UK Building Research Establishment – International Division

Overseas Building Note

OBN 198

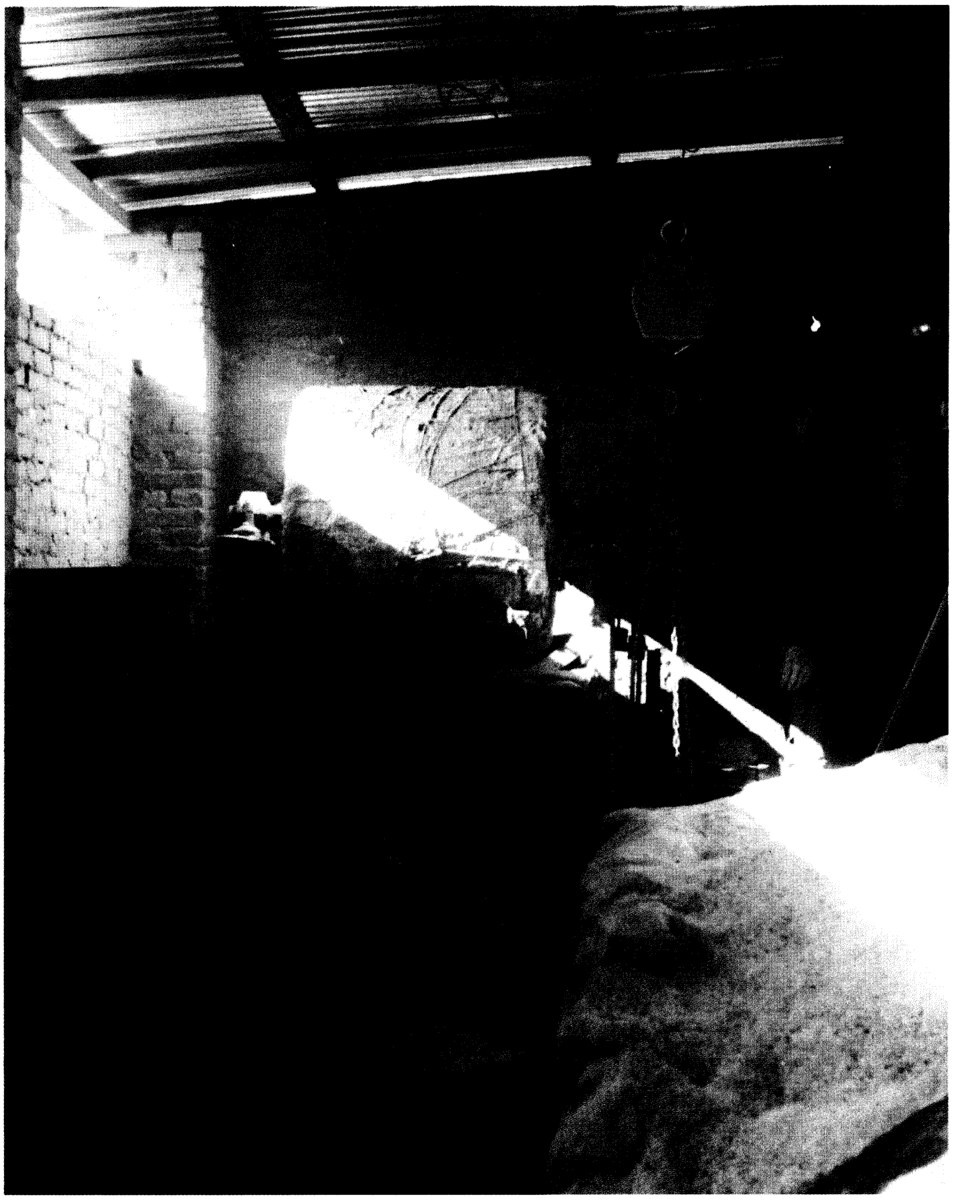
March 1993

Housing and construction information for developing countries

Nigel Wakeham

Alternatives to OPC

R G Smith



Making rice husk ash cement in Nepal

Building Research Establishment

International Division
Building Research Establishment
Garston, Watford, WD2 7JR, UK
Telephone 0923 894040
Telex 923220 Fax 0923 664010

SUMMARY

Building materials are constantly in demand and although ordinary Portland cement is manufactured in many developing countries, it is often in short supply or expensive.

Several types of alternative cement can be made from local resources using lime mixed with natural materials or waste materials. Ordinary Portland cement may be made to go further by addition of some of the same materials. Also gypsum plaster, mud with animal or plant extracts, and sulphur can be used.

This note explains the ways in which various cements work, describes manufacturing methods, methods of use, and gives properties of products made with these alternative cements. This information should assist planners and practitioners responsible for 'low-cost' building projects, and the producers of building materials in developing countries.

BIOGRAPHICAL NOTES

Ray Smith has led BRE research into local production of building materials for low cost housing since 1973, during which time he has worked in 16 developing countries. Prior to that he researched building materials for use in industrialised countries.

CONTENTS

ALTERNATIVES TO OPC
by R G Smith

1 INTRODUCTION

In building construction, cements are most often used for making mortar to use with regularly-shaped components such as bricks, or with irregularly-shaped components, such as aggregates, to make concrete. Cements work by filling the spaces between solid materials, binding them together and making the finished structure firm and stable.

Natural gypsum was one of the earliest materials used, some 4000 years ago, for the production of a cementing material. Lime, sometimes modified by addition of a pozzolan, has had a history of use as a cement for well over 2000 years. Bitumen has been used as a binder and water-proofer for thousands of years, and plant and animal products have a long traditional use in improving durability of building materials. Today the most widely known cement is ordinary Portland cement (OPC), so named because after setting it was considered to be similar in appearance to the natural stone quarried at Portland, in the south of England.

Since the first commercial production of OPC in the nineteenth century, most countries of the world now have taken up manufacture. It is generally produced to exacting standards in large plants. OPC is made from clay and limestone, by heating them to a high temperature (approximately 1450°C) to form a clinker. A small quantity of gypsum is added and the mixture is ground to a very fine powder. The choice of raw materials and control of the OPC production processes require care and skill to ensure a satisfactory product.

OPC is a well-known and versatile material used extensively for mortars, rendering and concrete. Mortars made solely from sand and OPC give a rather harsh mix, difficult to work with, and often harder and stronger than actually required. More workable mortars result from incorporating lime into the mix. OPC with coarse and fine aggregate is an excellent material for the production of concrete: proportions may be chosen to meet specific requirements for the concrete.

Worldwide there is a never-ending demand for construction. In consequence the requirement for building materials is great and OPC is in demand constantly, both in industrialised countries and in developing countries.

Production of OPC is usually in large manufacturing plants which are capital intensive and use large amounts of fuel. In developing countries the installation and operation of these plants often depends upon imported equipment and expertise. Often the demand for OPC exceeds the supply. Sometimes there are shortages of OPC, difficulties in transportation to points distant from the production factory, or the cost of the cement is too high.

As a means of obviating such problems in developing countries, the various possible alternatives to OPC ought to be considered and the benefits which might accrue from their use should be examined. Those cementitious materials which were in use before the invention of OPC may be relevant for particular circumstances today and in some situations they will have advantages over OPC. Other alternatives to OPC have been developed more recently.

2 SETTING AND HARDENING MECHANISMS

For use in construction, cementitious materials have to be of a consistency which enables them to be spread, poured, cast or otherwise placed in position. Usually water is used for this and indeed the water is usually also necessary for the setting process to take place. In the different types of cementitious materials which are available, the various mechanisms listed in the following sections operate to give the necessary hardening, adhesion or strength development. Examples are given for each mechanism.

Carbonation

Carbon dioxide reacts with calcium hydroxide, converting it to calcium carbonate.

An example of this is hardening of lime on exposure to air.

Reaction between components

Two separate components may react with each other to give a product which is hard and durable.

An example of such reaction is that between lime and pozzolans. Some volcanic ashes are pozzolanic. Hardening of the mixture when moist is due to the reaction of silica in the ash with the lime to form calcium silicate.

Hardening of gum, resin and other natural organic materials

Organic materials may harden or set and so be useful for binding materials together.

Examples are the use of cow dung to improve water resistance of mud mortar coatings or renderings on walls, and of bitumen to bind and waterproof soil mixes.

Crystallisation

Formation of a network of crystals as a material crystallises out from solution can impart considerable strength to the mass.

A clear example of this mechanism is the setting of gypsum plasters. To use plaster, it is first mixed with water to form a paste. Within a few minutes, needle-shaped crystals form and interlock in the paste causing it to stiffen and then to harden.

Drying
The liquid in cements is usually water. As this dries out, the fluid nature of the cement is reduced as the solid particles come closer to each other. When the particles are eventually in very close contact a rigid substance remains.

This mechanism is operative, for example, in mud mortar which is one of the oldest and simplest materials in which bricks may be laid. As the wet mud is exposed to the air, slow drying and hardening occur.

Solidification
A material which is melted for use can be adhesive and strong as it cools and changes into a solid.

Sulphur has been used in this way, for example in admixture with aggregates, to make sulphur concrete.

Gel formation
In some materials a gelatinous mass is developed which binds the particles together.

The setting of OPC is largely due to the formation of gel containing hydrated compounds. In practice several other of the mechanisms listed earlier can contribute to the complicated setting process in OPC.

