Accelerated Drying of Plaster Casts with a Microwave Oven

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Calcined gypsum (calcium sulphate hemihydrate, CaSO4 - 1/2H20), commonly known as plaster of Paris, is used extensively in forming casts to immobilize parts of the body and for making molds used in the manufacture of orthotic and prosthetic devices. Plaster models and casts have several advantages, and a few disadvantages. Widely available, plaster is inert, sufficiently stable dimensionally, for the use at hand, and is inexpensive. Its major disadvantage involves the time required for it to dry sufficiently so that it may be modified and used for forming orthoses and prostheses.

During its manufacture, plaster is prepared for use by reducing it to its powdery state. When it is used, it is mixed with water in approximately the proportions of two parts plaster to one part water. Plaster bandages are crinoline fabric strips in various widths and convenient lengths, rolled in the plaster to fill the interstices of the fabric with the powder. These are packaged and ready for dipping or wetting in water followed by application to the body or limb.

When plaster is mixed with water, crystallization occurs in a few minutes. The chemical reaction generates heat. Molding over the desired contours is done by rubbing and shaping with the hands before crystallization. When freshly poured, plaster passes through a glossy, creamy, intermediate stage to promptly become thickened and dull to light. This is the "setting" stage and further manipulation must be avoided because proper interlocking of the calcium crystals will be hindered.

Plaster models of limbs, extremities, and amputation stumps, are made by first wrapping the member with plaster bandages, removing them after they have set, and then pouring liquid plaster into the

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female cast. On setting and removal of the outer bandage cover an exact plaster model of the member remains. This model is used to shape and form the plastic and other materials required to produce the device.

Plaster casts will dry in time, of course, by simply exposing them to air at room temperature. Most often, however, they are dried in a warm, forced-air oven, at about 150 degrees F. Higher temperatures tend to crack casts and produce spalling. In our experience the times generally required for drying in 150 degree F. oven are:

Hand or arm casts	12 Hours
Partial foot & Syme casts	12 Hours
Above-knee casts - medium size	12 Hours
Shoulder-disarticulation casts	18 hours
Above-knee casts, large size	18 hours
Hip-disarticulation casts	24 hours
Body casts	24 hours

In an effort to reduce the present drying time of 12 to 24 hours, presently attained with hot-air ovens, experiments have been performed wherein "set" samples of wet plaster have been dried effectively in a microwave oven.

EARLY CONSIDERATIONS

In trying to reduce the time required before the model could be used we considered several different ways, including:

1. Procedures and tools that would minimize the problems of wet plaster occluding the tools used to modify the casts.

2. Providing a moisture barrier on the surface of the cast to eliminate the need for drying. Two procedures examined were:

a. Application of a chemical or paint to the wet surface to prevent migration of cast moisture.

b. Application of a film of sheet material or preformed bag to the wet cast to serve as a moisture barrier.

Retained moisture in the improperly dried cast may also affect the polymerization of certain plastic laminates in that it prevents the development of smooth surfaces needed for contact with the skin of the patient. To date, no really satisfactory moisture barrier has been found. Physical barriers such as rubber balloons reflected over the cast, tend to prevent passage of moisture but also disintegrate on contact with the laminating resins. Chemical solutions of several types were found to be similarly inadequate.

Our earlier considerations of the use of microwave energy had not preceeded beyond the academic stage until we were encouraged by Drs. Williams and Kesting, visiting from Chemical Systems, Inc. Our tests, using three approaches involving microwave equipment, included units belonging to Sears-Roebuck, Litton Industries, and the Bechtel Corporation.

