This research demonstrated that recycled gypsum from waste plasterboard can be converted to the high purity form of gypsum required for making plaster moulds.

This report details the development of the process and testing in factory environments, identifying further work required for its commercialisation.
WRAP helps individuals, businesses and local authorities to reduce waste and recycle more, making better use of resources and helping to tackle climate change.

Written by: Peter Hancock

Front cover photography: Teapots from gypsum moulds, awaiting firing

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Context

WRAP
WRAP (Waste & Resources Action Programme) works in partnership to encourage and enable businesses and consumers to be more efficient in their use of materials and recycle more things more often. This helps to minimise landfill, reduce carbon emissions and improve our environment.

Established as a not-for-profit company in 2000, WRAP is backed by Government funding from Defra and the devolved administrations in Scotland, Wales and Northern Ireland.

WRAP and plasterboard
Through its Construction Programme, WRAP is helping the construction industry cut costs and increase efficiency through the better use of materials.

Plasterboard is used extensively in the construction and refurbishment of buildings as a lining for walls and ceilings, and for forming structures such as partitions.

Plasterboard waste can arise on construction sites for a number of reasons, including wasteful design, off-cuts from its installation, damaged boards, and over-ordering. It is estimated that over 300,000 tonnes per year of waste plasterboard is produced on construction sites. It can also arise from strip-out activities during refurbishment and demolition projects; the waste arisings from this source are significantly higher. In total it is estimated that over one million tonnes of waste plasterboard are produced each year from construction and demolition activities.

Most of this waste is currently disposed to landfill, even though it can be easily recycled. WRAP receives funding from Defra through the Business Resource Efficiency and Waste (BREW) programme to divert plasterboard waste from landfill by working to overcome the barriers to plasterboard recycling. Additional funding is also received from the devolved administrations in Scotland, Wales and Northern Ireland.

WRAP is working to overcome the barriers through the following key areas:

- plasterboard waste minimisation;
- site waste management;
- segregation and collection of plasterboard waste;
- development of infrastructure, including waste logistics and recycling capacity;
- market development for materials from plasterboard recycling – recycled gypsum and reclaimed paper;
- education, awareness and behavioural change; and
- informing and influencing legislation, regulations and policy.

More information on WRAP’s work can be found at www.wrap.org.uk/construction
Executive summary

Over one million tonnes of waste plasterboard are estimated to be produced each year in the UK from construction and demolition activities. Most of this waste is currently sent to landfill, even though it can easily be recycled. WRAP is working to divert plasterboard waste from landfill by seeking to overcome the barriers to plasterboard recycling. One area of its work is to develop markets for the materials from plasterboard recycling (recycled gypsum and reclaimed paper). This project, undertaken by CERAM Research Ltd, evaluated the use of the patented CASO reconstitution process to produce high-grade plaster feedstock for making moulds for the ceramics and metal casting industries from gypsum (calcium sulphate) recycled from waste plasterboard.

The CASO process was originally developed at CERAM Research Ltd for use in recycling plaster moulds from the ceramics industry that had reached the end of their useful lives. It involves changing the hydration states of the calcium sulphate mineral forming the basis of the plaster so as to produce a material suitable for reuse in the preparation of moulds. This project investigated the feasibility of using the process to reconstitute gypsum from waste plasterboard into the hemihydrate form (a form from which plaster moulds can be produced).

Partners in the project alongside CERAM and CASO Ltd were Roy Hatfield Ltd (supplier of recycled plasterboard gypsum) and three users of plaster moulds – Josiah Wedgwood & Sons Ltd (producer of high quality tableware), Ideal Standard Manufacturing Ltd (sanitaryware manufacturer) and Doncasters Sterling (producer of automotive aluminium castings).

Plasterboard manufactured in the UK is now predominantly made from flue gas desulphurisation (FGD) gypsum, and so the recycled gypsum used in the research was from plasterboard of this type. Commercial plasters used for making moulds are of high-grade naturally occurring mineral gypsum. Comparisons of the recycled gypsum plaster were made throughout the project with a sample of a standard commercial plaster and a sample of ‘untreated’ plaster (plaster without the additives normally added to match the material to the requirements of specific end uses).

Initially, a small-scale batch (approximately 0.5kg) of recycled plaster was prepared by hand in the laboratory using the standard CASO procedure. This showed promise, but attempts to produce a larger batch (20–30kg) following the same procedure encountered problems including a lack of stability as the plaster sample aged. Investigations identified the most likely cause of the sample behaviour to be the use of FGD gypsum in the plasterboard rather than mineral gypsum normally used in plaster moulds and on which the CASO process was based. The procedure was therefore modified slightly to:

- accommodate the differences in the crystal structure and other properties of FGD gypsum and mineral gypsum; and
- address the issue of the residual paper content in the recycled gypsum derived from waste plasterboard.

This modified procedure was as follows:

1. Remove the facing paper from the plasterboard and crush the gypsum core.
2. Calcine at 200°C for 24 hours to convert the gypsum to soluble anhydrite.
3. Soak for 3 days in a minimum quantity of water to convert to gypsum with a suitable crystal structure.
4. Wet ball-mill the soaked material to give an average particle size of 20µm.
5. Sieve to remove any coarse contaminants and paper fibres.
6. Dewater the slurry by pressure filtration.
7. Dry at 40°C to constant weight without decomposing the dihydrate.
8. Calcine at 170°C to constant weight.
9. Expose to air for 100 hours to allow rehydration to a stable hemihydrate state.
10. Lightly crush any lumps to produce a free-flowing powder.

A large batch (approximately 30kg) of recycled plaster was prepared using this procedure and supplied to the project partners for their evaluation of its performance in a factory environment. These factory trials encountered varying degrees of success.

- At Wedgwood, moulds prepared for tableware manufacture were successfully made using their standard procedures, with plaster blending and set as anticipated. However, the moulds were found to have insufficient strength when put into use in a mechanised production line (plastic forming technique of cups).
At Ideal Standard, the moulds used for sanitaryware production were too large for a production mould to be made from the available amount of recycled plaster. Instead a smaller test mould (of the type used in their quality control procedures) was successfully made and tested alongside similar moulds made from their usual commercial plaster. The results were very promising with the test mould achieving a working life comparable with that of the standard moulds (typically more than 80 casts).

At Doncasters Sterling, aluminium components are cast by pouring molten metal into gypsum moulds which can be used only once. A quick mechanised production method for moulds is therefore necessary, different to the process for ceramics moulds. Unfortunately test moulds could not be made using the recycled plaster as its setting time could not be reduced to meet the production requirement for very rapid setting of the moulds.