3 PRODUCTION OF VARIOUS ALTERNATIVE CEMENTITIOUS MATERIALS

Lime
Limestone is one of the world's most common rocks and it has been exploited successfully for thousands of years. For the production of lime, the limestone must first be heated to a temperature within the range 1000 to 1250°C to produce quicklime. The calcination process can be represented in chemical symbols thus:

$$\underset{\text{(calcium carbonate)}}{\underset{\text{limestone}}{CaCO_3}} \xrightarrow{\text{heat}} \underset{\text{(calcium oxide)}}{\underset{\text{quicklime}}{CaO}} + \underset{\text{(carbon dioxide)}}{\underset{\text{gas}}{CO_2}}$$

Quicklime has a great affinity for water and will cause caustic burns on skin, as it reacts with any moisture on the skin, so protective clothing and great care are strongly recommended.

The calcination is a reversible reaction so that if insufficient heat is applied, and/or the carbon dioxide gas produced is not removed from the kiln, the reverse process could operate thus:

$$CaCO_3 \leftarrow CaO + CO_2$$

The exact temperature required to convert the limestone to quicklime will depend upon the size of the lumps of limestone and the rate at which the carbon dioxide gas is removed. It will take a long time for large lumps to get sufficiently hot in the centre and for the carbon dioxide to diffuse out; in fact there is a risk that the outer part may be over-burned and block the pores while the attempt is made to heat through to the centre by applying more heat. If pieces of limestone are too small, they will restrict the passage of gases between them and so calcination will be suppressed. Pieces of limestone of mixed sizes will calcine to different extents.

The kiln used for this calcination process can be designed to suit local skills and infrastructure, and of a size to match the market demand. On the simplest and smallest scale, a pit can be dug in the ground and alternate layers of limestone and fuel put in and ignited: the product is likely to be of poor, variable quality.

For more control, better fuel efficiency and a more consistent product, a vertical shaft kiln, constructed of brick or stone, is preferred. A shaft kiln may be operated either intermittently or continuously. For intermittent operation, one filling of limestone and fuel (usually wood or coal) is burned through completely, allowed to cool and then emptied out. The main advantage of batch operation is in being able to match production quantity to small, irregular demand. For continuous production, limestone and the solid fuel are added frequently at the top of the kiln as the calcined material is withdrawn from the bottom. Alternatively, limestone without the solid fuel can be fed at the top, and oil or gas burned as fuel, lower down, through the sides of the kiln. Continuous production in the vertical shaft kiln is more fuel efficient than batch production and a greater output can be obtained from a given size of kiln.

Consideration should be given to the effort required to put large quantities of heavy limestone into the top of the kiln and, if limestone is being dug from a hill as is likely to be the case, it would be wise to build the kiln into the hillside. Limestone can then be fed into the top of the kiln straight from the hillside without having to raise it from the bottom. Large stresses are induced in the structure of a vertical shaft kiln, particularly due to the thermal changes, so it is generally advisable to construct circular kilns rather than ones with a rectangular cross section. Bricks should be laid in lime sand mortar in preference to more rigid mortars which result from the use of OPC. Steel bands around the kiln will provide additional strength to the structure.

It is recommended that for a continuous kiln, the ratio of kiln height to diameter be at least 6:1, preferably 9:1. This provides a buffer storage zone and promotes pre-heating of components by the exhaust gases, correct burning, and initial cooling. Furthermore, if skills of construction are adequate, it is preferable to have the kiln increasing in diameter very gradually from just below the top to near the bottom to assist in the free passage of materials downward. At the base the diameter should then reduce more sharply to assist in extracting the quicklime from the bottom.

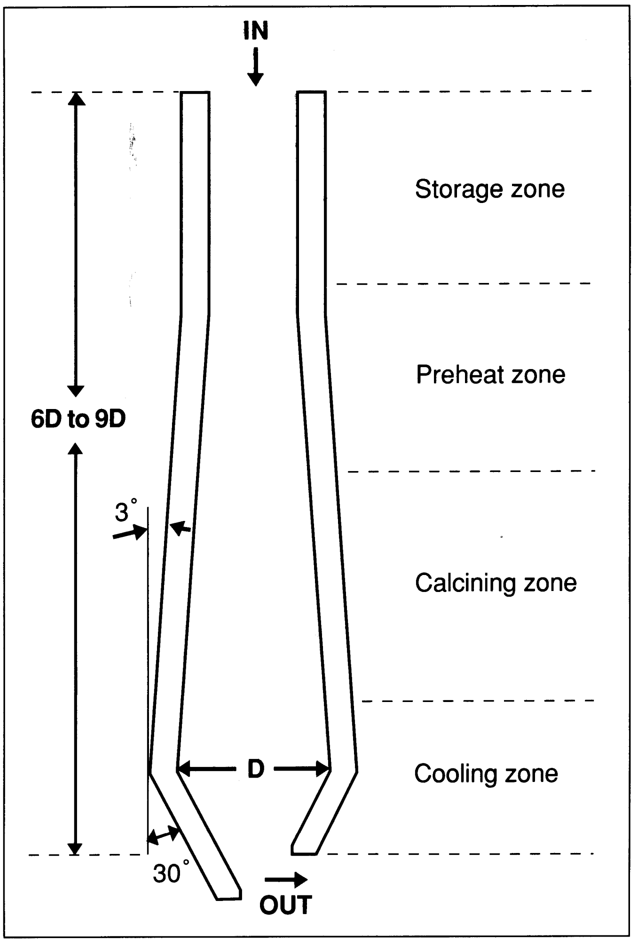


Figure 1 Cross section of tapered lime kiln

For a vertical shaft kiln, the limestone should be broken into pieces approximately 100×200mm (not smaller than 50×100mm; not more than 200×300 mm).

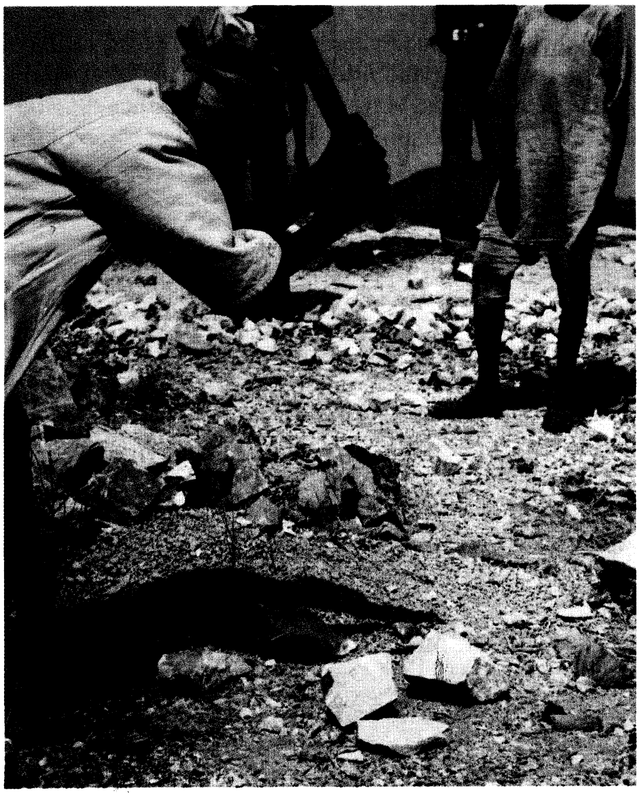


Figure 2 Breaking limestone in Sudan

Poke holes should be incorporated in the walls of the kiln, so that metal rods can be inserted to dislodge material which may be jammed in the kiln.

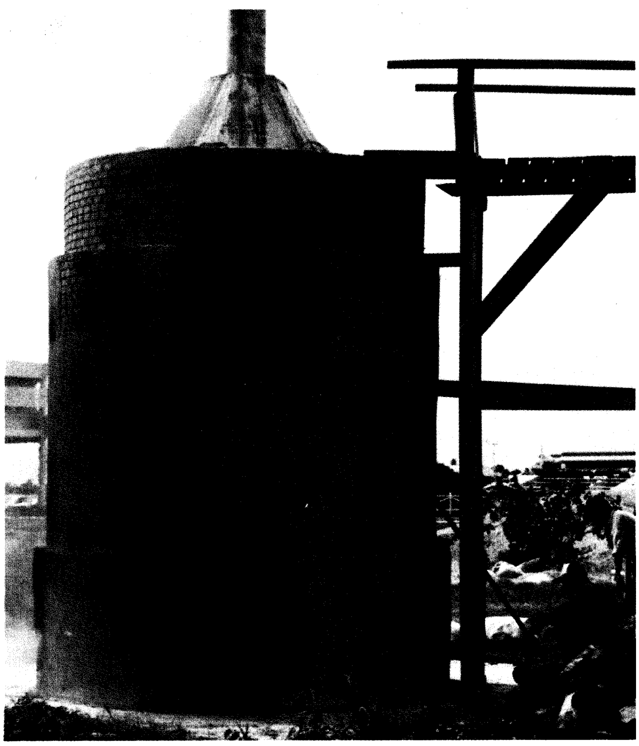


Figure 3 Operating a lime kiln in Guyana

A tonne of limestone will yield half a tonne of quicklime (assuming pure materials and 90% efficiency). In practice it can be expected that with continuous production methods, 2½ tonnes of quicklime may be obtained per day per square metre of cross section of the kiln.

Lime marketed for use is generally not quicklime but slaked lime (also known as hydrated lime). So after the quicklime has cooled, it should be spread thinly and evenly in a shallow pit or on a wooden or concrete platform with a raised periphery to retain the loose material. Water can be sprinkled on the quicklime using a watering can with a rose on its spout. Lumps of quicklime will fall apart on contact with water. It must be borne in mind that the hydration of quicklime generates a large amount of heat, so caution is required for safety's sake. If water is added too slowly, the temperature may rise fast and a gritty inactive product will be formed. If the water is added too quickly, a skin of hydroxide might be formed which will inhibit further hydration. Sufficient water should be used in the slaking pit to produce a crumbly material with a dry appearance.