SEARS-ROEBUCK MICROWAVE OVEN

The oven used (Fig. 1) was a demonstrator unit from the sales floor of the local Sears outlet. It was designed for use in the home and was Model #103 9927102-115 VAC/1560 watts - 14.5 ampere. The interior dimensions were slightly over 43 cm. W x 35 cm. D x 17 cm. H. This size would take care of our needs in smaller size casts but it would be

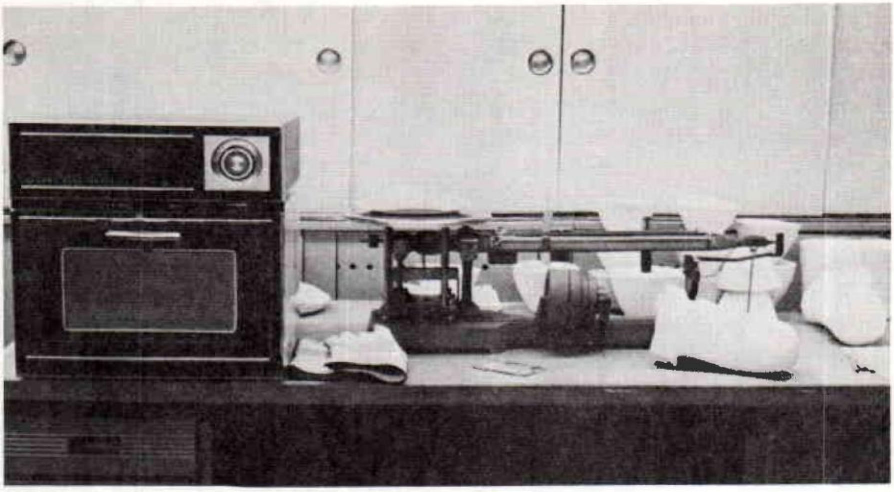

FIG. 1 Oven shown was supplied without charge by Sears. Also needed for the study were scales, plaster of Paris, water, a standard mixing bowl and a pair of heavy leather gloves—the latter for handling the hot plaster casts.

inadequate for "long leg" or large body casts. It did, nevertheless, alllow us to determine the feasibility of drying plaster with microwave energy.

To form the test models (Fig. 2) standard rubber bowls of the type used to mix small batches of plaster were used. The resulting models were bowl-shaped to thus represent a thick structure possessing both flat and curved surfaces. To further standardize the models we adopted the proportions of 800 grams of plaster to 400 grams of water for each model.

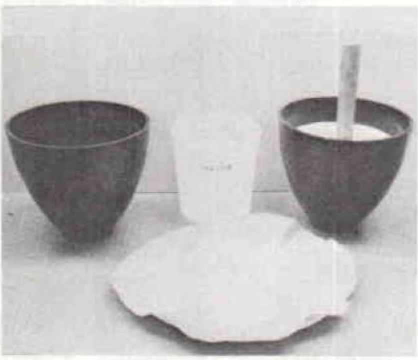

FIG. 2 Standardization of test models was achieved by using identical amounts of plaster and water, as determined by weight. All were mixed in standard mixing bowls, as shown, thirty minutes before each test.

For our initial experiments we placed the test model on a paper plate, which is unaffected by microwave energy, in the center of the oven and exposed the model for four-minute intervals (Fig. 3). The freshly mixed model was weighed

FIG. 3 Models were placed on standard paper picnic plates and energy was applied in increments of four minutes. Between each application the model was removed from the oven, weighed, replaced and drying continued.

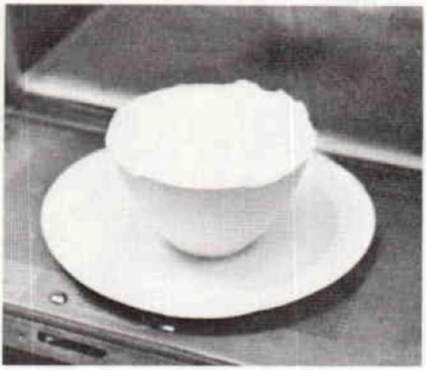

FIG. 4 After four minutes the outer surface of the plaster model was warm, damp, and water vapor was arising from the surface. There was a moderate drop in weight due to vapor loss.