It is estimated that the equipment costs for a plant to produce the recycled plaster using the modified procedure on recycled gypsum supplied by a plasterboard recycler, and capable of an annual output of 12,500 tonnes per annum, would cost approximately £894,000. The combined equipment and operating costs give an estimated supply price for the recycled plaster from waste plasterboard of £120–130 per tonne. Commercial plasters used for moulding currently cost in the region of £140 per tonne. Using recycled plaster from waste plasterboard could therefore save £10–20 per tonne consumed, a 7–14% saving. Using this material instead of fresh mineral plaster for slip casting in sanitaryware production could give potential cost savings of £20,000–40,000 per year in material costs alone. Further indirect savings are possible as a result of the material being delivered in a more stable condition than current fresh mineral plaster supplies.

Several of the major tableware factories in the Stoke-on-Trent area were surveyed for their plaster consumption. Similar percentage savings could be achieved in this sector provided further development can produce a recycled plaster with the required properties, but due to their lower plaster consumption converting to recycled plaster could give the potential of a £3,000–£6,000 per year cast saving for each factory.

**Conclusions**

- The CASO process is fundamentally suitable for reconstituting waste plasterboard derived recycled gypsum with only minor modifications;
- More intensive calcination is required for the recycled gypsum than natural mineral gypsum, as it contains a high proportion of gypsum of FGD origin;
- After calcination, the recycled plaster ‘ages’ to a stable condition much more rapidly than the mineral types tested previously;
- The set plaster strength of the recycled plaster is similar to that of untreated plaster, but lower than that of the commercial plaster tested. This suggests that, while there is no intrinsic strength deficiency, product development is required to produce the strength values seen in commercial plasters;
- The recycled plaster has good properties for slip casting, making it suitable for sanitaryware production.
- The reconstitution process will need to be optimised to give the best results for recycled gypsum of FGD origin.
- A material cost saving of 7–14% could be expected if the recycled material is used in place of a freshly mined mineral plaster.

**Recommendations**

A. Optimisation of the processing factors (calcination temperatures, calcination times, recrystallisation time) in the reconstitution process of the recycled gypsum of FGD origin to:
   - determine the influence of material and process variables on plaster performance, in particular those relating to strength and setting time;
   - identify solutions to enable recycled plaster to be used for plastic forming of ceramics and metal casting;
   - maximise throughput and minimise energy consumption in the reconstitution process.

B. Further trials of the reconstitution process using recycled gypsum to:
o ascertain the variability of the recycled plaster properties and their effect on mould making and casting; and
o identify ways of minimising the effect of any variability.

C. Investigation of the long-term stability of the recycled plaster so that an effective shelf life from production to use can be determined.

D. Investigation into whether the recycled plaster derived from FGD gypsum is likely to prove to be more resistant to ‘burning’ (degradation of the mould due to high temperatures during drying) and thus allow higher drying temperatures to be used and reducing the production bottleneck that mould drying presents. These benefits need to be quantified.

E. Conducting larger scale trials to give fully representative indications of performance. The need to process several tonnes of plaster for use in trial moulds would necessitate the involvement of a plaster supplier to provide suitable equipment (plus expertise on processing and additive packages).
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1.0 Introduction

This project evaluated the possible use of the patented CASO reconstitution process to produce plaster feedstock for making moulds for the ceramics and metal casting industries from gypsum extracted from waste plasterboard. It was undertaken by CERAM Research Ltd.

The CASO process was originally developed for use in recycling plaster moulds from the ceramics industry that had reached the end of their useful lives. Although successfully demonstrated in small-scale trials, it has never been employed on an industrial scale as many moulds are recycled by alternative routes, making the establishment of a CASO plant uneconomic.

Moulding plasters (Figure 1) are generally produced from quite high-purity natural gypsum deposits, as the presence of coarse insoluble impurities can lead to degradation of the mould surface in service. For comparison with the chemical composition of materials produced during the project, a sample of mineral plaster was obtained whose properties had not been modified by any of the additives used in all commercial plasters to match the material to the requirements of specific end uses. This comparison sample was provided by BPB Formula, being taken from production before any additive treatment. This material is referred in this report as ‘untreated’ plaster.

The project involved:

- using the CASO process to reconstitute recycled gypsum from waste plasterboard into the hemihydrate form (a form from which plaster moulds can be produced);
- processing a small initial sample to enable the blending properties of the plaster produced to be measured;
- preparing larger quantities of plaster for use in determining mould properties and in pilot-scale trials at factories operated by the project partners;
- determining whether the CASO processing route was suitable for use with recycled gypsum from waste plasterboard;
- identifying the need for any modifications to the process;
- assessing the potential of the material generated for industrial use;
- assembling information on acceptance testing procedures for plasters used for tableware and sanitaryware applications in the ceramics industry, and also in the metal casting industry;
- developing test procedures for the large plaster samples produced during the later stages of the project; and
- carrying out an economic analysis.
1.1 Project team

The project was undertaken by the Process and Materials Division of CERAM Research Ltd, a research and technology organisation working primarily in the field of ceramics.

The project was lead by Peter Hancock, CERAM's principal specialist in sanitaryware materials and processes.

The other partners in the project were:

- CASO Ltd – a company set up to exploit the patented process on which this project is based;
- Josiah Wedgwood & Sons Ltd – producer of high quality tableware, especially bone china. A high proportion of the company’s ware is produced using plaster moulds as it is the only technique available for fabrication of complex-shaped hollowware;
- Ideal Standard Manufacturing Ltd – producer of sanitaryware, relying totally on casting. The company uses some pressure casting (with synthetic porous moulds) but also relies on plaster moulds to maintain production flexibility.
- Doncasters Sterling (part of Doncasters Group Ltd) – producer of cast aluminium turbocharger components through the suction of molten alloy into plaster moulds; and
- Roy Hatfield Ltd – recycler of various materials including waste plasterboard. The company provided recycled gypsum for use in the project and helped to provide data.

2.0 Plaster reconstitution process

The process covered by the patent for plaster reconstitution [1] held by CASO Ltd was developed at CERAM during earlier projects aimed at recycling gypsum moulds into a plaster feedstock for further mould making.

