FROM SCULPTURE LAB TO INDUSTRIAL SETTING–

University Study Explores Building Investment Casting Shells Using Rapid-setting Stucco Compounds

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Traditional shellbuilding for the investment casting process can take as long as two or three days because of the time required to thoroughly dry each layer between dips. Several efforts have been made recently to shorten that time. Among these are using faster drying solvents, drying tunnels, organic absorbent polymers[1], infrared light with its wavelength tuned to the spectrum of water[2], and heating the shell while it is being made[3]. To date, none of these techniques has been universally accepted.

A new method, recently reported at the Investment Casting Institute's 54th Technical Conference in Milwaukee, provides a promising option. The new technique uses traditional-formula stucco modified with amorphous mineral silicate and corn starch.

Experimental Procedures

Litter box, industrial setting

In one industrial setting, shells were built with two standard slurries and three stucco mixtures that contained standard stucco components plus the amorphous mineral silicate and corn starch materials. Wax trees were dipped in slurry, then the stucco was hand sieved on the surface. Within the first 10 to 20 minutes of drying, the outer surface of the stucco began to swell, and often some of the stucco fell off. After 20 to 30 minutes, the loose stucco was removed with a gentle stream of air (~5 psi) or by tapping, and the tree was redipped and stuccoed. This process was repeated to build up the desired number of layers and ended with a seal coat. The loose stucco was removed before each redip.

Litter box method, University of Wisconsin-Whitewater

At a University of Wisconsin-Whitewater sculpture studio, shells were built using a single slurry and a single stucco that contained amorphous mineral silicate and corn starch. Using a litter box method of applying stucco, shells for non-ferrous alloys had as few as two, but more usually four or five coats of slurry plus stucco (hereafter a layer of slurry plus stucco is called a shell coat) and a seal coat. Shells for cast iron had six or more shell coats plus a seal coat. Drying times were as short as 20 minutes between each redip, and loose stucco was blown off before each redip.

Fluidized bed, industrial setting

In another experiment, researchers used mixture of coarse fused silica, amorphous mineral silicate, and corn starch in the fluidized bed. These components were partially mixed prior to being poured into the fluidizing tank, and were mixed in the tank by the boiling action. The air flow was adjusted from a low to high boil to examine what effect different boiling rates had on mixing and dipping. For these initial studies, only one stucco was used for all applications. Wax trees were dipped in the slurry then immersed in the fluidized bed. The air flow was adjusted so the tree easily penetrated the bed. The stuccoed tree was hung to dry for 30 minutes. In contrast to the litter box method, no loose stucco was observed on the surface of the tree. Researchers had expected there would be a thin layer of loose stucco on the tree that should be removed before redipping. At the end of the 30-minute dry time, the tree was immersed in a fluidized bed that contained pure fused silica. Only a minute amount of stucco came off in the fluidized bed, so this abrasion step was omitted for all subsequent dips. The tree was coated with a total of seven shell coats plus a seal coat. The modified stucco was used for all seven layers. Drying times between dips ranged from 30 to 60 minutes. The total time from the first dip to applying the seal coat was six hours. The shells were dried over a weekend then autoclaved, heated at 1600ºF, and filled with stainless steel at 3050ºF.

Mechanical testing, industrial

To measure mechanical properties, bar-shaped shells were fabricated using the litter box method. Shells with four shell coats plus a seal coat were made using one slurry and three different stucco mixtures. Standard shells were made with the three standard stuccos for base-line measurements, and modified shells were made with the three standard stuccos to which amorphous mineral silicate and corn starch was added. Standard shells were dried two hours, and modified shells were dried one hour between dips. The modified shells were gently tapped to remove the loose stucco before redipping.

Before testing, the shells were allowed to dry 16 and 60 hours to simulate drying overnight and over a weekend. **Table I** lists the samples that were tested. Bending tests were run to failure to determine the modulus of rupture (MOR) and modulus of elasticity (MOE). Tests were run on the samples cut from the shells af-

Table I: Drying times for samples used for mechanical measurements. Shells were made with 4 shell coats plus a seal coat

Sample Name	Stucco	Drying time between dips (h)	Drying time after applying seal coat (h)
Std-60	Standard	2	60
Mod-16	Modified	1	16
Mod-60	Modified	1	60

FIGURE 1. Modified shell after being pulled out of the fluidized bed. There is little dust being generated in the bed.