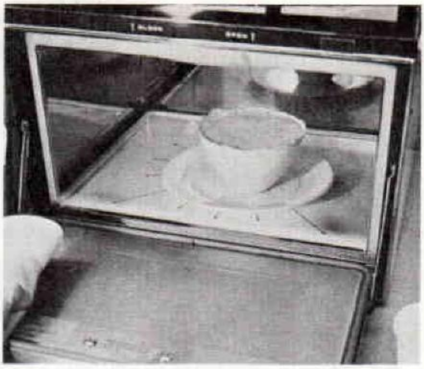

FIG. 5 Droplets of water appeared on the surface of the model and a small puddle of water had formed on the paper and plate, soaking into same. Weight loss was almost three times that of the first drying interval.

initially and reweighed at the end of each drying interval. After four minutes the model felt damp and warm and wisps of water vapor arose from its surface (Fig. 4). There was no evidence of water absorption in the paper plate. At the end of the second four-minute interval the cast was warmer, there was more vapor, and a suggestion of dampness on the paper plate was noticed (Fig.5). At the end of the third four-minute interval, drops of water were present on the surface of the cast, and the plate was almost filled to the brim with water.

The same procedure was continued for four additional four-minute intervals. The cast was perhaps dry enough to work at the

DRYING TEST OF PLASTER MODEL — SEARS MICROWAVE OVEN

Starting Weight = 1,166 grams - freshly mixed

Time (min.)	Weight (grams)	Weight Loss (grams)	Comments
4	1,152	14	Warm/vapor from surface
8	1,112	40	Hot/vapor + puddle of water
12	1,062	50	Same
16	1,015	47	Hot/water boiling
20	942	73	Hot/surface dry for work
24	902	40	Hot/surface damp
28	842	60	Hot/surface damp
32	804	38	Hot/surface damp
36	799	5	Hot
40	796	3	Suitable for lamination
44	792	4	Crack developing
48	783	9	Crack larger
52	782	1	Crack larger
56	781	1	Test discontinued

end of the fifth interval, or a total exposure of twenty minutes in the microwave oven, but not enough to allow for lamination. We were impressed with the results shown in the table on page 27.

LITTON INDUSTRIES MICROWAVE OVEN

At this point we were able to obtain a demonstrator oven manufactured by Litton Industries. This larger oven, designed for restaurant use, featured a half-power switching arrangement found to be quite convenient. The Litton oven measured about 35 cm. x 61 cm. x 25 cm., sufficient for all except our largest lower-limb and body casts.

The results of the power of the Litton oven were soon apparent. Two test models exploded, but without injury to personnel or equipment (Fig. 6). On inspection of the broken pieces of the case it appeared that water vapor deep within the cast was being converted to steam, and that the water was being forced from deep inside the cast to the outside surfaces. We repeated several of the earlier experiments using test models of differing plasters ordinarily used in orthopaedic, prosthetic, and orthotic practices. The additional power and size of the Litton oven represented an advantage.

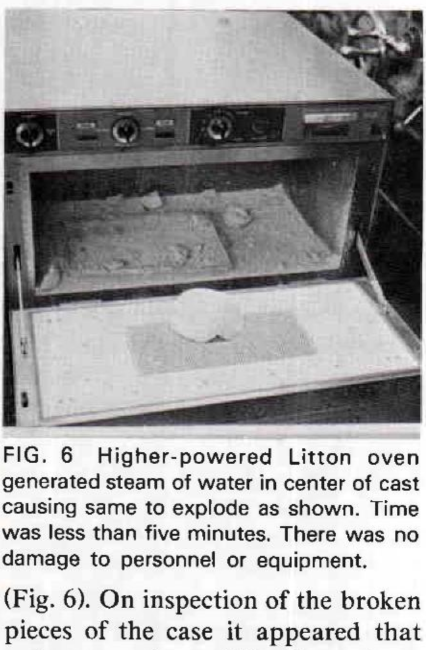

FIG. 6 Higher-powered Litton oven generated steam of water in center of cast causing same to explode as shown. Time was less than five minutes. There was no damage to personnel or equipment.

Sufficient dryness for use in forming orthotic and prosthetic devices, is of course, reached well before all the water is extracted from the cast, and therefore it was desirable that simple tests be developed that would allow us to determine when the cast was sufficiently dry for use. We used an open mesh abrasive (Sand Screen 8 M7555, No. 180 mesh, made by Carborundum) with which we rubbed the test surface. When the plaster was too wet to work, the interstices of the screen filled with the wet material thus destroying its abrasive effectiveness. When dry, the plaster tends to fall away from the screen.

