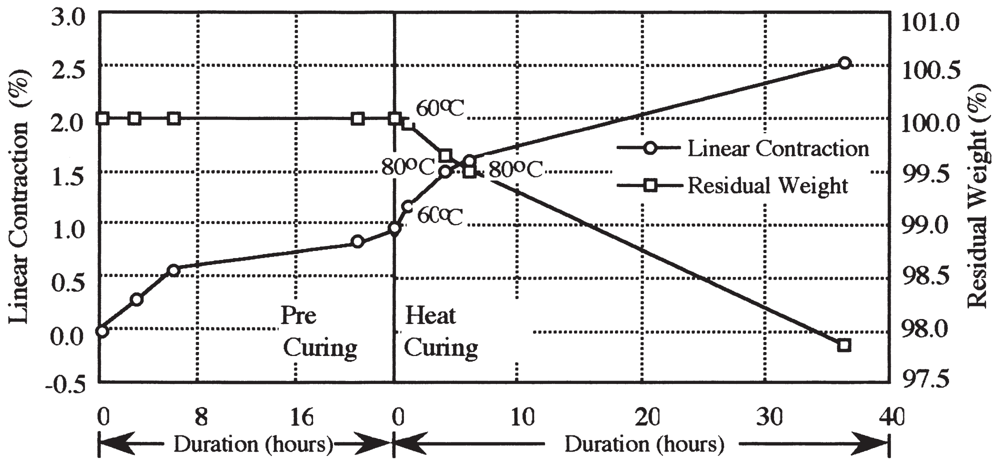


Fig. 12. Plots of shrinkage due to relaxation and setting shrinkage, and residual weight as a function of time during at various stages of precuring and heat curing (precuring was done at room temperature and humidity).