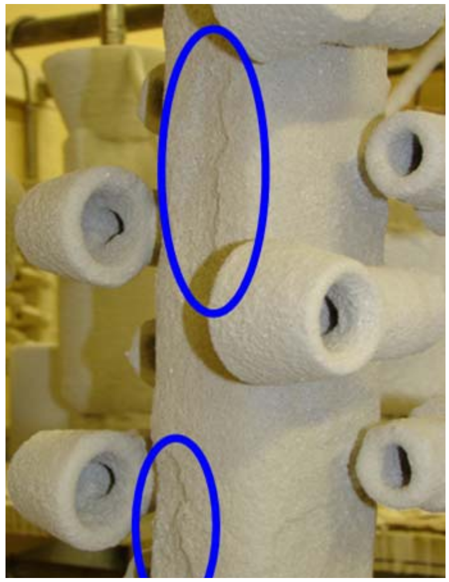

FIGURE 2. Modified shell made using the litter box method. The circled regions show where loose stucco fell off during drying

FIGURE 3. Surface of a modified shell made by the litter box method after loose stucco was blown off.

ter drying 16 or 60 hours (green), on samples immediately after coming out of the autoclave (hot wet), and on samples at room temperature after being fired at 1800ºF for 2.5 hours (fired).

Shellbuilding Results

Although the amorphous mineral silicate is very light and fluffy, there was no dust problem using the litter box approach with a dust collection system. However, dust was initially a serious issue using the fluidized bed. The fused silica, amorphous mineral silicate, and corn starch were coarsely blended then poured into the fluidized bed. When the air was turned on to mix the components in the fluidized bed, enormous amounts of dust billowed out of the bed. In the first experiment, the dust collection system only surrounded the rear half of the fluidized bed tank, and this was not adequate to keep up with the dust generation. By putting a cover over part of the fluidized bed, the dust collection system was able to remove all the dust, and in approximately 30 minutes the bed was generating very little dust. **Figure 1** shows a tree after being pulled out the fluidized bed. There is very little dust above the bed.

Fluidized bed

Before the components in the fluidized bed were fully mixed, the bed was stratified with the amorphous mineral silicate and corn starch on top. When air flow was decreased in the stratified bed, boiling stopped, and air came out though large blow holes in the top layer. The components were mixed in ~20 minutes with vigorous boiling. After the components were mixed, there was no stratification and large blow holes did not form when the air flow was reduced. Shells were built for a day with the modified stucco. The fluidized bed had to be topped off during the day. Each time, it took roughly 20 minutes to mix the components, and dust was not a problem when a cover was used over the fluidized bed. At the end of the day, all the stucco was scooped out of the tank; it was thoroughly and uniformly mixed from top to bottom. Using the same boil rate as that for traditional stucco, it was easier to immerse the tree in the modified stucco compared to the standard stucco.

Litter box

For shells made with the litter box method, immediately after hand-sieving stucco on the slurry, the surface appeared to be mainly the fine amorphous mineral silicate. This top layer of stucco began to swell and loosen, and it was not uncommon for regions of the loose stucco to fall off the shell after about 10 minutes. **Figure 2** shows a shell where regions of stucco have fallen off during drying. The entire tree was blown off with a gentle stream of air just before redipping to remove the loose stucco. Figure 3 shows the surface after removing the loose stucco. It is very uniform. About 25 wt % of the stucco layer was removed. After removing the loose stucco, gray amorphous mineral silicate was still present in the underlying layer, but the surface was rougher because it contained a higher fraction of grains of fused silica than the original surface, indicating the amorphous mineral silicate was preferentially removed.

When shells were made using the fluidized bed, the stucco did not appear to swell during drying as it had with the litter box method. After drying, the first shell coat for 30 minutes, the tree was immersed in a fluidized bed that contained only fused silica to abrade any loose stucco off the surface. No significant difference was observed on the surface before and after abrading. Since only a tiny amount of amorphous mineral silicate came off in the fluidized bed and no additional fused silica stuck to the shell, the shells were not abraded before redipping.

There was very little delamination on redipping litter box samples after removing the loose stucco and fluidized bed samples that had not been abraded.

The normal cycle time between dips with ideal drying conditions (temperature, humidity and air flow) is 20 minutes. However, the modified shells made with the flu-

FIGURE 4. Modified shells with 304 stainless steel poured at 3050ºF.