The larger size of the Litton oven allowed us to study its drying capabilities with a full-size cast. These duplicated a below-knee amputation stump. To assure their standardization they were made from a common wrap cast and with identical amounts of plaster and water. We also used wood dowels rather than the usual sections of metal pipe for handling the casts, since metal acts as a heat sink in microwave ovens.

The freshly mixed plaster cast was placed in the center of the Litton oven, resting in a quantity of ceramic beads in a glass baking dish. Neither the beads nor the glass dish are affected by microwave energy. Full power was applied at intervals of two mintues, and between intervals the cast was weighed quickly in order not ot interfere with the drying process to any practical extent. Time and weight losses were recorded. Loss in weight was, of course, due to water loss, and therefore represented the drying rate of the system. The plaster duplicate of the BK stump was subjected to microwave energy in intervals of two minutes. At the end of the second interval—a total of four minutes—the cast was warm to the touch and water vapor was arising from its surface. At eight minutes the entire cast was dripping wet with water collecting in large droplets. Some droplets ran off onto the floor as the cast was removed for weighing.

Both the Sears and Litton ovens were equipped with air fans to discharge the warm, moist air through their perforated front panels. It occurred to us that for our selective use we could use a higher heat and higher volume of air flow, sufficient, perhaps, to prevent the coalescence of water vapor into droplets, and therefore further reduce the drying time.

Shrinkage of plaster was the subject of a comparative investigation of the accelerated drying of plaster by microwave energy and the conventional hot air drying technique.

Two identical plaster duplicates of the same amputation stump were produced and their measurements were checked at some eight points in addition to circumferential measurements at identical levels (Fig. 7). One cast was dried in the conventional way, in a 150 degree F. oven, overnight, and the other in the Sears oven. No significant differences were found in the comparative measurements of the two casts following the drying procedures.

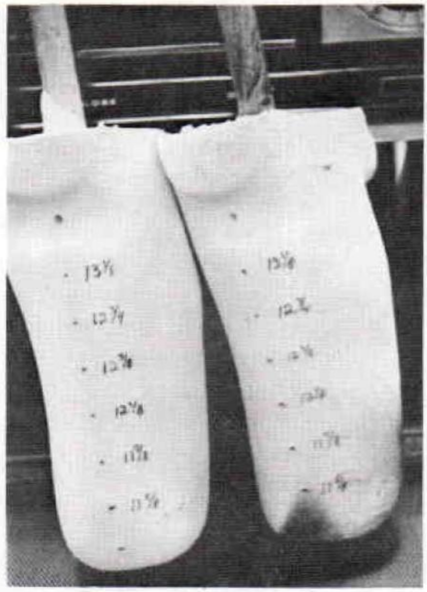

FIG. 7 Identical plaster stump reproductions were dried, one in a 150 degree F. heated oven overnight, the other in the microwave oven for 50 minutes. There comparable dimensions demonstrated no measurable difference.

BECHTEL CORPORATION STUDY

As a result of our experiments we contracted for independent feasibility studies with the Bechtel Corporation, a commercial firm having the capability of designing a microwave drying system for our particular use. We supplied Bechtel with plaster of Paris for our own supplies, molding equipment, and associated materials for making their test casts. In addition, to assure identical tests values in the beginning, we also provided a staff member who actually made all plaster casts. These duplicated those made in our own laboratory, ranging in size from the small, bowl-shaped casts to large torso casts weighing ten to eleven kilograms.

Bechtel used thicknesses ranging

from 5 to 30 cm. They felt that an oven with a rectangular cavity of 43 x 61 x 41 cm. would be sufficient and should include a mode stirrer and turntable to achieve uniform power density. For testing, power at 2450 MHz was provided with adjustable power output up to 2.5 kw.

In the laboratory oven configuration used, the casts received only 75% to 90% of the 1.5 to 2.5 kw. microwave energy available. A plot of energy versus weight reduction for heavy and light samples is shown in Figure 8. In a production unit designed specifically for this application, Bechtel feels that these percentages can be increased.

Qualitative judgment of the samples indicated that workability (sufficient dryness) was achieved at 72% of initial weight (Fig. 9).