The process involves changing the hydration states of the calcium sulphate mineral forming the basis of plaster (Table 1).
<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum (calcium sulphate dihydrate)</td>
<td>CaSO₄·2H₂O</td>
<td>This is the form in which the mineral is mined and also the state of the plaster in a finished set mould. It is a fully hydrated material and is stable at normal temperatures, but will partially dissociate at temperatures between 50°C and 170°C to form the hemihydrate.</td>
</tr>
<tr>
<td>Hemihydrate</td>
<td>CaSO₄·0.5H₂O</td>
<td>This is the form in which plaster for use in a mould is supplied. In most commercial plasters, this form is stable for several months but reacts when mixed with water to form gypsum. This form can produce slurries in water with a high solids content that can allow long blending times before setting commences.</td>
</tr>
<tr>
<td>Soluble anhydrite</td>
<td>CaSO₄</td>
<td>Formed when gypsum or hemihydrate are heated to temperatures above 170°C. It readily hydrates to form gypsum in contact with water, but its slurries have high viscosities (hence low solids content) and also set very rapidly.</td>
</tr>
<tr>
<td>Insoluble anhydrite</td>
<td>CaSO₄</td>
<td>Chemically identical to soluble anhydrite, but has a different crystal structure. Formed when the hydrated forms or soluble anhydrite is heated to temperatures in excess of 300°C. Will only hydrate over periods of decades (as a minimum) and shows no setting properties.</td>
</tr>
</tbody>
</table>

The reconstitution process developed at CERAM involved six stages:

A: Remove metal and plastic components from the used plaster moulds.
B: Crush the moulds to 10–20mm.
C: Calcine the crushed material for 24 hours at 200°C to convert the gypsum from the moulds into soluble anhydrite.
D: Soak the calcined material in the minimum amount of water for 3 days so that it is converted to gypsum with a crystal structure suitable for preparing slurries with a high solids content.
E: Dry the gypsum and then calcine it for 40 minutes at 170°C to form the hemihydrate for mould making. A small amount of soluble anhydrite will generally be formed in this stage, requiring the plaster to be aged (potentially using steam conditioning - Section 5) to give suitable properties. Longer calcination times produce large amounts of soluble anhydrite, requiring extended aging to make the plaster usable.
F: Grind the hemihydrate to a fine powder such that it remains in suspension in a slurry and dissolves readily to allow setting to occur.

3.0 Feedstock material analysis

An initial sample of recycled gypsum was supplied by Roy Hatfield Ltd to CERAM during December 2005. Hatfield's main plasterboard recycling plant was undergoing commissioning modifications at the time so the sample was, of necessity, small (~0.5 kg).

Only modern-type, white-coloured plasterboard was available. Roy Hatfield Ltd stated that only a very small percentage of the material it handled was the older pink-coloured type and it could not provide a suitable sample. The more recently manufactured white-coloured plasterboard is predominantly made from flue gas desulphurisation (FGD) gypsum as opposed to the naturally occurring mineral gypsum forming the older pink-coloured plasterboard.

Although the material supplied was quite clean and appeared relatively free of contaminants, a significant number of paper fragments had remained in the material when the facing paper of the plasterboard was stripped off. Discussions with Roy Hatfield Ltd established that it aimed for a maximum paper residue content of 1% by weight in current processing. Although this level of paper contamination is acceptable in many applications, it was considered high for mould making use (this issue was addressed in subsequent processing - see Sections 5 and 6).

The paper fragments were removed from the material by hand, then the gypsum was analysed by X-ray diffraction (XFD) and X-ray fluorescence (XRF) to determine its chemical and mineralogical composition (see detailed results in Appendix A). The results were analysed to give a calculated composition for the recycled gypsum (Table 2). Calculation was necessary because:
some of the minerals present in the plasterboard sample would have decomposed during the chemical analysis test; and

the mineralogical analysis did not give a quantitative value for gypsum.

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium sulphate (hydrates/anhydrite)</td>
<td>95</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>2.5</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.6</td>
</tr>
<tr>
<td>Clay, mica, other trace minerals</td>
<td>1.9</td>
</tr>
</tbody>
</table>

As anticipated, the material was primarily calcium sulphate dihydrate (gypsum). It also contained small quantities of calcium sulphate hemihydrate (possibly formed from gypsum as a result of the energy input when stripping and crushing the plasterboard) and anhydrite (the insoluble form).

Higher purity grades of mineral gypsum are used for moulds – generally stated to be 98% pure (99% pure in the BPB untreated sample). However, it was believed that acceptable results could be achieved with the recycled gypsum.

During processing at Roy Hatfield Ltd, 7–8% by weight of the initial weight of the plasterboard is lost when the facing paper is stripped off. At this level of purity, the total recoverable gypsum of initial plasterboard weight therefore represents approximately 88% of the initial feedstock weight.

Roy Hatfield Ltd subsequently reported that its processing plant had been modified to reduce the amount of residual paper and other contaminants in the gypsum recovered from the waste plasterboard.

4.0 Small initial sample of recycled plaster

The first sample of recycled plaster was prepared from the small initial quantity of recycled gypsum supplied by Roy Hatfield Ltd in December 2005.

Approximately 0.5 kg of plasterboard gypsum was processed at the CERAM laboratories by hand using small-scale equipment. This produced sufficient material to establish that:

- the material produced set effectively;
- the developed phases could be analysed; and
- blending properties could be measured using a small-volume viscometer.

A commercial plaster and a sample of additive-free mineral hemihydrate (untreated plaster) were used in the tests for comparison.

The plaster sample produced from the recycled gypsum was shown to set effectively, but to contain much more anhydrite than the mineral sample.

Both samples had shorter blending times than the commercial grade plaster, but this was expected as ceramic casting plasters are treated with retarders to allow for air bubble clearance during blending.

Both samples had substantially higher slurry viscosity values than the commercial plaster (Section 7.1). The viscosity values fell with ageing of the plaster and addition of tri-sodium silicate retarder, but the recycled sample remained at a higher slurry viscosity.

Based on these indications, it was decided to proceed with the preparation of larger-scale samples for semi-industrial trials.

5.0 Preparation of increased-scale plaster samples

The first attempt to produce a trial batch of 20–30kg of recycled plaster followed the established procedure developed by CERAM and CASO for recycling spent moulds from the ceramic industry. The only change was in the method used for final grinding of the plaster powder to size. The previous motorised pestle and mortar
The sample showed the initial signs of setting, with the slurry viscosity increasing and the slurry becoming immobile. However, it would not proceed to the final set and the samples did not develop any strength or hardness. When analysis of the sample revealed a high level of anhydrite present, its behaviour was attributed to an excessive energy input by the grinding system leading to the formation of insoluble anhydrite. As the grinding system operates with small quantities of dry powder within the grinding chamber, rapid temperature increases can be produced.

A revised procedure was adopted for a second large batch. The particle size of the material was set by ball-milling it after Stage 3 of the reconstitution process (i.e. soaking in water after the first calcination at 200°C; see Section 2). The wet material was in a friable state and could be reduced to a mean particle size of 20µm in approximately 1 hour. After ball-milling, the slurry was sieved through a 150µm sieve; this was effective in removing any paper fibres present. The slurry at this stage was very fluid and had a relatively low solids content. It was dewatered rapidly by pressure filtration before being dried at 40°C. Existing procedures were used for the other stages of the process.

The sample's setting properties were acceptable shortly after preparation, but setting tests made after a few weeks showed no usable hardness or strength could be achieved which indicated it had deteriorated when it aged. XRD analysis of samples from this second batch showed that most of the material in the sample had changed spontaneously to gypsum (60%), leaving only 30% as hemihydrate with smaller quantities of anhydrite, calcite and other minor constituent minerals.