FIGURE 5. Stainless steel casting from a modified shell that has been partially bead blasted to show the surface finish. There is no evidence of burn in or other surface defects.

FIGURE 6. Modified shell and stainless steel casting after cooling. The modified shell broke into large pieces during cooling

idized bed method described here were built during a cold Wisconsin winter, and the shell room was not adequately heated. Consequently, drying times ranged from 30 to 90 minutes.

Modified shells are lighter and ~ 7% thinner than the baseline standard shells. Yet, the same number of shell coats is needed for modified and standard shells built using the litter box and fluidized bed methods. Shells for nonferrous metals required four or five shell coats plus a seal coat. Shells for ferrous alloys required six or more shell coats plus a seal coat.

Dewaxing and pouring

Modified shells with as few as two, but more regularly four to six shell coats, plus a seal coat are routinely made using the litter box method in the sculpture studio. The cycle time for dipping with ideal drying conditions is 20 minutes, and the seal coat is dried for 60 minutes. At this point, the shells can be flashfired in a furnace at 1850ºF for 60 minutes, then taken out of the furnace and immediately filled with molten metal. This generates nonferrous and ferrous castings that have excellent surface qualities with no casting defects.

Modified shells have also been autoclaved to remove the wax. These shells were made using the litter box method with non-ideal drying conditions, requiring drying times between dips from 30 to 90 minutes. The seal coat was applied and allowed to dry overnight or longer before the shell was autoclaved.

The original plan was to remove the wax from the shell in an autoclave immediately after the modified shells were built, as was done with flashfiring. However, because of difficulty coordinating shellbuilding with the autoclave schedules, modified shells were built with a total of six shell coats plus a seal coat over two days. The first four shell coats were applied on day one with 30 to 90 minute cycle times between coats, dried overnight; the final two shell coats and the seal coat were applied on day two with 30 minutes between dips. The seal coat was allowed to dry 60 minutes before the shells were placed in the autoclave. There were no cracks in any of these shells after autoclaving. After being taken out of the autoclave, the modified shells were placed in a flash furnace, preheated for 60 minutes at 1600ºF, then immediately filled with molten stainless steel.

Figure 4 shows modified shells being filled with molten stainless steel at 3050ºF. These castings had no burn in, had excellent surface quality, and the dimensional tolerances were within the specifications for the parts. **Figure 5** shows the excellent surface finish of stainless steel parts that were cast at ~3000ºF.

Shell removal

It is easier to remove the modified shell than the standard shell from the casting. The relative ease with which the shell is removed from different metals has the same temperature dependence for both modified and standard shells: ease of removal from most difficult to easiest is aluminum alloys, bronze, cast iron, and stainless steel. **Figure 6** shows how the modified shell broke away in large sheets as a stainless steel casting cooled.

Shell mechanical properties:

Data for the modulus of rupture (MOR) and modulus of elasticity (MOE) are given in **Table II**. The MOR and MOE are significantly higher for the modified shell after firing compared to the standard shell.

The University of Wisconsin-Whitewater sculpture studio has more than four years of practical experience making modified stucco shells using the litter box method. Over this time, they have continually improved the process, until they now can build a shell and cast the piece in one day. The amorphous mineral silicate and corn starch in the modified stucco does not cause the slurry to gel. It is not toxic or hazardous, and the modified shell material is not a hazardous waste, so no change in handling and disposal procedures has been necessary. The work described here is the first experience building modified shells using the fluidized bed method.

While the amorphous mineral silicate, and possibly corn starch, initially presented a dust problem in the industrial setting, the dust is not a toxic hazard, and there are two methods of control.

First, an adequate dust collection system can safely remove the dust in litter box applications and from fluidized beds. Covering over the fluidized bed above the dust collection system when mixing the components is recommended so the dust is confined to the fluidizing tank and can be collected by the dust removal system. This prevents the dust from going into the room. An additional method of control is to make the fine particles less susceptible to becoming air borne. This can be done by coating the amorphous mineral silicate and corn starch with a small amount of food-grade mineral oil before mixing with the other stucco components.

Researchers in this project speculated the modified stucco speeds up shell building because the amorphous mineral silicate wicks water out of the slurry and allows it to evaporate at the outer surface of the shell. This is shown schematically in **Figure 7** for the litter box technique. **Figure 7a** shows the slurry and stucco layer (shell coat) on the wax pattern. **Figure 7b** is a magnified view showing water from the slurry mixed with fused silica and amorphous mineral silicate from the stucco. The blow-up of the amorphous mineral silicate particle shows its surface covered with water molecules.