When the sample reached this weight loss, the exterior surface of the cast was hot and slightly damp. The surface temperature ranged from 120 to 140 deg. F. Higher interior temperatures, in the order of 220 deg. F., still forced small quantities of moisture to the surface. Allowing the sample to cool for several minutes produced a dry, completely workable, surface.

Exhausting the mositure laden air from the oven at a rate of 2.24 cubic meters per minute (80 cfm) greatly reduced the accumulation of water on the bottom of the cavity. The concurrent introduction of a 160 deg. F. hot air supply afforded a small additional improvement. A hot air supply alone had little effect in reducing accumulated condensate. The air system reduced the length of time that the surface of the cast remained wet, but the weight loss versus total incident microwave energy curve remained essentially unaffected. The most notable effect was that when the air system was not used the plaster usually spalled and cracked.

In addition, measurements made on 3 kg. knee casts at 27% weight

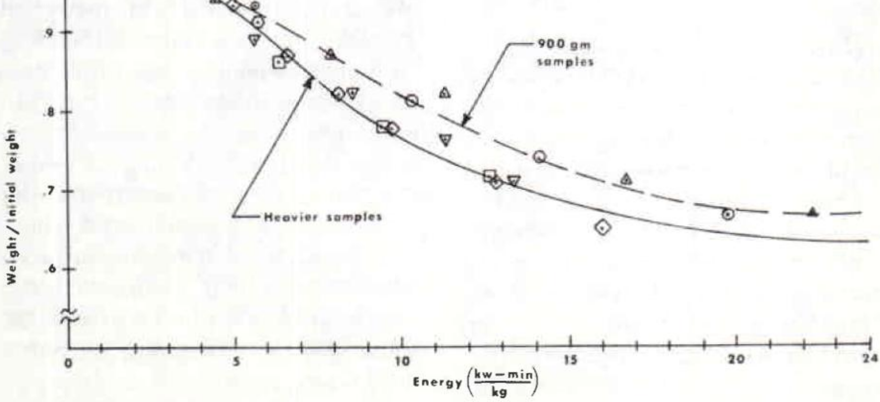

FIG. 8 Rate of drying vs. energy required for microwave/air drying.

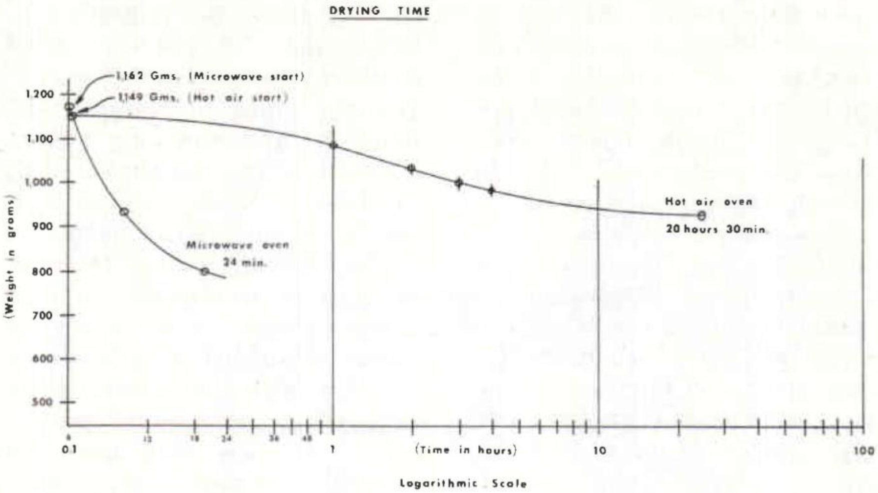

FIG. 9 Loss in weight vs. time for hot air oven and for microwave oven.

loss showed that the air system affected the interior temperature, as measured 3.81 cm. below the surface. With both the hot air supply and exhaust operating, the internal temperature was 217 degrees F. With only the exhaust system operating, this temperature rose to 224 degrees F. With neither system operating, the interior temperature was 228 degrees F. This data indicated that if the water was not removed from the surface of the plaster by the air system, a higher internal temperature or driving force is generated to bring the remaining interior water to the surface, and the temperature moderating effect of evaporative cooling at the surface was not as pronounced. This effect is likely responsible for the higher incidence of spalling and cracking experienced without the air system.