The mechanism of the hydration process is represented by the equation:

CaO	+	H_2O	$\rightarrow$	$Ca(OH)_2$
quicklime		water		hydrated lime (slaked lime or calcium hydroxide)

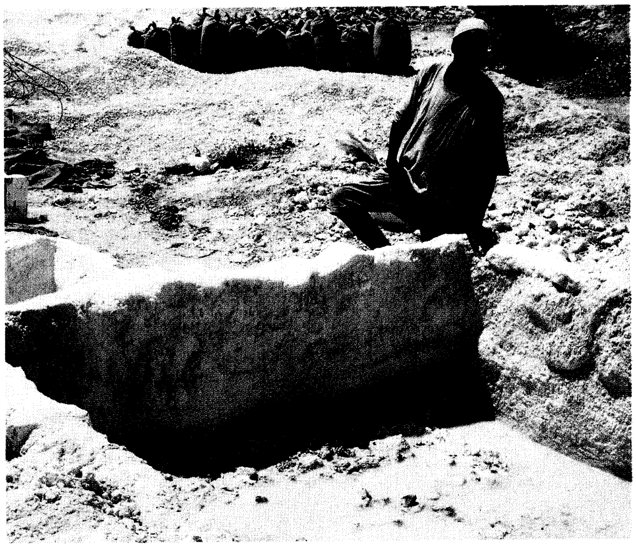


Figure 4 Slaking quicklime in Sudan

The hydrated lime should be allowed to cool, then put in bags and stored in a dry place until required for use.

Where large quantities are required and finance and infrastructure allow, the more mechanised rotary horizontal shaft kiln may be installed and operated to calcine the limestone, giving good control over product quality. A rotary kiln is cylindrical with its axis slightly inclined to the horizontal to facilitate movement of the charge from one end to the other. A typical rotary kiln would be 4 metres diameter and 60 metres long, manufactured from steel plate and lined with refractory bricks. Installation of this type of equipment may require materials and expertise not much less sophisticated than for OPC plant, but this may be an acceptable option in circumstances where resources and demand can sustain operation of such equipment. It may be appropriate in such circumstances to use a mechanical hydrator in which water is sprayed on to the quicklime in a closed box, the mix being agitated with motorised mixing blades.

The above comments are basically for a raw material with a high content of calcium carbonate from which the product is high calcium lime. Sometimes, as in dolomite and magnesian limestone, magnesium carbonate occurs integrally with the calcium carbonate. Calcination of magnesium carbonate takes place at a lower temperature than required for calcium carbonate and hydration of the magnesium oxide is slower than that of calcium oxide. Consequently manufacture is more difficult than with high calcium materials, especially if the proportions of magnesium to calcium vary from one day to another. Therefore in practice it is best to use limestone with less than 3% of magnesia (MgO) if it is available.

The identification of suitable limestone for burning to make lime is a subject for the geologist or minerals specialist, perhaps with the back-up of a laboratory. However, in the absence of such people and facilities, either local tradition may lead to suitable sources or practical experimentation with materials can be helpful. For the latter, a very small, simple kiln can be constructed of local building bricks and iron bars. Then lumps of limestone can be heated, using wood or other locally available fuel. If the limestone pieces decrepitate (break up explosively) they will form much smaller pieces, which block the air flow so the limestone is not a good raw material. After heating and cooling, the quicklime formed can be placed in a pit and sprinkled with water. Much steam and a vigorous reaction is indicative of a good material.

The centres of large particles of the quicklime are not so readily hydrated as are their outsides or the whole of smaller particles. If hydration is not complete during manufacture, delayed hydration may take place in the material after if has been incorporated into the building. As hydration is accompanied by the creation of expansive forces, stresses will develop in the structure, and these may lead either to expansion and possible cracking, or the blowing away of small particles from the surface of building components immediately over the pieces of insufficiently-slaked lime.

As a practical test for quality, water can be added to the slaked lime to enable it to be spread on a test wall. Any subsequent popping of this coating, after it has set solid, will indicate a problem caused by delayed hydration of particles of quicklime. This may be exacerbated by the presence of magnesium compounds in the raw material.

Because the rate of carbonation of lime is very slow, strength of a mortar will be low initially and it will be very slow to gain strength. If some silica also is present naturally in the limestone then, after calcination, it may provide material with which the hydrated lime can react; such reactive materials yield hydraulic limes. The setting and hardening are faster than with high calcium limes. Materials containing silica may be added to high calcium lime as described in some of the following sections. Alumina also can take part in these reactions with lime.

Deposits of sea shells and coral limestone may well be suitable for lime production and indeed have often been used successfully in many parts of the world. However their use may be illegal in some locations for reasons of conservation, coastline protection, etc.

Although this note is concerned primarily with the production of lime for building, commercial viability of a lime production facility may be influenced by the possibility of any other outlets for the product. Thus it is important to investigate the market for lime in road construction, agriculture, paper-making, the leather industry, water treatment, sugar refining, or minerals and chemicals industries for example, as these industries may make production sustainable in situations where building by itself would not.

Pozzolanic cements

As mentioned in the previous section, silica or alumina can be added to high calcium lime to make hydraulic lime. These additives, if possessing the property of reacting with the lime, are defined as pozzolans and the products are generally described as pozzolanic cements. Several pozzolans have been used; some are naturally occurring, others are by-products of various industries.

It cannot be assumed that all such materials have good pozzolanic properties and tests must be carried out to ascertain their reactivity. Where adequate laboratory facilities are available, a quick check can be made by the method of British Standard 4550. The material for test is mixed with a standard OPC and water, then the residual lime remaining in solution and the quantity of silica which has gone into solution are determined and compared. Alternatively, where other test facilities are available, a simple, practical but slower check can be made by fabricating cubes of the material mixed with lime and determining their compressive strengths after 28 days: the higher the strength, the greater the pozzolanicity. Indian Standard 1727 gives detail of test procedures and Indian Standard 4098 indicates acceptable levels of compressive strength for these materials to be used in construction.

Volcanic ash: Material thrown out by volcanoes in recent times or long ago may contain finely divided material, high in silica or alumina. This may be known as volcanic ash, tuff, trass or pumice. It may be reactive with lime, in the presence of water, to form calcium or alumino silicate hydrates. These are the same classes of compounds which are developed in the setting of OPC. The process has been used since the time of the Romans approximately 2000 years ago and was used to some extent by the Greeks before them. Some of these ancient structures remain today as a testimony to the great durability of volcanic ash and lime.

Volcanic ash is still used in several countries at the present time.

Figure 5 Commercially-exploited pozzolana deposit in Cape Verde

To obtain good performance, volcanic ash should be ground down to a very fine powder.

The ash may be used also in admixture with OPC.

Burnt clay: Artificial pozzolan can be made which will behave in a similar manner to volcanic ash. If clay is heated to approximately 700°C and then ground to a fine powder, it will be suitable for reaction with lime. Some clays will be better than others, depending upon their mineralogical composition. This technique was used by the Romans as a substitute for volcanic ash approximately 2000 years ago.

Calcined basalt stone: Research has shown that basalts heated to a temperature in the range 500 to 800°C have pozzolanic properties and can be used with lime or OPC. The optimum temperature will differ from one stone source to another.

Pulverised fuel ash and blast furnace slag: Those electricity generation plants which use powdered coal for fuel, produce large quantities of very fine ash, known as pulverised fuel ash (pfa) or fly ash. It contains silica and some alumina, and has proved useful as an addition to OPC, the gels forming during the setting process being slightly modified from those in OPC alone.

Countries which have indigenous iron and steel industries will generate slag waste. When ground to a fine powder, it can be mixed in with OPC and will act in a similar manner to fly ash. Blast furnace slag is preferred to steel slag as the latter tends to be more variable in composition and may not be very stable in the long term.

Agricultural wastes: Many plants, during their growth, take up silica from the ground into the structure of their leaves, stalks and other parts. When plant residues are burned, organic material (which is the largest proportion) is broken down and disappears as carbon dioxide, water vapour, etc. The ash remaining contains inorganic residues, notably the silica. Of all plant residues, the ash of rice husks contains the highest proportion of silica so it is of most interest in relation to providing a pozzolan for making an alternative cement.

- *Rice husk ash*

Approximately 20% of the weight of rice paddy processed in the rice mills of the world is discarded as husk. About 100 million tonnes of husk are produced in the world annually. A small proportion of this waste material is used as a fuel, for chicken litter, or as a constituent in animal feed but generally it presents a big disposal problem in rice growing countries.

The rice husk ash (rha) remaining after husks have been burned constitutes 20% of the weight of the husks, so a substantial disposal problem remains even after burning. If the husks are burned in a large heap, there is no particular control over the burning conditions though they may be satisfactory in producing an ash with good pozzolanic properties.

Figure 6 Measuring temperature of burning rice husk in Suriname

To reduce the risk of producing unsatisfactory ash, the husks are best burned in a purpose-made incinerator with the aim of restricting the temperature of burning to no more than approximately 750°C. A variety of types of incinerator have been used in various countries, some of which are described here.

Cylindrical wire mesh baskets, supported on steel frames have proved suitable for experimental production of good quality ash though the baskets must be protected from draughts as they produce fast burning and attainment of excessively high temperatures.