Such behaviour is not typical of mineral plasters or those produced during mould recycling experiments. It can take several weeks to complete the hydration of the soluble anhydrite in these materials to hemihydrate. During the mould recycling studies, a method of accelerating hydration by passing dry steam though a bed of the calcined material had to be used to achieve rapid results. After this, the material was stable for several months unless it came into contact with liquid water. The sample of mineral hemi-hydrate supplied by BPB Formula for use in the project still gave good setting properties after nine months in the laboratory, as did commercial plaster samples.

5.1 Investigation of the causes of instability

To resolve these issues, CERAM undertook several trials of the calcination behaviour of the recycled gypsum with XRD analysis of the resulting material. These studies were not part of the original work programme.

The conversion of the dihydrate form to hemihydrate was found to be much slower than previously seen in untreated mineral samples or in the recycling of moulds. It was also found that, if the recycled gypsum was calcined to constant weight at 170°C (converting it entirely to the soluble anhydrite form), it gained weight rapidly on exposure to air and became stable after 100 hours; the weight increase was equivalent to hydration to the hemihydrate form. In this condition, the material showed good setting properties (giving adequate hardness and strength) which were stable over a six-week period.

When processing mineral plasters, it is normal to slightly over-calcine the material as the presence of residual gypsum results in rapid setting. However, this effect is limited as the rehydration of the soluble anhydrite to hemihydrate would normally take several weeks.

Investigations at CERAM identified the feedstock as the most probable influence on sample behaviour. The commercial plaster used in moulds is from natural mineral sources and the procedures used to date were developed for that source. However, most plasterboard produced in the UK currently employs FGD gypsum. This gypsum is a synthetic by-product of chemical scrubbing of the combustion gases from coal-fired power stations to remove sulphur dioxide. During the treatment, the sulphur dioxide reacts with limestone (calcium carbonate) to form calcium sulphate (gypsum).

Little published data could be found on the calcination properties of FGD gypsum. One article [2] refers to it requiring more intensive calcination than mineral gypsum as the crystals in FGD gypsum take longer to break down at calcination temperatures.
CERAM carried out some basic trials on the use of FGD gypsum for mould making several years ago, but these were not pursued due to the lack of a commercial source of the FGD material. These trials also showed a need for longer, more intensive calcination. They also indicated quite rapid ageing of hemihydrate samples.

This suggests that, while the procedure used to prepare the plaster samples was effective for mineral gypsum, some modification is necessary when it used with FGD gypsum. Although no published data on the rapid hydration of the samples from soluble anhydrite to hemihydrate were available, there appeared to be grounds for attributing this behaviour to the different source material.

6.0 Preparation of plaster samples for semi-industrial trials

The behaviour of the plasterboard material during calcination and ageing indicated that the presence of any residual gypsum would promote and/or accelerate hydration of the remaining material to dihydrate. Therefore, it appeared essential that the final calcination of the material was complete, i.e. to constant weight. The rapid hydration of the material from soluble anhydrite to hemihydrate facilitated this requirement, as ageing to a stable condition would be more rapid than in a slightly over-calcined mineral gypsum sample.

The following procedure was therefore adopted for processing plasterboard made from FGD gypsum to produce plaster samples for use in the trials:

1. Remove the facing paper from the plasterboard and crush the gypsum core.
2. Calcine at 200°C for 24 hours to convert the gypsum to soluble anhydrite.
3. Soak for 3 days in a minimum quantity of water to convert to gypsum with a suitable crystal structure.
4. Wet ball-mill the soaked material to give an average particle size of 20µm.
5. Sieve to remove any coarse contaminants and paper fibres.
6. Dewater slurry by pressure filtration.
7. Dry at 40°C to constant weight without decomposing the dehydrate.
8. Calcine at 170°C to constant weight.
9. Expose to air for 100 hours to allow rehydration to a stable hemihydrate state.
10. Lightly crush any lumps to produce a free-flowing powder.

At this stage of the proof of concept, it was important to eliminate any influence from contaminating materials and to ensure source material of a known origin. New plasterboard sheets were therefore used as the feedstock for the process rather than samples of recycled gypsum from waste plasterboard (Figure 2) supplied by a plasterboard recycler. The sheets were BPB British Gypsum ‘Gyproc’ brand marked ‘Made with flue gas gypsum’. Although the source material from the plasterboard was white in colour, it became grey during the calcination process.

Almost 30kg of the processed material was produced, homogenised and tested to ensure that stable setting properties had been achieved. The material was divided into samples supplied to Wedgwood, Ideal Standard and Doncasters for factory trials (see Section 8). A smaller quantity was retained at CERAM for characterisation tests (see Section 7). Figures 3–8 show various stages of the plaster preparation procedure outlined above.
Plaster moulds using recycled gypsum from waste plasterboard

**Figure 3** Stage 2 - Calcination

**Figure 4** Stage 4 - Milling
Figure 5 Pouring milled slurry into sieve

Figure 6 Stage 5 – Sieving milled slurry
Figure 7 Residue after sieving

Figure 8 Final product
7.0 Characterisation tests on plaster samples

7.1 Blending properties
The development of viscosity in a plaster/water slurry determines the blending time that must be used before pouring to form the mould. Settling of the particles and some non-homogeneity are observed in early-poured samples, while late-poured samples have high viscosity values and can entrap air pockets during pouring.

Due to the limited amount of material available for the initial sample (Section 4), viscosity measurements were made using a Brookfield RVDV2 viscometer fitted with a small sample adaptor with a 13mm diameter cell and a 9mm spindle. This required a sample volume of 6cm$^3$. The viscometer was run at 100rpm to minimise any tendency for the sample to settle. A plaster/water ratio of 100 : 85 was used (54% solids content in slurry).

Both the initial recycled sample and the BPB untreated plaster sample showed a relatively high slurry viscosity and rapid increases in viscosity compared with a well-aged commercial sample (Figure 9). The commercial sample contained an additive to retard settings (a retarder) to allow for long enough blending times for industrial applications.

The recycled sample was more viscous and showed a more rapid increase in viscosity when fresh, but this became less marked with ageing. Figure 9 shows the results obtained when the recycled sample was well-aged.

![Figure 9 Development of slurry viscosity in initial trials (aged samples)](image)

A viscosity development test on the recycled plaster from the large batch (Section 6) gave the pattern shown in Figure 10. This demonstrated that the process used had made a long blending time of up to 15 minutes possible - one similar to that of the well-aged commercial sample (which contains some retarder). The actual blending time required in an industrial situation will be shorter as the viscometer applies a relatively low blending energy. The initial viscosity of the slurry was higher than obtained with the mineral plaster samples.
Figure 10 Development of viscosity in slurries made from the large batch of recycled plaster

When the samples were supplied to Doncasters Sterling, concern was expressed about the long setting time as its process requires rapid setting of a maximum of 3.5 minutes. In an attempt to make the sample more suitable, additions of set gypsum were made (known to greatly accelerate setting) and the setting process monitored. Additions over 1% resulted in the slurry viscosity being above the measurable range before the sample was in place on the viscometer, so only final set times could be monitored (Table 3). On the basis of these results, an addition of 2% set plaster was recommended for testing at Doncasters Sterling.