It is theorized that the small size of these particles and their chemical nature allow water to rapidly wick along their surface from the inner region of the slurry/stucco coating to the outer surface of the stucco layer where the water evaporates into the moving air stream. In the litter box method, the outer surface of just-applied stucco looks fluffy because it is composed mainly of amorphous mineral silicate particles that are not glued to the shell by the underlying slurry. As the stucco is applied, the larger grains of fused silica that are not anchored by the slurry fall off leaving the fine particles of amorphous mineral silicate that can adhere even without being glued by the slurry. When the water wicks out, this poorly adhering layer of mainly amorphous mineral silicate particles swells and loosens from the underlying stucco that is anchored by the slurry.

Removing this loose layer of stucco just before redipping physically removes the water on the amorphous mineral silicate and exposes the underlying stucco that is anchored to the shell. This newly exposed surface is much rougher because it is a mixture of fused silica and amorphous mineral silicate that is anchored by the slurry. In this project, when the loose stucco was not removed, significant delamination occurred on redipping.

The same wicking process occurs in modified shells built using the fluidized bed method. The major difference compared with the litter box method is the fluidized bed abrades the loose material off the outer surface of the shell when the tree is pulled out of the bed. The surface of the stucco was rough as it came out of the fluidized bed and looked like the stucco layer on a litter box shell after the loose stucco had been removed. Any stucco that was not anchored to the shell by the underlying slurry abraded off as the tree was pulled out of the fluidized bed. This eliminates the extra step of removing loose stucco that is required for the litter box method. In modified shells made using the fluidized bed, all of the water is removed by being wicked away and evaporating.

Initial speculation was that the amorphous mineral silicate would demix in the fluidized bed. When mixing began, the top of the bed was mainly amorphous mineral silicate and corn starch. When a tree was immersed into this poorly mixed, striated bed, the tree easily penetrated the upper layer, then met more resistance as it went through the lower layer that was mainly fused silica. Increasing the air flow increased the boil rate, which increased mixing. At a vigorous boil, the stucco components became well mixed throughout the entire bed in ~20 minutes. An experienced operator noted he could push the shell into the bed of modified stucco more easily than into the standard stucco.

The modified shells can be used for a wide range of alloys. Shells have been cast with nonferrous alloys (mainly aluminum and bronze) and ferrous alloys (mainly gray cast iron and stainless steel). All the cast metals displayed excellent surface qualities and dimensional tolerances. This indicates the modified shells have adequate permeability for all the alloys. To date, the largest modified shells have contained 50 pounds of stainless steel.

Some vitrification in the inner layers of modified shells has been observed when pouring stainless steel.

Table II shows the mechanical properties of the shell materials. The MOR and MOE of green samples were measured after drying 16 and 60 hours. These measurements were also attempted on modified shell after drying two hours. However, test bars could not be made from the two-hour modified shells because the shell material was too damp to be cut into test specimens. The MOR of the green modified shell after 16 and 60 hours was comparable to the standard shell, but the MOE of the modified shell was slightly smaller than the standard shell. This shows that the rapidly-built, modified shells were as strong as the standard shell.

Table II – MOR and MOE for samples

Sample	MOR (psi)	MOE (psi)
— Green—		
Std-60	783 ± 22	100 ± 8
Mod-16	766 ± 26	85 ± 7
Mod-60	814 ± 25	70 ± 7
— Hot wet (immediately after autoclaving) —		
Std-60	370 ± 18	69 ± 8
Mod-16	216 ± 23	28 ± 4
Mod-60	371 ± 16	44 ± 5
— Fired (at room temperature after 1800ºF / 2.5h) —		
Std-60	274 ± 21	35 ± 4
Mod-16	1076 ± 64	152 ± 13
Mod-60	572 ± 39	65 ± 7