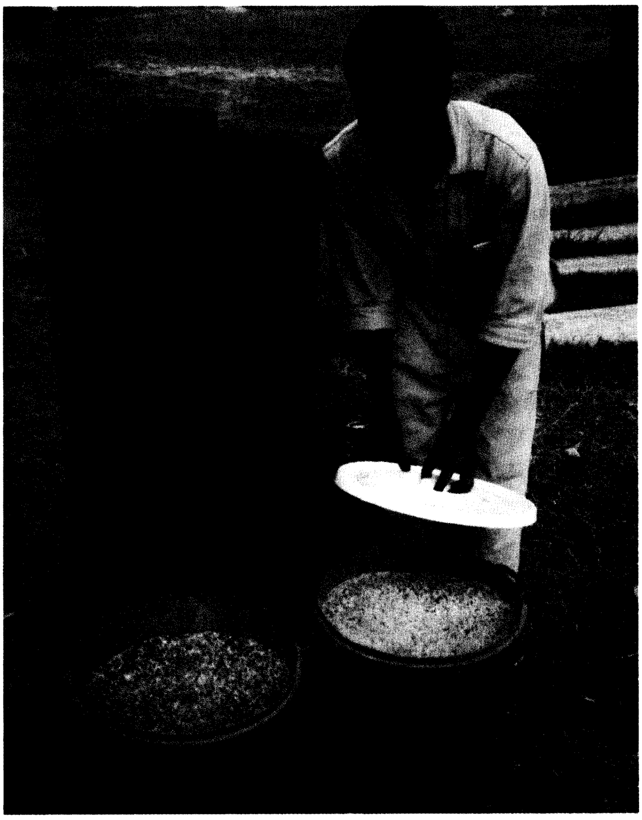


Figure 7 Small wire basket incinerator for rice husk in Malawi

A pilot scale incinerator built from steel sheet, and with air access by perforated tubes passing up though the husk, has been operated successfully.

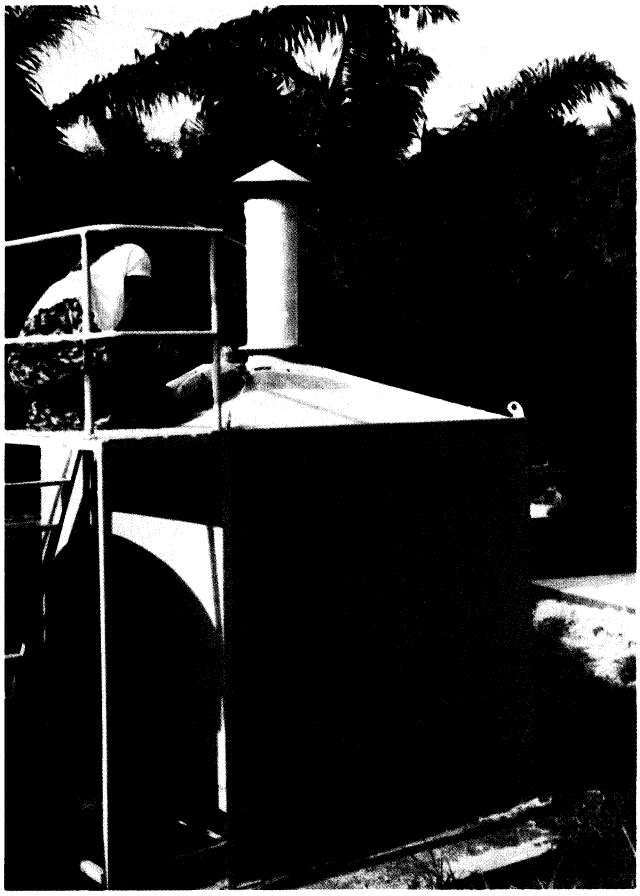


Figure 8 Metal sheet incinerator for rice husk in Malaysia

Small incinerators have been made from ordinary building brick, laid without any mortar, with access for the combustion air through cracks between the bricks. This is only a temporary structure but adaptable, cheap and effective for initial experiments and production of small quantities of ash to determine its properties.

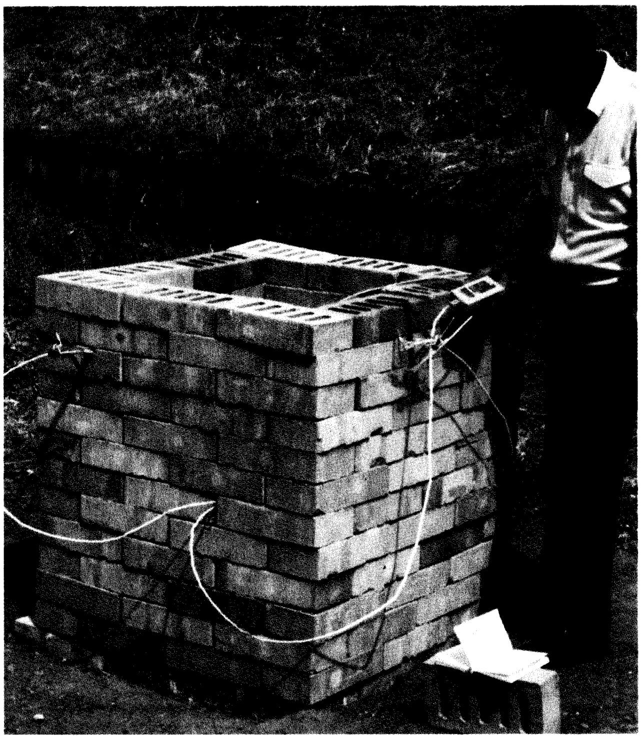


Figure 9 Monitoring burning of rice husk in Sierra Leone

Larger and more substantial incinerators can be modelled on the above. Bricks can be laid in mud mortar, with occasional gaps to allow some access of air for burning and cooling. A small quantity of wire mesh may be used to retain the husks and ash in the incinerator. Such brick-built incinerators are cheap to construct.

Figure 10 Rice husk ash at commercial size incinerator in Guyana

For commercial production plants, corners of incinerators may be strengthened with concrete. Incinerators are usually less than 2 metres high and can be operated with one batch filling at a time, or continuously, with ash being shovelled from the bottom before new husk is added to the top.

Figure 11 Commercial production of rice husk ash cement in India

As the husk burning process is slow, it has been found practicable to operate with only one shift of workers since an incinerator filled up at the end of the afternoon will still be well alight the following morning.

Laboratory tests have shown that if the temperature rises above 750°C, crystobalite, a crystalline, less reactive form of silica, starts to develop, instead of the required highly active amorphous (non-crystalline) type. Temperatures higher than approximately 900°C favour formation of tridymite, yet another poorly-reactive crystalline type of silica. The simplest way to avoid excessively high temperatures from developing is to design the incinerator so that no part of the burning husk is more than approximately half a metre from the outside air so that the heat generated can escape. This may be achieved by making incinerators narrow, or by incorporating vertical air supply ducts which also povide cooling through the burning husks.

To bring the constituents closely together and to provide a large surface area for reactions to take place, the ash must be ground to a very fine powder, resembling the fineness of OPC. This grinding is best done in a ball mill: with reactive ash, half an hour may suffice.

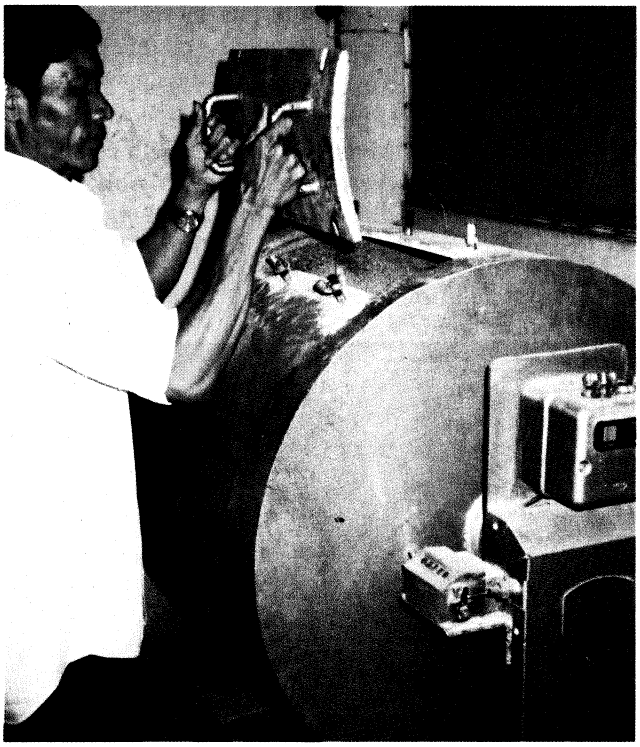


Figure 12 Ball mill for grinding husk in Thailand

In the event of a low reactivity ash being produced, it may still be of use for making rha cement but it will require an extended period of grinding, up to several hours, to increase its surface area and activity in order to produce good quality rha cement. Cost of the ball mill and energy to drive it are major items of expenditure of the whole process, especially in the small scale, labour-intensive technologies which would be appropriate in many developing countries. Residual carbon in the ash, up to 10% by weight, does not particularly affect the mechanical properties of the rha cement; the ash does not have to be white.

Cement may be produced by mixing two parts of ash by weight with one part of lime. Alternatively one part of ash with two of OPC can be used. In the short term, when commercial trials are in hand, the mixing can be done in the same ball mill as used for grinding the ash. This avoids having to acquire an additional mixing machine. If demand for the rha cement increases, the ball mill should not be tied up in the mixing process but should be more profitably employed in grinding the next batch of ash. A blending machine, which is cheaper, can be used for the mixing process. Site mixing of the ingredients of rha cement is possible but will require proper supervision and it has not been substantiated as a reliable method.