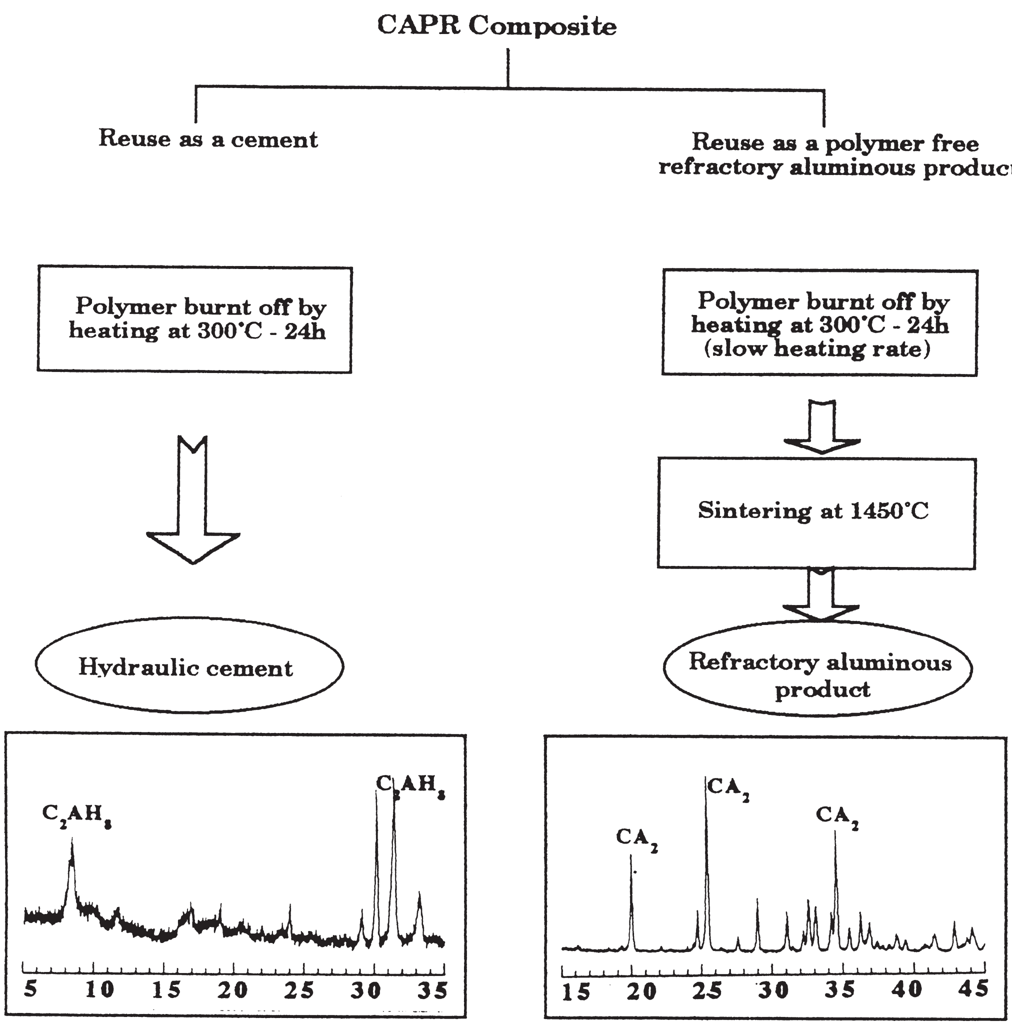


Fig. 13. Proposed scheme for recycling of CAPR composite.

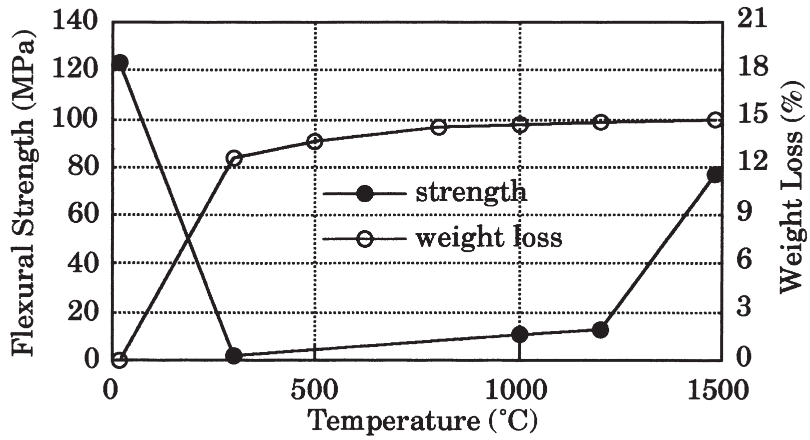


Fig. 14. Flexural strength and weight loss of the CAPR composite as a function of temperature.

composite as a hydraulic cement. CAPR composite was found to keep its strength when heated at 250°C for 6 h, but the strength became one third of the original when heated at 300°C for 24 h; sheets become powder when heated at 300°C for 24 to 48 h without releasing any toxic gas. The remaining powder may be used as a hydraulic cement. One interesting observation is that this remaining powder directly formed an intermediate hydration product (C_2AH_8) in water at 20°C within 24 h, which is normally formed by high-alumina cement in water at around 40°C.

The CAPR composite also can be converted to a refractory product as shown in Fig. 13. Fig. 14 shows changes in strength and weight upon heating. The flexural strength values shown in Fig. 14 were measured after cooling and at ambient temperature. The strength decreases upon heating due to the decomposition of the polymer phase and increase in porosity, reaching a minimum value at 300°C. Further heating to 1450°C induces sintering and produces a solid-state ceramic bond and an increase in strength. A polymer-free refractory aluminous product with 75-MPa flexural strength can be obtained. The X-ray diffraction profile of this refractory aluminous product reveals that it is rich in calcium dialuminate, whereas the original cement was richer in monocalcium aluminate.

6. Concluding remarks

The authors have pointed out some applications for this novel cement-based composite. Because the processing cost is high, there is a small chance this material could be applied in the civil and architectural fields. The CAPR composite should be utilized in other engineering areas presently dictated by metal, plastics, and ceramics. Considerably good machineability of the material in comparison to ceramics is attractive. Stability at high temperatures compared to fiber-reinforced plastics, lower specific gravity, and noncorrosiveness compared with metals also are appreciable. The authors have shown some of the merits in using this material to make three-dimensional shapes.

Very often the benefits from a new material are offset by the additional cost of production. High shear mixing in a twin roll and calendering were the essential steps to make the CAPR material, but both of them are expensive methods. High shear mixing is chemically active. Are there any other inexpensive methods that can make cross-links between alumina cement and phenol during mixing? The seeds of the possible engineering applications have been sown, and the authors are anxiously expecting several unconventional cement products in the future.

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