To reduce the number of unknown factors, most of the experiments were conducted without the insertion of a handle into the cast. In separate, controlled, experiments, several types of rods were evaluated for use as handles. Both fiberglass and polypropylene caused the plaster to crack. Because polypropylene is relatively transparent to microwave energy, it is likely that conduction heating of this material by the hot interior of the plaster caused thermal expansion sufficient to produce the cracking. A section of teflon tubing provided the only successful handle. Because the microwave transparency of teflon is similar to that of polypropylene, it can be postulated only that the success was due to the hollow cross-section. This configuration is assisted by some degree of cooling due to the interior air column. Also it is less rigid and more able to absorb thermally generated stresses. It appears that a metal rod inserted in and secured to a teflon or polypropylene tube will provide a satisfactory handle.

CHEMISTRY

Based on the assumption that the "as received" plaster powder was 100% calcium sulfate hemihydrate ($CaSO_4 \cdot 1/2H_2O$), the weight losses measured for samples dried by microwaves to workability exceeded the weight loss expected in drying to the normal dihydrate ($CaSO_4$ -

2H2O) state. For the hemihydrate, mixed in a 2:1 ratio, by weight, with water, curing to the dihydrate would have resulted in a 20.9% weight loss. Returning to the hemihydrate state would have produced a 33½% weight loss and curing to the anhydrous state would have yielded a product with a 39% loss. Optimum microwave drying, as determined by workability, required a 28 to 30% weight loss. To determine the hydration state of the plaster in all phases of processing, samples were weighed and dehydrated in an air oven.

Samples of the "as received" plaster powder were placed in an air oven at 150 deg. F. for 72 hours. There was no noticeable weight loss that would indicate the presence of free water. These samples were then heated to 425 deg. F. and held there for two hours. The measured weight loss after this period indicated that the "as received" powder had been mainly CaSO4 - 1/2H20. Exposure to higher temperature (1400 deg. F.) failed to produce a further weight reduction. Several of the air-oven dried 900 gram samples were weighed and dehydrated at 425 deg. F. The resulting weight loss indicated that these samples were in the dihydrate state. Similar measurements showed the microwave-dried samples to be primarily hemihydrate.

Information from the United States Gypsum Corporation confirmed that most plaster of Paris is shipped in the hemihydrate state and subsequently cured to the dihydrate. The majority of the chemical action occurs in 10 to 20 minutes with the removal of excess water comprising the remainder of the process. Normal cure tempature is 120 deg. F. Above 200 deg. F. the plaster goes to the hemihydrate state and reaches the anhydrous state above 350 deg. F. The hemihydrate is weaker and subject to greater shrinkage than the dihydrate. This shrinkage likely refers to tolerances of few thousandth of an inch acceptable in precision metal casting. Measurements made on laboratory samples failed to show a difference in shrinkage between air and microwave dried plaster. Also there was no obvious qualitative difference in strength or workability noted between the air-oven cured control samples and the microwave dried samples.

From weight loss date and temperature measurements, it appears that the microwave drying produces a cast with a hemihydrate core and dihydrate exterior.

CONCLUSIONS

Experimental results appear to justify the following conclusions:

1. Microwave drying of "set" orthopaedic plaster is a feasible process.

2. The drying time of a 3 kg. knee cast to a level of mechanical workability can, for example, be reduced from the twelve hours required by a hot air oven to 30 minutes with the air-assisted microwave oven.

3. The use of air in conjunction with microwave energy is beneficial in achieving high drying rates and a good quality product.

4. Microwave/air drying appeared to yield a product having a hemihydrate core and a dihydrate exterior.

5. No observable differences in strength, shrinkage and mechanical capability were noted in the micro-

wave/air dried samples compared to control samples dried in a hot air oven.

6. Sufficient knowledge of the microwave drying parameters of plaster molds in the size range of interest was obtained to permit establishing design specifications for a prototype oven.