Although the possibilities of making rha cement have been known for several decades, commercial production was not initiated until 1971 in the United States of America. Since then several plants have been operated in Guyana, India, Malawi, Nepal, Pakistan, Thailand, etc. Tests and experience in use have shown the material to be satisfactory.

- *Rice straw ash*

Experiments have shown that rice straw burns quickly and easily to give an ash containing 65% silica, which is less than in rha. The pozzolanicity was also much less so straw will be less useful than husk for cement making. Moreover, wherever straw is available, the more-suitable husk will be available and it may be more appropriate to plough back the former into the ground

Figure 13 Rice straw in Malawi

- *Bagasse ash*

After the sugar has been extracted from sugar cane, there remains a fibrous waste known as bagasse and this material poses a disposal problem. Some bagasse is burned at the sugar refineries to raise steam but this still leaves the problem of disposing of the bagasse ash. Although the silica content is only 60% to 70% (which is much less than in rha) there is also approximately 9% alumina and approximately 3% iron oxide present and these compounds may all take part in cement-like setting reactions with lime or with OPC. In addition to the quantities of bagasse burned in the above manner, it could also be specially burned to ash for making a cement-like product in a manner similar to that developed for rha cement.

Other natural organic materials

A variety of materials exists which can be used to bind particles together or to impart water resistance to buildings to improve their performance and therefore they can be considered as alternatives to OPC.

Cow dung has been used traditionally in many places, including the Indian sub-continent, to improve cohesion and water resistance of mud plasters, especially on the outside of buildings. Bull's blood, glue made from bone, hoof or horn and casein made from milk — all have similar potential use.

Drying oils such as linseed oil, plant juices from banana and latex from certain trees also have application.

Bitumen is a mixture of a range of hydrocarbons, occurring naturally, especially in areas of the world where oil and petroleum products originate. It will bind materials together and provide resistance to water. Bitumen has been used as a mortar since the ancient times of the Babylonian Empire, some 3000 years ago, and may still be a viable option where the material is cheaply available.

Gypsum plaster

Mineral gypsum is a crystalline form of calcium sulphate which occurs naturally as a soft rock in many parts of the world. It has been exploited for construction purposes since the time of the ancient Eygptians, 4000 years ago.

When calcined by heating to approximately 165°C gypsum releases three quarters of its water of crystallisation to give hemi-hydrate plaster, known also as plaster of Paris. If calcination is for an extended time, or the temperature is well above 165°C, all the water will be released, and anhydrite will be formed. These reactions are represented by the equations:

$$\underset{\text{gypsum}}{CaSO_4.2H_2O} \xrightarrow{\text{heat}} \underset{\text{plaster of Paris}}{CaSO_4.{}^1\!/_2H_2O} + \underset{\text{water}}{1{}^1\!/_2H_2O}$$

$$\underset{\text{plaster of Paris}}{2CaSO_4.{}^1\!/_2H_2O} \xrightarrow{\text{heat}} \underset{\text{anhydrite}}{CaSO_4} + \underset{\text{water.}}{H_2O}$$

The most basic method of calcination is to mix fuel with lumps of the broken gypsum rock, in a heap or in a pit, and burn it for several days. A stone or brick vertical shaft kiln will give better control.

In some parts of the world, notably in northern Africa and also in the Cape Verde Islands, the gypsum occurs as a fine sand. Then no preliminary crushing is required. The material is heated on a flat metal sheet by a fire beneath, the operators raking the product to one side as soon as they perceive a lightening in colour - indicative of the completion of the calcining to the hemi-hydrate stage.

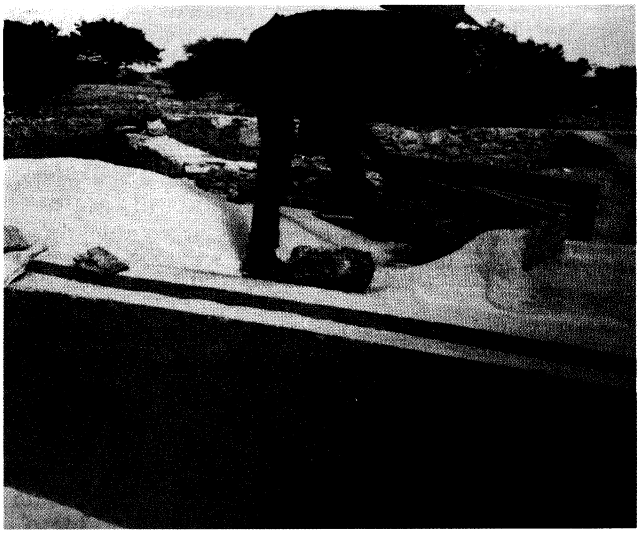


Figure 14 Production of gypsum plaster in Cape Verde

In more industrialised locations, a mechanised plant has been used utilising a rotating pan, heated from beneath, and containing broken rock, turned over and broken down as the pan rotates by heavy metal chains. More advanced enclosed kilns, known as gypsum kettles, are used in more developed countries and rotary kilns can be very effective in producing a consistent product.

In processes where fine particles of gypsum are heated, the surface of the powder appears to boil as water is expelled. Visual observation of the cessation of 'boiling' is a useful indicator of the completion of conversion to the hemi-hydrate form. If heating were continued, a 'second boil' would occur and anhydrite would be formed.

If the plaster is to be stored, it must be kept dry.The hardening of the plaster takes place in less than 10 minutes, so for many construction purposes a retarder is added during manufacture. Many organic materials retard the set, but keratin has often been used; it is made from animal hoof and horn. Experiments in Cape Verde showed glue made from waste fish bone to be effective.

Figure 15 Experiment with fish glue as plaster retarder in Cape Verde

There are natural deposits of anhydrite in some locations and it can be used for construction. However its hydration, with resultant hardening and setting, is very slow so an accelerator is required. Crystalline inorganic materials such as alum are effective in accelerating the process.

Occurrences of mixed deposits of gypsum and anhydrite are difficult to process and use, and are best avoided.

In addition to the large production of gypsum for the manufacture of plasters, another major market for gypsum is as a controller of the rate of set of OPC. Production of gypsum has been required also for many years for pharmaceutical, medical and dental purposes, for mould making in the pottery industry, in artistry, where plaster of Paris is well known for its ease of moulding and carving, as a fertiliser and as a filler in paper-making and the plastics industry. Such alternative uses will enhance the feasibility of setting up gypsum plaster production.

Mud

Wet mud may be used as a mortar in which to lay bricks. Even in dry climates the mud mortar may be eroded, not only by such rain as may fall occasionally, but also by wind or sand storms, while in damper climates the erosion by rain will be greater. Therefore a water resistant rendering will be required to protect the mud. Use of mud mortar is compatible with the use of mud brick and such a building method has the advantage of using materials which are local and are of almost zero cost, so their use should be considered for lowest cost building schemes.

Mud renderings may be modified by incorporation of fibrous material such as straw or by mixing in cow dung or bull's blood, bituminous material or vegetable oil.

Sulphur

Sulphur is found occurring naturally in areas of volcanic activity, for example, in Sicily, Chile and Mexico. The naturally occurring sulphur may contain 80% of impurities. Where sulphur occurs deep below the ground surface, it may be extracted by sinking a pipe down which super-heated water is forced to melt the sulphur: compressed air is injected to raise it to the surface.

A traditional method of purifying the raw material was to ignite it in a sulphur kiln. The heat of combustion caused the sulphur to melt; it was then run out of the bottom of the kiln and cast into blocks. If higher purity sulphur is required (for example in the chemical industry), refining is done by distillation.

Sulphur occurs naturally also compounded with other metal ores such as galena, zinc blende and iron pyrites and can be separated from these ores by chemical processes. Sulphur is generated in some countries as a by-product in the de-sulphurisation of petroleum and natural gas.

Sulphur was known to the ancient Greeks and in the Middle Ages was considered to be a principal component in fire. Its combustible nature is a factor to be borne in mind in any building use. Use of sulphur for construction purposes should be considered where the material is locally available and cheap.

Sulphur is produced for industries other than construction, for example in the production of sulphuric acid and manufacture of fertilisers and insecticides.

4 METHOD OF USE OF ALTERNATIVE CEMENTS

To make strong concrete or mortar, all the spaces between large particles should be filled with small particles, and all the spaces between the small particles should be filled with a cementitious binder. Thus for concrete, proportions of 1:2:4 cement:fine aggregate:coarse aggregate are normal and for a mortar, volume proportions of 1:3 cement to sand are normally required regardless of the actual nature of the cement used.

Lime

For use as a mortar the hydrated lime, mixed with three times its volume of sand, should be wetted with sufficient water to give it a workable consistency so that it may be spread evenly and at the correct thickness for laying bricks or blocks.

Because the rate of carbonation of the high calcium hydrated lime will be slow, strength developed by carbonation will be minimal for many weeks. Consequently, only a few courses of bricks can be laid at a time. The work must be left until the mortar has stiffened sufficiently, by the evaporation or absorption of water into the bricks, to ensure that the mortar is not squeezed out as load is imposed by subsequent courses being laid above. Though this type of mortar is not particularly useful for bedding bricks and blocks, it is satisfactory for rendering the surfaces of walls.

Hydraulic lime mortar may be used both for bedding bricks and blocks, and for rendering as it will set and harden much more quickly than the high calcium lime mortar.