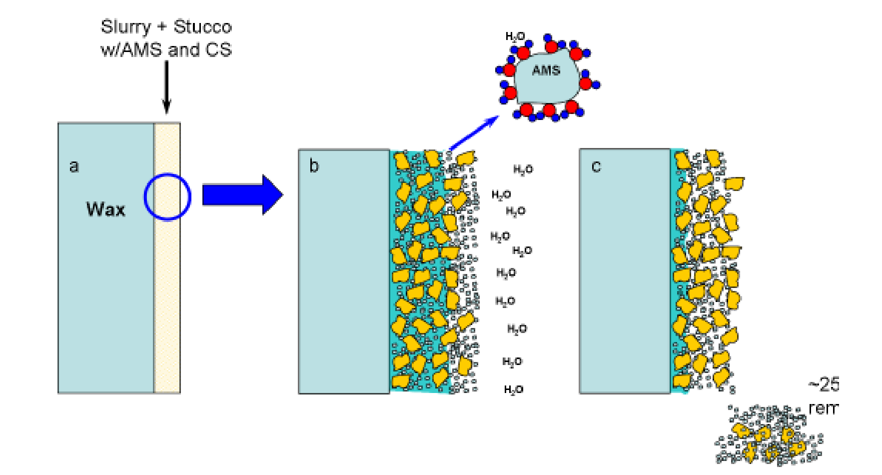

FIGURE 7. Schematic diagram showing how water is removed from the slurry in a shell made using the litter box technique. (a) Slurry and modified stucco mixture on a wax tree. (b) Detail of the slurry and stucco mixture showing the large grains of fused silica and the small grains of amorphous mineral silicate. The blow up shows water molecules on the surface of an amorphous mineral silicate particle. Water wicks along the surface of these particles to the outer surface of the stucco layer where it evaporates into the air. (c) A layer of loose stucco that is mainly amorphous mineral silicate is removed by blowing or tapping before redipping. About 25 wt% of each stucco layer is removed. AMS = amorphous mineral silicate; CS = corn starch

This is likely due to the corn starch in the modified shell.

The samples measured in the hot wet condition showed variations in the MOR and MOE between standard and modified shells. The standard and modified shells dried for 60 hours had comparable MORs, but the MOE was lower in the modified shell. Again this is likely due to the corn starch strengthening the modified shell. In contrast, the modified shell dried for 16 hours had a lower MOR than the standard shell, and a much lower MOE. This may be due to not having had time for all the chemical reactions involving corn starch to go to completion with only 16 hours of drying.

After firing at 1800ºF for 2.5 hours, both modified shells had higher MOR and MOE than the standard shell. The MOR for the modified shells dried 16 and 60 hours were ~4 and ~2 times larger, respectively, than the standard shell. Researchers do not have an explanation for this, but note that it is not due to corn starch in the fired samples, as it burned out during the heat treatment.

The modified shell material came off the castings easier than the standard shell material. For stainless steel castings, the modified shell came off in bigger pieces than the standard shell. Initially this was thought to be due to glass formation[4], but the authors now believe this is due to forming more cristobalite in the modified shell that cracked on cooling. Future plans include testing this hypothesis.

There are three primary ways the modified stucco can reduce operating costs. The shorter drying time allows more castings to be made per unit time. The amorphous mineral silicate is less expensive than the components it replaces in the stucco. Shells made with the modified stucco are thinner, which means less stucco is used per shell.

Summary

- Shells can be built using standard techniques with standard slurries and modified stuccoes composed of standard stucco to which amorphous mineral silicate and corn starch is added.
- Shells can be built using a 20 minute cycle time between dips with ideal drying conditions. This allows shells to be built, dewaxed, and poured on a single shift.
- The modified stucco does not cause the slurry to gel.
- Using a fluidized bed, the shell building procedure is identical for standard and modified shells.
- Using the litter box technique, building a modified shell requires an extra step to remove loose stucco before redipping.
- Dust initially appeared to be a problem with the fluidized bed, but can be controlled with adequate dust collection and using a small amount of mineral oil.
- The number of shell coats is the same for standard and modified shells.
- The modulus of rupture and modulus of elasticity of green shells are about the same for modified and standard shells, and are about two to four times greater for modified shells than standard shells at room temperature after firing at 1800ºF for 2.5 hours.
- Aluminum, bronze, cast iron and stainless steel castings from modified shells have excellent surface properties and excellent dimensional tolerance.
- The ingredients in the modified stucco and the modified shells are not toxic or hazardous and can be handled and disposed of using existing procedures.
- Modified shells are thinner and lighter than standard shells
- Modified shells can save money in three ways: shorter times are needed to build shells, they use less expensive stucco materials, and they require less stucco.

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