Table 3 Final set times for recycled plaster samples

<table>
<thead>
<tr>
<th>Set gypsum addition (%)</th>
<th>Final set time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

7.2 Strength

The strength of the recycled plaster was compared to that of the BPB untreated plaster.

Square-section test bars (100mm long × 14mm wide and 11mm thick) were cast from slurries with 100 : 85 plaster/water ratios (54% solids); the slurries were hand-blended to a point where their viscosity had increased sufficiently to prevent particle settling after pouring. After the samples had set and been removed from the mould, they were allowed to dry naturally in the laboratory at 20°C to avoid any risk of the results being influenced by ‘burning’ (degradation of a mould due to exposure to high temperatures during drying). Samples cast from a commercial plaster grade intended for use in sanitaryware casting were prepared and tested to complete the comparison.

The test bars are shown in the background of Figure 11.
When dry, the samples were subjected to a three-point bending test over an 80mm span using an Instron testing machine (Figure 12) set to give a crosshead speed of 0.5mm per minute. Table 4 summarises the results.

Table 4 Strength values measured on plaster samples (100 : 85 plaster/water ratio)

<table>
<thead>
<tr>
<th></th>
<th>Mean modulus of rupture (MPa)</th>
<th>Standard deviation (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled plaster</td>
<td>3.47</td>
<td>0.41</td>
</tr>
<tr>
<td>BPB untreated mineral</td>
<td>3.18</td>
<td>0.27</td>
</tr>
<tr>
<td>Commercial plaster</td>
<td>4.44</td>
<td>0.60</td>
</tr>
</tbody>
</table>
These figures indicate slightly higher strength for the recycled plaster, though the significance of this result (as indicated by the standard deviation) is not high.

The results show there is no inherent strength penalty in using the recycled plaster. However, the higher values obtained from the commercial plaster sample suggest that increases in strength would be obtained through optimised processing and additive packages for the intended end use.

7.3 Air permeability
The plaster slurry batches used to form the strength samples were also cast to form cylindrical pieces for permeability tests. These were allowed to dry naturally in the laboratory before testing and are shown in the foreground of Figures 11 and 13.

The permeability of these samples was measured using a technique developed by CERAM for quality control of plaster moulds. The test involves drawing a partial vacuum in an apparatus of known volume which seals itself onto the surface of the sample and then measuring the time taken for the vacuum to decay between two predetermined values. This is a non-destructive test and can be carried out rapidly.

![Figure 13 Permeability test](image)

Two batches of samples of each of the recycled plaster, the BPB untreated plaster and the commercial plaster sample were prepared.

All the samples showed somewhat higher permeability values (Table 5) than normally used for moulds for ceramics use – typically 2–3cm²/s/cm water. However, this difference could be corrected by optimising the blending procedure for each plaster type; longer or more intensive blending would reduce the permeability of the samples to the required value [3].

The results suggest that:
- the recycled plaster should follow the principles established for mineral plaster; and
- relatively minor modifications to blending procedures would be required to achieve acceptable results.
Table 5 Air permeability measurements on plaster samples

<table>
<thead>
<tr>
<th>Sample batch</th>
<th>Average permeability CERAM units (cm$^2$/s/cm water)</th>
<th>Average permeability (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled plaster, sample 1</td>
<td>6.50</td>
<td>$6.63 \times 10^{-7}$</td>
</tr>
<tr>
<td>Recycled plaster, sample 2</td>
<td>5.70</td>
<td>$5.81 \times 10^{-7}$</td>
</tr>
<tr>
<td>BPB untreated plaster, sample 1</td>
<td>5.20</td>
<td>$5.30 \times 10^{-7}$</td>
</tr>
<tr>
<td>BPB untreated plaster, sample 2</td>
<td>3.90</td>
<td>$3.98 \times 10^{-7}$</td>
</tr>
<tr>
<td>Commercial plaster, sample 1</td>
<td>4.75</td>
<td>$4.84 \times 10^{-7}$</td>
</tr>
<tr>
<td>Commercial plaster, sample 2</td>
<td>4.42</td>
<td>$4.51 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

8.0 Factory trials with recycled plaster samples

8.1 Josiah Wedgwood & Sons Ltd

The plaster sample supplied to Wedgwood was used at its factory in Barlaston, Stoke-on-Trent, to produce moulds for producing bone china cups. The mould making process is illustrated in Appendix B.

The production process used for tableware such as cups is ‘plastic forming’. In this process, moist clay blanks are fed into the mould where a profiled tool rolls or presses it onto the working face, forming both front and back faces very rapidly. This process is illustrated in Appendix C. This technique is widely used in the tableware manufacturing sector as it allows high levels of output from a limited number of moulds of any pattern.

The plaster was reported to blend and set as anticipated; no difficulties were reported during mould making. But when the test moulds were put into use on a production machine, the bottoms broke away from the main body of the moulds after only a very few cycles through the machine (see Figure 14 and the visible crack in the right-hand mould). This indicates that the moulds had insufficient strength to withstand the mechanical loading applied by the machine during the forming of the product. The reduced strength of the plaster relative to the commercial plaster would appear to explain this shortcoming; a more fully developed product would be required for a full trial.

A dark staining of the outer surfaces was noticed after drying the moulds produced from the recycled plaster (Figure 14). This appeared to be due to soluble matter deposited in the mould surfaces during the drying of the mould. The inside moulding surface was not stained.

8.2 Ideal Standard Manufacturing (UK) Ltd

A sample of plaster was supplied to Ideal Standard's factory at Middlewich in Cheshire. All ceramic sanitaryware at the factory is formed by a slip casting process. In this process a liquid slip (suspension of the compounded body mineral materials) is poured into the mould, which draws water from the slip by capillary action, causing a

Figure 14 Commercial plaster mould on left, recycled gypsum plaster mould on right
semi-solid layer (the cast) to be deposited on the mould surface. When a sufficient thickness of cast has been formed, the excess slip can be drained from the mould and the cast allowed to harden sufficiently to be handled, before it is removed from the mould.

As sanitaryware production moulds are very large and heavy (up to 150kg), it was not possible to produce a mould for a production item from the available amount of recycled plaster. Therefore it was used to produce a small bowl-shaped mould of a type used in quality control testing in the factory laboratory. These test pieces are cast with the production slip each day for a set time so that the slip's casting under standard conditions can be quantified.

The mould making procedures used are very similar to those at the Wedgwood tableware factory, though on a rather larger scale. The mould makers found that the slurry required pouring earlier than anticipated from the laboratory trials, presumably due to a more energetic mixing action applied during slurry blending.

After drying, the moulds were used in monitoring trials on production slip samples (Table 6).