A very satisfactory range of mortars can be made by using various proportions of OPC and lime with sand. This note concentrates upon alternatives to OPC but mixes of lime and OPC might be considered as they can reduce the amount of OPC required for any particular job. Where air-entraining agents are available, they can be incorporated in mortar mixes so decreasing the amount of mixing water required. This can result in either increasing the strength of the mortar or reducing the quantity of cement and lime requires to give a mortar of a specified strength.

If hydrated lime is not available from suppliers, then quick lime may be obtained instead and hydrated in a slaking pit at the building site. It is good site practice to leave the material after hydration with an excess of water to form lime putty, which should be left covered to protect it from the air and the weather for several weeks or months. This extended period will ensure that hydration is thoroughly completed, so obviating the risk of lime blowing.

Addition of much more water will produce a wet slurry known as milk of lime. This material can be used for lime-washing buildings, to make them white to reflect the radiant heat of the sun and to improve the weathering properties of walls.

A very good lime wash may be made by the addition of tallow during the slaking process so that the evolved heat melts the tallow. The mix should then be diluted with water. Proportions of 3:1:7 of quicklime:tallow:water are recommended, but additional water may be required subsequently, at the time of use, to make the mix suitable for application by brush. Mixes containing less tallow have also been suggested (eg 13:1:13).

Pozzolanic cements

Volcanic ash: The reactivity of volcanic ash varies a great deal and it cannot be assumed that all such ashes will be of commercial value for making cements. Tests must be carried out to determine their activity.

With a suitably reactive ash, one part by weight of lime might be added to two part of the ash to make a so-called pozzolanic cement.

In some countries, at the present time, trass and lime are used in the production of building blocks.

Alternatively, volcanic ash may be added to OPC and this is in fact being done commercially by cement manufacturers. Up to 30% replacement of OPC is quite likely to be feasible and even higher percentages may be worth investigation.

Burnt clay: Use of clay burned to approximately 700°C as a pozzolan is long established, and has continued in use for mortars, especially in the Indian sub-continent where it is known as surkhi. Tiles and bricks which have been rejected because they have been under-burnt in production, may be pulverised to make a useful component in mortars. Surkhi is produced also by specially heating clay. The commercial product is of coarse particle size and has only a small reaction with lime. Research has shown that if it is broken down to a much finer powder, its pozzolanic properties are increased. In practice, the cost of making it fine must be weighed against the benefits obtained.

Calcined basalt stone: The calcined stone must be ground to a fine powder. Research in Vietnam has shown that this powder mixed with lime in proportions 70:30 respectively gives a satisfactory cement. An addition of 4% gypsum is very advantageous in enhancing the properties.

Alternatively, up to 30% replacement of OPC by the calcined basalt powder may be made.

Pulverised fuel ash and blast furnace slag: Up to 30% replacement of OPC by pfa or finely ground blast furnace slag have been proved to be satisfactory. The mixing of components has been carried out in practice at the cement factory. Both products have been marketed successfully for several decades.

Agricultural wastes: Ash remaining after agricultural wastes have been burned can be used with lime or OPC.

- *Rice husk ash*

RHA cement can be used to make mortars and renderings.

Figure 16 Rice husk ash cement used in mortar in India

RHA cement is also suitable for making concrete blocks.

Proportions of constituents will depend upon their quality and upon the properties required in the final product. Experiments should be carried out in any particular project, to determine the optimum.

Proportions of 1:2 lime:ash may be satisfactory if the ash is fairly reactive but variations on these mix proportions should be tried before a final decision is made. Similarly 70:30 OPC:ash may be taken as a guideline mix but variations should be tried.

It is recommended that the proportioning and mixing be carried out under factory conditions, prior to delivery to the construction site, as better processing is likely to be carried out than if mixing is done on site.

- *Rice straw ash*

Proportions of straw ash similar to those for husk ash might be used but the product is likely to be inferior to the rha cement.

- *Bagasse ash*

Research into various mix proportions has shown that a 20% to 30% replacement of OPC gives a useful cement.

Other natural organic materials

Mud renderings on the outside of walls may be made more water-resistant by the incorporation of cow dung. A thin paste made by adding water to a mix of one part dung and five parts soil may also be used as a wash on a mud rendering.

Additions of bull's blood, glue made from bone, hoof or horn and casein made from milk also have use. Drying oils such as linseed oil, rubber latex and plant juices have application.

Bitumen can be used by melting it or dissolving it in a solvent such as kerosene or naphta, or dispersing it in water as a fine emulsion. When in a solvent base, it is termed cut-back bitumen, and this or the emulsion will waterproof materials: it can be mixed in with earth to make mud bricks, whether or not compaction pressure is applied in forming the bricks.

Gypsum plaster

For use water must be added to the plaster of Paris. The plaster combines with the water, crystallising into the same form as the original mineral:

$$\underset{\text{plaster of Paris}}{CaSO_4.{}^1/_2H_2O} \quad + \quad 1{}^1/_2H_2O \quad \rightarrow \quad \underset{\text{set plaster}}{CaSO_4.2H_2O}$$

Plaster may be used with or without the addition of up to three parts of sand, made up with water into a paste, for finishing the surface of interior walls and for decorative work indoors. For external rendering, sometimes either lime or OPC is added to improve durability of gypsum plaster.

A similar mix to that used for rendering may be used as a mortar. The quick setting of the plaster of Paris makes it ideal for domes, vaults and arches, constructed without supporting formwork or centring. Building can proceed as new bricks are laid upon ones which have been laid only a short time before, yet are able to take the superimposed load of the new as the plaster has set so quickly. Arches, for example, are built simultaneously from both sides until the topmost brick or keystone is laid and the arch is complete. This mode of building has been practised, for example, in Iran.

Building blocks can be produced by mixing with coarse aggregate.

Figure 17 Gypsum plaster and aggregate being mixed in Cape Verde

The mix is then cast in simple moulds. As the plaster is fast-setting, the moulds can be re-used within only a quarter of an hour so effecting economies in the provision of equipment. This process is used successfully for example in the Cape Verde Islands, where a gypsiferous sand occurs locally. The blocks are used in local housing.

Figure 18 Internal wall of plaster/aggregate block in Cape Verde

If lightweight aggregate such as pumice is available, it may be used to produce lightweight gypsum blocks: some experiments have been conducted at BRE, demonstrating the ease with which these materials can be mixed and used.

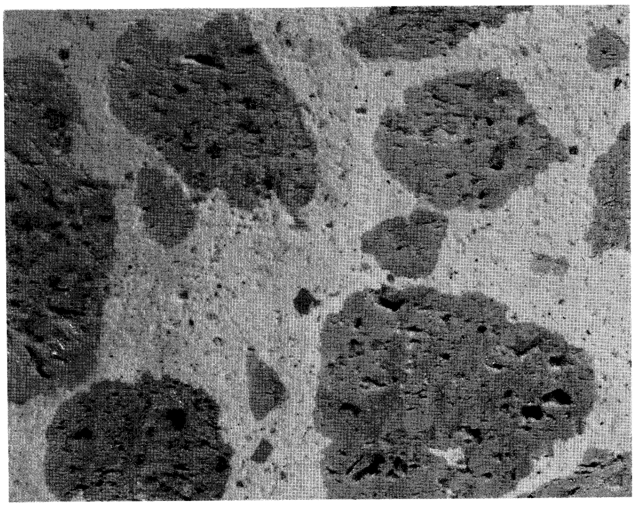


Figure 19 Cross-section through plaster/pumice block

Lightweight blocks will impose less load on foundations and will have improved thermal insulation.

A fast-setting but weak type of concrete can be made by placing coarse aggregate in suitable formwork and then pouring in a gypsum plaster slurry, 2:5 water:plaster by weight. This method has found some application in North Africa.

In industrialised countries gypsum boards are made with a strong paper board surface, which not only gives a very good finish but also imparts excellent mechanical properties to the board. However the process is capital intensive, it needs very accurate control and the required grade of paper accounts for a high proportion of the cost of the board. As an alternative method of strengthening the gypsum, instead of the paper facings, fibres can be added to the wet mix of plaster. Addition of sisal fibres has been made in commercially operated plant, for the fabrication of gypsum boards and panels. A paste of gypsum plaster is spread on a horizontal flat bed, fibres are laid in by hand and then the fibres are covered with another layer of the paste. The reinforced sheet is removed from the bed as soon as it has set. To allow further strength development, the sheet should be kept in a damp atmosphere for a day whilst further crystallisation of the gypsum takes place: damp storage is particularly important in arid climates. Sisal reinforced gypsum boards were made and used successfully for several years in Australia and the process could be appropriate in those developing countries where gypsum and indigenous fibres are available.

Rigid storey-height gypsum panels have been produced using fairly simple technology. One skin of a sandwich panel, complete with a honeycomb-shaped strengthening, is first cast in a rubber-faced mould. As soon as the plaster has set, it is de-moulded and the honeycomb side is laid onto a freshly poured second skin of plaster: as the latter sets, it bonds to the honeycomb to form the complete sandwich panel.

Mud

The cementing effect of mud is due chiefly to the properties of the very small particles of clay in the mud. High clay contents will result in large drying shrinkage and risk of cracking, so such soils should be mixed with sand to reduce the net proportion of clay. Soils low in clay exhibit poor adhesion and strength so would require additions of other material with a high clay content.

If oils, bituminous material or cow dung are mixed in, they will improve the durability of the mud.

Sulphur

It is not necessary to have high purity sulphur and raw material with only 30% sulphur may be useful. With high sulphur content raw material, sand or coarse aggregate will be added. The principle of use is to melt the sulphur mixed with aggregate or coat building elements with the molten sulphur. As it cools, it solidifies into a crystalline form (known as β-sulphur).