<table>
<thead>
<tr>
<th>Date</th>
<th>Trial wet cast weight (g)</th>
<th>Standard mould wet cast weight (g)</th>
<th>Trial mould moisture pick-up (g)</th>
<th>Standard mould moisture pick-up (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 January 2007</td>
<td>1069.8</td>
<td>1093.2</td>
<td>140.5</td>
<td>133.5</td>
</tr>
<tr>
<td>25 January 2007</td>
<td>1065.6</td>
<td>1050.4</td>
<td>122.9</td>
<td>139.2</td>
</tr>
<tr>
<td>26 January 2007</td>
<td>1012.8</td>
<td>1081.3</td>
<td>120.8</td>
<td>133.9</td>
</tr>
<tr>
<td>29 January 2007</td>
<td>1030.1</td>
<td>1069.7</td>
<td>121.7</td>
<td>130</td>
</tr>
<tr>
<td>30 January 2007</td>
<td>979.2</td>
<td>986.8</td>
<td>127.5</td>
<td>124</td>
</tr>
<tr>
<td>31 January 2007</td>
<td>978.7</td>
<td>1070.6</td>
<td>118.7</td>
<td>129.1</td>
</tr>
<tr>
<td>1 February 2007</td>
<td>1023.4</td>
<td>1023.4</td>
<td>122.3</td>
<td>132.5</td>
</tr>
</tbody>
</table>

In general, there was a lower pick-up of moisture during casting in the recycled plaster trial mould. However, there are frequently variations of this order between individual moulds due to differences in the intensity of blending; a low permeability mould tends to produce a greater capillary suction due to its finer pore structure.

The results suggested that an optimised blending procedure would give predictable results. The high cast weight and moisture take-up of the trial mould on its first cast is normal for plaster moulds and is a recognised cause of production losses when moulds are first put into use.

The trial mould continued in use with casts being made on each working day. By late March 2007, the pattern had continued as above with no discernable deterioration in relation to the standard mould used for the control test. All plaster slip casting moulds undergo a progressive deterioration in performance during extended use and the effective life of a mould in sanitaryware production is 80–100 fills. By this date, the trial mould was approaching the length of a standard mould's working life.

8.3 Doncasters Sterling

The Doncasters Sterling factory in Coventry uses plaster to form moulds into which molten metal is cast to form automotive components such as turbocharger impellers. If this was carried out using normal set plaster moulds, the heat from the molten metal would cause large volumes of water vapour to be evolved as the plaster dissociated, probably resulting in the moulds bursting and/or creating gas voids in the metal cast. To avoid this, the plaster is calcined after the mould has been formed to shape so that all of the water of crystallisation is driven off. This produces anhydrite, which has little strength; to compensate for the inherent weakness of the mould after calcination, proportions of wollastonite and cement bond are blended in to the plaster before use. This blend is bought in ready-mixed.

The casting process dictates that the moulds can be used only once, so rapid mechanised production of the moulds is required to satisfy the demands of component production. To fit into the mould production system in operation at the factory very rapid setting is required, with very close tolerances on setting time; the time from the start of blending to completion of set is 3–3.5 minutes.
Pilot tests using the recycled plaster were carried out at Doncasters and also at its plaster blend supplier, but the setting time could not be reduced below six minutes. This made the material unsuitable for use in the mould production system, preventing practical trials with metal casts at this factory.

9.0 Review of moulding plaster market

Some changes occurred in the UK ceramics manufacturing market after the project began. The recent high cost of natural gas placed pressure on ceramics manufacturing, which in turn resulted in a decline in sanitaryware capacity in the UK with production being relocated to other countries with lower cost bases. Similar pressures and relocations also applied to tableware manufacturing.

These changes reduced the estimated total UK market size for moulding plaster from 19,700 tonnes per annum (tpa) at the beginning of the project in November 2005 to around 15,500tpa in March 2007 (Table 7).

### Table 7 Estimated moulding plaster market (tpa)

<table>
<thead>
<tr>
<th>Sector</th>
<th>November 2005</th>
<th>March 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanitaryware and tableware</td>
<td>14,700</td>
<td>10,500</td>
</tr>
<tr>
<td>Refractories</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Aluminium casting</td>
<td>2000</td>
<td>(2000)*</td>
</tr>
<tr>
<td>Decorative mouldings</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>19,700</strong></td>
<td><strong>15,500</strong></td>
</tr>
</tbody>
</table>

* Dependent on development of suitable setting properties.

10.0 Economic analysis

10.1 Production of recycled plaster

CASO produced detailed estimates for equipment and staffing requirements for different levels of plaster production from used plaster moulds. These form the basis of the calculated production costs for recycled plaster.

Some changes from the standard procedure would be necessary if waste plasterboard was used as the starting material. The initial stage of removing metal and plastic components from used moulds before crushing them to particles of <10mm in size would have to be replaced with an initial process appropriate to plasterboard. The existing plasterboard processing facility at Roy Hatfield Ltd could achieve this as the plant has been continually developed to minimise the amount of contaminating material such as paper passing into the final product. The delivered price of recycled gypsum from waste plasterboard quoted by Roy Hatfield Ltd is £8–12 per tonne depending on specification and delivery location.

With an appropriate milling system to minimise the heating effect of particle crushing (as specified in CASO’s procedure), size reduction could be performed in the dry state as is the normal practice for commercial plaster production. Thus, this part of the procedure would not require alteration.

One stage in the original CASO process that does not appear to be required if the feedstock is plasterboard originating as FGD gypsum is the steam conditioning of the final product to rapidly ‘age’ the material into a stable condition. This is required for mineral plasters as stability is not achieved for several weeks when simply exposing them to air after production. As shown in the development of the sample production process, FGD gypsum achieves a stable condition very rapidly when exposed to air.

Table 8 gives estimated costs for equipment identified as necessary for producing recycled plaster for making moulds, by two options:

- recycling of used moulds using the original CASO process; and
- using waste plasterboard derived recycled gypsum supplied by a plasterboard recycler, using the CASO process modified to accommodate gypsum of FGD origin.

Combining the equipment costs with operational costs gives an estimated supply price for recycled plaster from waste plasterboard of £120–130 per tonne.
Table 8  Equipment cost estimates (£) for recycled plaster processing plant capable of 12,500tpa output

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Original CASO process for recycling used moulds</th>
<th>Process modified for FGD gypsum (recycled gypsum supplied by plasterboard recycler)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loader</td>
<td>25,000</td>
<td></td>
</tr>
<tr>
<td>Jaw crusher</td>
<td>25,000</td>
<td></td>
</tr>
<tr>
<td>Elevator</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Screen</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Elevator</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Dust control system</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Buffer hopper feed</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Bag filter</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Rotary calciner</td>
<td>300,000</td>
<td>300,000</td>
</tr>
<tr>
<td>Mixer</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Recrystallisation tanks</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Water treatment plant</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Vacuum filter</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Vibrating conveyor</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Two bag filters</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Conveyor (air handling)</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Micro-mill and filter</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Two bag filters</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Boiler</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Steam heater battery</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>Fluidised bed conditioner</td>
<td>30,000</td>
<td></td>
</tr>
<tr>
<td>Conveyor (air handling)</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Bagging plant</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Palletisation</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Fork lift truck</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>Ancillaries</td>
<td>150,000</td>
<td>150,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>994,000</strong></td>
<td><strong>894,000</strong></td>
</tr>
</tbody>
</table>

10.2  Use of recycled plaster

10.2.1 Ceramics production

Depending on the production method and the product surface quality requirement of the manufacturer, the life of a mould ranges from 40 to 100 fills. Continuous production of replacement moulds is therefore required. Current commercial plasters used for moulding are marketed at approximately £140 per tonne. At an estimated supply price of £120 – £130 per tonne, using recycled plaster from plasterboard gypsum could save £10 – £20 per tonne consumed, i.e. 7–14%.

The semi-industrial trials (Section 8) indicated that the recycled plaster has good properties for slip casting, making it suitable for sanitaryware production. In the case of a sanitaryware factory producing 1 million pieces per year, approximately 2000 tonnes of plaster would be consumed. This equates to an annual plaster purchase cost of £290,000 or approximately £20 per tonne of saleable product (using 2007 production figures and assuming an average piece weight of 14.5kg across a range of shapes and sizes of piece). Using recycled plaster in place of fresh mineral plaster would give potential cost savings of £20,000-40,000 per year in material costs alone. Further indirect savings are possible as a result of the material being delivered in a more stable condition than current fresh mineral plaster supplies. This would reduce losses stemming from variations in mould properties.

Several of the major tableware factories in the Stoke-on-Trent area have been surveyed for their plaster consumption. Typically, a factory of this type would consume 300 tonnes of plaster per year, depending on the
methods of production employed (which are more varied than for sanitaryware). This would equate to a plaster cost of £42,000 per year. Output levels of 2500 – 3000 tonnes of fired product would be expected, which would give a plaster cost of £15 – £20 per tonne of fired product. Converting to recycled plaster gives the potential of a £3,000 – £6,000 per year cast saving for each factory.

10.2.2 Metal casting

If further development can produce a variant of the recycled plaster with sufficiently rapid setting properties, a proportional reduction in mould material cost of 7–14% could also be achieved. A metal caster in the UK using approximately 1000tpa of material could thus save £10,000–20,000 per year in material costs.

11.0 Conclusions

The following conclusions can be drawn from this project to evaluate the reconstitution of waste plasterboard derived recycled gypsum for use as a moulding plaster:

- The CASO process is fundamentally suitable for reconstituting waste plasterboard derived recycled gypsum with only minor modifications (e.g. to remove any residual paper fibres);
- More intensive calcination is required for the recycled gypsum than natural mineral gypsum, as it contains a high proportion of gypsum of FGD origin;
- After calcination, the recycled plaster ‘ages’ to a stable condition much more rapidly than the mineral types tested previously;
- The set plaster strength of the recycled plaster is similar to that of untreated plaster, but lower than that of the commercial plaster tested. This suggests that, while there is no intrinsic strength deficiency, product development is required to produce the strength values seen in commercial plasters;
- Slip casting in moulds produced from the recycled plaster gave similar results to those from moulds produced from fresh mineral plasters, with no significant deterioration in performance over extended use that was approaching a mould’s working life;
- The reconstitution process will need to be optimised to give the best results for recycled gypsum of FGD origin (as most plasterboard used in the UK).
- A material cost saving of 7–14% could be expected if the recycled material is used in place of a freshly mined mineral plaster.

12.0 Recommendations

Further work is needed in several areas to promote the adoption by industry of recycled plaster reconstituted from waste plasterboard.

A. Optimisation of the processing factors (calcination temperatures, calcination times, recrystallisation time) in the reconstitution process of the recycled gypsum of FGD origin to:
   - determine the influence of material and process variables on plaster performance, in particular those relating to strength and setting time;
   - identify solutions to enable recycled plaster to be used for plastic forming of ceramics and metal casting; and
   - maximise throughput and minimise energy consumption in the reconstitution process.

B. Further trials of the reconstitution process using recycled gypsum to:
   - ascertain the variability of the recycled plaster properties and their effect on mould making and casting; and
   - identify ways of minimising the effect of any variability.

C. Investigation of the long-term stability of the recycled plaster so that an effective shelf life from production to use can be determined.

D. Because the plaster derived from recycled gypsum of FGD origin requires more intensive calcination during processing, it is likely to prove to be more resistant to ‘burning’. ‘Burnt’ moulds suffer major losses of strength and crumble when subjected to mechanical loading or handling. Their performance can also degrade during ceramic production. A greater resistance to ‘burning’ would confer a production advantage to the FGD recycled plaster as higher drying temperatures could be used, reducing the production bottleneck that mould drying presents. These benefits need to be quantified.
E. Conducting larger scale trials to give fully representative indications of performance. Such trials would require the production of several tonnes of recycled plaster for use in trial moulds and the involvement of a plaster supplier (the quantities involved are beyond the scope of laboratory processing). The latter would introduce specialist expertise on processing and additive packages to meet the requirements of specific end uses, particularly where rapid setting is required.

13.0 References


14.0 Glossary

**Additives**
Small chemical additions to the plaster that are intended to modify its behaviour.

**Ageing**
A spontaneous process in which moisture is absorbed from the atmosphere and the plaster achieves a relatively stable condition in terms of slurry viscosity and blending/setting time. This can take several weeks in mineral plasters.

**Anhydrite**
Calcium sulphate with no water bound into its crystal structure. This can be a soluble form (which can react with water) or insoluble (which has a different crystal structure and does not react with water).

**Blending**
Mixing plaster powder with water to form a homogeneous, free-flowing slurry. Control has to be exercised over mixer speed and the time that the slurry is stirred to fully control the properties of the resulting moulds.

**Blending time**
A characteristic of a particular plaster. The plaster must be poured once its viscosity has increased as the plaster starts to go through the first stages of setting. Changing the blending time has a strong influence on mould permeability.

**Calcination**
Heat treatment of gypsum to drive off some of the water bound into its crystal structure. This can either be to remove most of the water to give hemihydrate or to remove all of the water to give anhydrite.

**Dihydrate**
The basic feedstock material of calcium sulphate, with two molecules of water bound into its crystal structure for every molecule of calcium sulphate.

**Flue gas desulphurisation (FGD) gypsum**
A synthetic by-product of the chemical 'scrubbing' of power station combustion gases to remove sulphur dioxide. This is gypsum calcium sulphate dihydrate, as in mineral source material. Most UK plasterboard is produced from this material.