Sulphur concrete may be made with proportions of 1:1:2 sulphur:sand:coarse aggregate. Either the sulphur and aggregate are mixed together in a heated mixer at approximately 150°C or the aggregate is raised to approximately 180°C first so that, on mixing with sulphur, the latter is melted by the hot aggregate. Sulphur concrete must be poured whilst still hot. Surfaces of loose-laid bricks or blocks can be coated with molten sulphur, with a brush or a roller, to stabilise and strengthen the structure and to make it waterproof, a technique which may be especially useful for gypsum blocks.

5 PROPERTIES OF ALTERNATIVE CEMENTS

Lime

Lime develops strength by carbonation and the rate of gain in strength is very slow. An advantage of lime mortars is that they are able to accommodate internal stresses within brickwork and blockwork more than do OPC mortars.

Mixes of OPC and lime with sand are being designated in European (CEN) Standards. Minimum requirements for strength of site-mixed mortars are:

Mortar designation	Proportion dry material by volume			Minimum compressive strength after 28 days
	cement	lime	sand	N/mm²
(i)	1	0 to 1/4	3	10.0
(ii)	1	1/2	4 to 4 1/2	5.0
(iii)	1	1	5 to 6	2.5
(iv)	1	2	8 to 9	1.0
(v)	1	3	10 to 12	–

Pozzolanic cements

The rate of setting of lime is accelerated, and the compressive strength increased if pozzolans are added to the lime. Concrete made from OPC can be made more resistant to aggressive chemicals and its strength may be improved, under certain conditions, by admixture of a pozzolan with the OPC.

Volcanic ash: Some naturally-occurring pozzolanas from volcanic sources have been used to improve concrete strength. For example, in Kenya, 15% and 30% of a yellow tuff added to OPC, increased the compressive strength (at 28 days) by 20% and 2% respectively. However, the same proportions of a pumice reduced the compressive strength by 8% and 21%, appearing to act as little more than inert aggregate. This emphasises the need for proper investigation of resources.

Burnt clay: Though coarse surkhi has little reaction with lime, acting largely just as aggregate, powdered surkhi and lime gives mortars with compressive strengths up to 7 N/mm² — which is generally adequate for single or two storey constructions. Lime-surkhi mortars have less shrinkage and greater impermeability than OPC-based mortars and are more able to accommodate internal stresses.

Calcined basalt stone: Calcined basalt stone, replacing 15% of the OPC, gives higher 28-day strengths than does OPC alone. Larger replacements give progressively lower strengths.

Replacement of OPC by calcined basalt stone	28 day compressive strength
%	N/mm²
nil	32
10	32
15	34
20	30
30	28

Experiments carried out elsewhere with basalt dust which was not calcined have shown no such strength gains. In this case the un-calcined dust is acting merely as an inert aggregate.

Pulverised fuel ash and blast furnace slag: Incorporation of pfa or powdered blast furnace slag makes a given quantity of OPC go further and gives better chemical resistance. These materials have been used successfully in industrialised countries for several decades and are well authenticated. Research and experience in some of the developing countries which generate electricity from coal has indicated the process to be worthwhile there also.

With replacement of OPC by up to 30% of fly ash, or more in some cases, the compressive strength of the concrete may be as great as if no replacement had been made. An additional benefit is realised in large concrete structures where the low heat of hydration gives smaller thermal stress than would have occurred with OPC.

Variation in the nature of the pfa will lead to variation in the quality of the concrete produced so analysis and control of the process are necessary in order to provide a consistent product.

Agricultural wastes: More development work has been carried out with rha than other plant wastes, so more data are available on the former material.

- *Rice husk ash cement*

In tests carried out in Malawi the initial and final setting times of lime:ash mixes were 4 hours and 7 hours respectively.

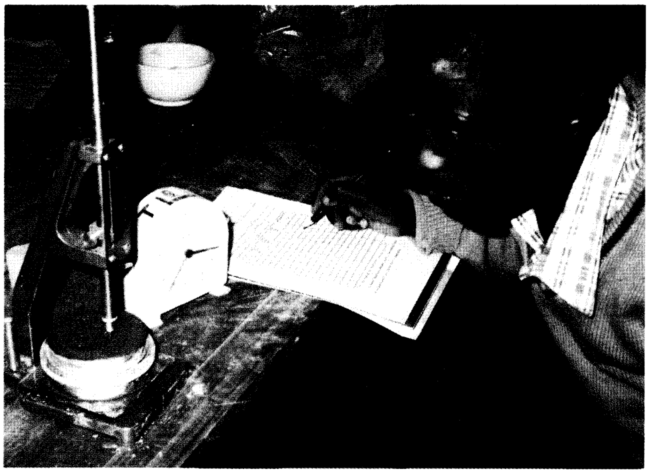


Figure 20 Checking rice husk ash cement setting time in Malawi

The 28-day compressive strength of 1:2 lime:ash mortar was up to 4 N/mm^2, depending upon period for which the ash was ground in a ball mill as follows:

Period of grinding minutes	28-day compressive strength N/mm^2
120	4.6
30	3.7
5	0

From this and other work, it is concluded that 30 minutes is generally sufficient grinding time.

Test walls built with bricks laid in rha cement mortar, and partly rendered with the same mix, have proved the good durability of the rha cement when exposed to the weather in Malawi. These properties are adequate for the general purposes of constructing low-cost shelter.

Research in Guyana showed that higher strengths were obtained with OPC:ash mixes than with the lime:ash mixes. With as much as 50% of the OPC replaced by ash, the compressive strength of mortar and of concrete at 28 days was similar to that of OPC alone; higher replacement gave only slightly less strength:

Mix proportions	28-day compressive strength of mortar
ash:OPC	N/mm^2
OPC alone	17
1 : 1	16
2 : 1	14

Building blocks have been made with rha cement concrete and, exposed to the local climate in Guyana, have proved their good durability.

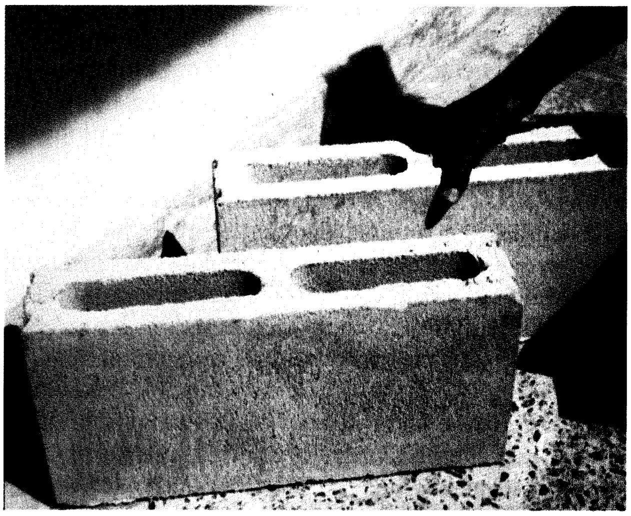


Figure 21 Blocks made from rha cement (front) and OPC (back) during weathering test in Guyana

In research elsewhere into mix proportions, a 30% replacement of OPC gave a cement slightly less strong than OPC alone after 28 days' storage. The mix continued to gain strength, and after a year approached the strength of OPC .

- *Rice straw ash cement*

The pozzolanicity of rice straw ash burned in Malawi was much less than that of rha and mortar cubes made with finely ground straw ash had only half the strength of rha cement cubes. Hence rice straw is unlikely to be a viable alternative to rice husk.

- *Bagasse ash cement*

Research has shown that addition of 20% bagasse ash to an ordinary cement gives a very slight reduction in strength at early age but that after three months, the strength is similar to that of mortar made from ordinary cement and sand only.

Other natural organic materials

Wide variations exist in materials, traditions and climate but the beneficial effects of cow dung, bitumen, etc have been proved through many years of use.

Rubber latex has been shown to improve workability of cement mixes, and to improve bond of cement on to steel, but the compressive strength is reduced.

Gypsum plaster

Compressive strength of gypsum plaster blocks, even when tested after soaking in water for 24 hours, is more than is required for low cost building schemes. Addition of pumice reduced the strength, as shown.

Mix proportions		28-day compressive strength
plaster: pumice		N/mm^2
100	0	14.6
80	20	11.0
58	42	10.4
20	80	4.4

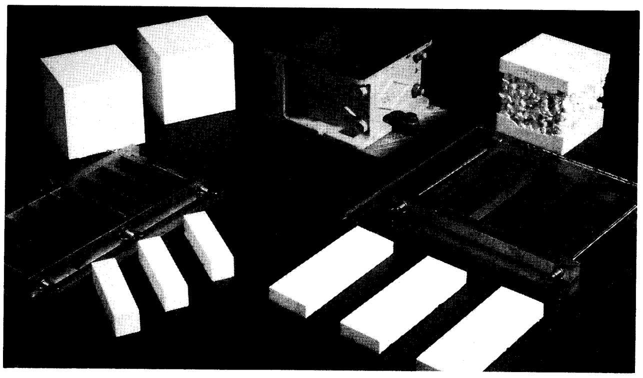


Figure 22 Gypsum samples made up for laboratory testing at BRE

Gypsum plaster is slightly soluble in water, to the extent of 2 grammes per litre of water. Consequently, it is eroded by running water, though wet static conditions will not cause catastrophic failure as the water in the near vicinity of the gypsum will soon become saturated and dissolution will then cease.

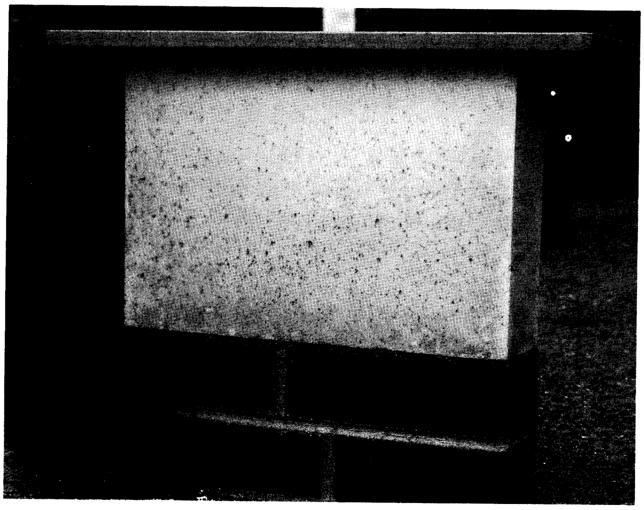


Figure 23 Gypsum plaster block on exposure test at BRE

In arid climates gypsum plasters can be used externally without excessive deterioration. This is traditional in Cyprus but in practice a small amount of repair and maintenance is required to maintain the material in good condition in the long term. In wetter climates any external gypsum plaster work should be protected from driving rain by providing generous roof overhangs and balconies. No faults in rain-water goods can be tolerated lest the water flow over the surface of the plaster. Durability of gypsum plaster may be improved by addition of 5 to 10% of lime.

Products made from gypsum have good fire resistance because of the inherent water of crystallisation in their structure which has to be evaporated off first before the product is weakened and damaged.

Mud

Mud is effective as a binder in dry climates but will be weakened when moistened, and washed away if water flows over its surface. Where mud is used as a mortar for laying bricks or blocks, some protection may be advisable therefore. A mud rendering reinforced with cow dung, which is traditional in the Indian sub-continent, can be effective in reducing erosion, not only of the mud mortar itself but also of the bricks if they too are made of mud. The waterproofing effect of oils or bitumen also enhances the resistance to erosion by water.

Sulphur

A mix of 1:1:2 sulphur:sand:coarse aggregate has a compressive strength of 40 N/mm^2 at 28 days which is similar to that of traditional 1:2:4 OPC:sand:coarse aggregate concrete (made with water). However the strength development of the sulphur concrete is very much faster, 90% of the 28 day figure being attained within only 6 hours.

Sulphur concrete cast at elevated temperatures of approximately 150°C exhibits a thermal shrinkage as it cools. The magnitude of this thermal shrinkage is similar to the moisture shrinkage of OPC concrete in 28 days. Consequently, if a wall is cast *in situ* in a number of separate vertical batches or 'lifts', and each lift cools before the next is poured on top of it, large thermal stresses will develop between adjoining lifts. It is advisable to pour a new lift as soon as possible to minimise temperature difference at the join of successive lifts.

The creep of sulphur concrete is greater than that of OPC concrete.

Sulphur gives a building material which is hard, strong and waterproof. However it will change into another crystalline form with passage of time (giving α-sulphur). Although the newly formed α-sulphur crystals themselves are more stable, the transition is accompanied by a breakdown of the original form and in effect the sulphur crumbles to powder. The rate of change may be very slow in cold climates but this phenomenon should be taken into consideration and checked before construction decisions are made.

Dicyclopentane, which is derived from the petroleum and coal industries, can be added to the melt to slow down this change in crystalline form. Also it has the additional advantage of improving fire resistance, yet it is not an expensive material.

Sulphur surface-bonded houses constructed in Colombia, were in excellent condition after 12 years.

6 CONCLUDING COMMENTS

This Overseas Building Note makes clear that there are many alternatives to OPC, especially for making mortars in which to lay bricks and blocks, and with which to render the surface of walls.

Local conditions and requirements must be used to determine the best way to proceed. Availability of raw materials, infrastructure and geography, labour and skills, building requirements and performance, health and safety, all should be considered. Before venturing into any new production and use, careful study should be made of all these points, the market for the product should be researched and the economic feasibility examined.

Lime is a component of many of the OPC alternatives so the possibilities of its production are likely to be especially relevant. Nevertheless, for any particular location, all possibilities ought to be considered. With small scale production technologies, which are often appropriate for OPC alternatives, even quite small quantities of raw materials which may not have been identified in any national survey of available resources can be helpful in alleviating a small local need for materials and the subsequent provision of shelter and communal facilities.

7 ACKNOWLEDGEMENTS

Production of this note, and some of the research work to which reference is made, was funded by the UK Overseas Development Administration as a part of the UK aid programme to developing countries

8 BIBLIOGRAPHY

Cementitious materials in general

Lea F M. The chemistry of cement and concrete. Arnold, London, 1970.

Taylor H F W. Cement Chemistry. Academic Press, London, 1990.

Lime

Bessey G E. Production and use of lime in developing countries. Overseas Building Note 161, Building Research Establishment, Garston, 1975.

Boynton R S. Chemistry and technology of lime and limestone. Interscience (Wiley), New York, London, Sydney, 1966.

Hill N R. Field testing of limestones for limemaking, Proc first international seminar on lime and other alternative cements, Stoneleigh, Intermediate Technology Publications, London, UK, 1993.

Wingate M. Small-scale lime-burning. Intermediate Technology Publications, London, 1985.

Pozzolanic cements

British Standards Institution. Methods of testing cement. BS 4550:1970; part 2, BSI, London, 1970.

Cabrera J G and Cusens A R. The use of pfa in concrete. Proc international Leeds University/ Concrete Society/CEGB symposium, Leeds, England, 1982.

Galal A F, Shater M A and El-Didamony H. Portland-basalt mixed cement, Proceedings of a CIB/RILEM Symposium, Appropriate building materials for low cost housing, pp 84-89, Nairobi, 1983, Spon, London, 1985.

Hidayat Y S and Idris A A. The possibility of using fly ash as a partial cement replacement in massive concrete. Masalah Bangunan, Vol. 30, No 3-4, Bandung, Indonesia, 1989.

Hough J H and Barr H T. Possible uses for waste rice husks in building materials and other products. Agricultural Experimental Station, Louisiana State University,Bulletin 507, 1956.

Indian Standards Institution. Specification for lime-pozzolana mixture, IS 4098, ISI, New Delhi, India, 1976.

Indian Standards Institution. Methods of test for pozzolanic materials, IS 1727, ISI., New Delhi, India, 1967.

Kapur P C. TiB: tube in basket rice husk burner for producing energy and reactive rice husk ash, Proc third workshop on rice husk ash cement, New Delhi, India, Rural Centre for Technology Transfer, Bangalore, India, 1981.

Mehta P K. Rice husk ash cement - high quality, acid resisting. Journal of the American Concrete Institute, Vol.72, pp.235-6, New York, 1975.

Mohamedbhai G T C and Baguant B K. Possibility of using bagasse ash as partial substitute for cement in Mauritius, University of Mauritius, 1985.

Ngo V M. Basaltic stones for cement and other binders, Proc first international seminar on lime and other alternative cements, Stoneleigh, Intermediate Technology Publications, London, UK, 1993.

Smith R G and Tait G. Rice husk ash cement in Guyana. Proc third CIB/RILEM symposium, Mexico, 1989.

Smith R G. Rice husk ash cement: progress in development and application. Intermediate Technology Publications, London, UK, 1984.

Smith R G and Kamwanja G A. The use of rice husks for making a cementitious material. Proc. joint CIB/RILEM symposium, Baghdad, 1986.

Smith R G. Rice husk ash cement - Small scale production for low cost housing, Proc international conference on low cost housing for developing countries, CBRI, Roorkee, India, pp. 687–695. Sarita Prakashan, Meerut, India, 1984.

Smith R G. Consultant's report on production of rice husk ash cement in Suriname, 19 pp., UNCHS (HABITAT), Nairobi, Kenya, 1988.

Smith R G. Rice husk ash cement, Proc first international seminar on lime and other alternative cements, Stoneleigh, Intermediate Technology Publications, London, UK, 1993.

Tuts R. Potentialities and constraints for using pozzolanas as alternative binders in Kenya, Proc first international seminar on lime and other alternative cements, Stoneleigh, Intermediate Technology Publications, London, UK, 1993.

Other natural organic materials

Gazely K F. Aspects of the modification of Portland cement with natural rubber latex. NR Technology, Vol 10, part 2 1979, The Malaysian Rubber Producers' Research Association, Hertford, UK.

Gypsum plaster

Coburn A, Dudley E and Spence R. Gypsum plaster: its manufacture and use. Intermediate Technology Publications, London, UK, 1989.

Smith R G. Gypsum. Proc one-day meeting on small-scale manufacture of cementitious materials. London, UK, 1974.

Smith R G. Small-scale production of gypsum plaster for building in the Cape Verde Islands. Appropriate Technology Vol 8 No 4. Intermediate Technology Publications, London, UK, 1988.

Mud

Stulz R and Mukerji K. Appropriate building materials. Swiss Center for Appropriate Technology, St Gall, Switzerland, 1988.

Sulphur

Loov R E, Vroom A H and Ward M A. Sulfur concrete - a new construction material. Journal of the Pre-stressed Concrete Institute, Jan/Feb 1974, pp 86–95, 1974.

Ludwig A C. Sulphur surface bonding of mud blocks in Africa. Techniques for sulfur surface bonding for low cost housing. South-west Research Institute, Houston, Texas, USA, 1977.

Printed in the UK for HMSO Dd.8379498, 3/93, C15, 38938