**Gypsum**
Calcium sulphate dihydrate. Also used in this report as the general term for the feedstock material.

**Hemihydrate**
The active plaster supplied to the end user. The crystal structure has one-half of a water molecule for each calcium sulphate molecule present. It reacts readily with water to form the dihydrate while setting.

**Mineral gypsum**
Gypsum obtained from mineral beds laid down by the evaporation of sea water.

**Permeability**
The ability of a mould to allow air (or water to pass) through it. In some ceramic industry applications, this is a critical factor as a vacuum is applied to hold the clay blank onto the mould. Used to assess the microscopic structure of a finished mould.
| **Plasterboard** | Product composed of a plaster core encased in, and firmly bonded to, strong durable paper liner to form a flat rectangular board. The paper surfaces may vary according to the use of the particular type of board and the core may contain additives to impart additional properties. |
| **Reconstitution** | Processing used plaster or gypsum to restore it to the reactive hemihydrate form so that it can be reused in the production of moulds. |
| **Recycled gypsum** | Gypsum recycled from waste plasterboard. In general, the recycling process involves removing contaminants from the collected waste, then the plasterboard is fed into specific equipment which separates the paper from the gypsum core then crushes the gypsum to a fine granular powder. |
| **Retarders** | Chemical additives intended to delay the commencement of setting of the plaster. These are important in ceramic moulds as they allow the plaster to be thoroughly dispersed, removing lumps and air bubbles before the viscosity of the slurry starts to increase. |
| **Setting** | The process in which hemihydrate reacts with water to form dihydrate. In this process, the hemihydrate dissolves in the water in the slurry and then crystallises out as dihydrate, which forms needle-like crystals that lock together to form a strong but porous structure. |
| **Setting time** | The time at which the mould can be removed from the ‘case’ mould that forms it. By this stage it has developed enough strength to be handled without being damaged. |
| **Untreated plaster** | A sample of hemihydrate provided by a plaster supplier for comparison with the recycled plasterboard gypsum. This material had only received the calcination heat-treatment and had no additives incorporated within it. All commercial plasters contain additive packages and cannot be compared directly with an untreated material such as the one produced during the project. |
## Appendix A Analysis results on gypsum feedstock

### Table A1 Results of XRD analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula</th>
<th>Unit</th>
<th>Recycled gypsum plaster</th>
<th>‘Neat’ mineral plaster (no additives)</th>
<th>Recycled gypsum plaster (-80 sieve)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite</td>
<td>CaSO₄</td>
<td>%</td>
<td>1.5</td>
<td>0.4</td>
<td>9.8</td>
</tr>
<tr>
<td>Bassanite</td>
<td>CaSO₄·0.5H₂O</td>
<td>%</td>
<td>1.8</td>
<td>99</td>
<td>90</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
<td>%</td>
<td>2.5</td>
<td>Major</td>
<td>0.1</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
<td>%</td>
<td>Major</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Muscovite</td>
<td></td>
<td>%</td>
<td>Trace</td>
<td>ND</td>
<td>Trace</td>
</tr>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
<td>%</td>
<td>0.6</td>
<td>0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>UKAS accredited</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

1 CERAM Sample Reference (056578)-28346; Material type: recycled plaster; Date of test: 1 December 2005 to 20 December 2005.
2 CERAM Sample Reference (06425)-2223; Material type: plaster; Date of test: 27 January 2006 to 2 February 2006.
3 CERAM Sample Reference (056578)-2224; Material type: plaster; Date of test: 27 January 2006 to 2 February 2006.

ND = not detected; Major = >10%; Minor = 2–20%; Trace = <2%.
### Table A2 Results of XRF analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula</th>
<th>Unit</th>
<th>Recycled gypsum plaster</th>
<th>‘Neat’ mineral plaster (no additives)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide</td>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>1.67</td>
<td>0.46</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>0.03</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>%</td>
<td>0.45</td>
<td>0.11</td>
</tr>
<tr>
<td>Iron(III) oxide</td>
<td>Fe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>%</td>
<td>0.26</td>
<td>0.06</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>CaO</td>
<td>%</td>
<td>32.63</td>
<td>38.13</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>MgO</td>
<td>%</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>Potassium oxide</td>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>%</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>Na&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>%</td>
<td>&lt;0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Phosphorus pentoxide</td>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>%</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Chromium(III) oxide</td>
<td>Cr&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>%</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Manganese(II,III) oxide</td>
<td>Mn&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>%</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Zirconium oxide</td>
<td>ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Hafnium(IV) oxide</td>
<td>HfO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Lead oxide</td>
<td>PbO</td>
<td>%</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>ZnO</td>
<td>%</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Barium oxide</td>
<td>BaO</td>
<td>%</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Strontium(II) oxide</td>
<td>SrO</td>
<td>%</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Tin(IV) oxide</td>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Copper oxide</td>
<td>CuO</td>
<td>%</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Loss of Ignition (LOI)</td>
<td>%</td>
<td></td>
<td>19.38</td>
<td>6.90</td>
</tr>
<tr>
<td>LOI temperature</td>
<td>°C</td>
<td></td>
<td>1025</td>
<td>1025</td>
</tr>
<tr>
<td>Total</td>
<td>%</td>
<td></td>
<td>57.74</td>
<td>45.99</td>
</tr>
<tr>
<td>Sulphur remaining&lt;sup&gt;4&lt;/sup&gt;</td>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>%</td>
<td>45.57</td>
<td>53.89</td>
</tr>
</tbody>
</table>

1 Sample bias: dried to 110°C. Results are quoted to two decimal places but are accurate to three significant figures or the number of figures given, whichever is the lesser.

2 CERAM Sample Reference (056578)-28346; Material type: recycled plaster.

3 CERAM Sample Reference (06425)-2223; Material type: plaster; Date of test: 31 January 2006 to 16 February 2006.

4 The sulphur remaining is not a total sulphur figure, but that remaining after LOI and fusion.
Appendix B Tableware mould making process

Figure B1 Measuring water by weight

Figure B2 Moulding plaster supply
Figure B3 Measuring gypsum plaster by additional weight to water

Figure B4 Blending plaster using rotary stirrer
Figure B5 Spraying releasing liquid onto the mould former

Figure B6 Pouring plaster into mould former casing
Figure B7 Releasing air bubbles

Figure B8 Filled mould former, plaster setting
Figure B9 Scraping excess plaster from mould base

Figure B10 Removing mould former case
Figure B11  Tidying mould

Figure B12  Removing mould from former
Figure B13  Quality check of final mould

Figure B14  Plate moulds in drying oven
Appendix C Plastic forming process

Figure C1 Clay blanks
**Figure C2** Loading the clay blank into the mould

**Figure C3** Plaster moulds with clay shape inside
Figure C4 Removing the clay shape (a cup) from the mould

Figure C5 Teapot in mould, showing separate mould pieces
Figure C6 Teapots drying

Figure C7 Finishing pieces before firing