IMPROVING PERFORMANCE OF JEWELRY INVESTMENT POWDER

Ralph Carter

In each step of manufacturing jewelry, there are many factors that can adversely affect quality. Because of this, process control is very important. The investing process is one of those steps in which process control is vital. Multiple process factors will be focused on including water quality, the temperature of the water and of the powder, and also the water-to-powder mixing ratio. This paper will show how dependent the properties, and thus the performance, of gypsum-based investment are to these factors.

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INTRODUCTION

Like many manufacturing processes, it is tempting to think of jewelry manufacturing primarily from the standpoint of increasing throughput and therefore reducing the cost per item. However, increased efficiency may become elusive if casting quality is reduced, and the time spent finishing each item increases. There are certain aspects of the jewelry investment casting process that should not be rushed, skipped, or overlooked. Some examples include water quality, equipment cleanliness, temperature controls, measuring of water and powder, bench cure time, careful burnout cycles, etc. Focusing primarily on the investing steps of the jewelry investment casting process, this paper shares data that demonstrates the magnitude of impact some of these aspects have on the process.

BACKGROUND

Jewelry investment casting powders consist of three types of materials. These are refractory materials, bonding materials and controlling chemicals. Refractory materials can withstand high temperatures without decomposing or changing significantly. Bonding materials are what hold the refractory materials in place to form a mold. Controlling chemicals are used to control how quickly the bonding materials set up and to accentuate various investment properties.

In the jewelry casting industry, there are commonly two types of investments used. These are gypsum-based and phosphate-based investments. The type indicates the material that is used to bond the refractory materials together. Gypsum investments initially contain calcium sulfate hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$), which is commonly known as plaster of Paris. When water is mixed with the investment, the plaster of Paris hydrates to form calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), which is gypsum.[1] Phosphate investments are a more diverse group of investments. These contain one or more phosphorous containing materials.

Each type of investment undergoes a chemical reaction during the investing process. The rate at which the chemical reaction progresses will determine how much time it takes the investment to transition from liquid to solid and ultimately set. Most rates of reaction are very dependent on such things as temperature, interfering compounds, particle size of the reactants, mixing time, and mixing intensity.[2] The reactions that investments undergo are no exception.

Investment manufacturers provide investment products that will consistently take the same amount of time to complete these reactions. This is accomplished by keeping the reactants within a tight particle size range, recommending specific mixing methods and the addition of various controlling chemicals. However, these efforts can be negated by not following the recommendations for storage, handling, mixing and curing the investment.

STORAGE

Because both major types of investment casting powders, gypsum and phosphate, contain bonding materials that will react with water, they need to be protected from water until it is time for mixing. If the package is left open, the investment will react with the water in the air. This not only affects the working time of the investment but reduces the resulting mold strength, increasing the chances of finning on the castings. Resealing the bag after use is important.

More extreme foundry observations include packages receiving over-spray from a nearby washing operation and packages sitting in a puddle of water. These will result in lumps forming in the package, which can damage mixing equipment, change the working time and fluidity and create a non-homogeneous mold.

Related to storage is proper stock rotation. Investments do change with age. The working time will lengthen, and the strength will reduce as the material ages. Therefore, it is important to rotate the stock such that the oldest is used before the youngest.

EQUIPMENT CLEANLINESS

Vessels used for measuring powder, scoops and mixing equipment need to be kept clean. Only a little bit of set investment will reduce the working time of the investment. If the investing equipment is used for both gypsum and phosphate investments the effects are even more pronounced. Very little phosphate investment will cause a gypsum investment to never set. Even the dust of a phosphate investment that clings to a scoop is enough to dramatically extend the set time of a gypsum investment.

TEMPERATURE

The temperature of the water and investment powder have an effect on the reaction time. This is observed by the working time and set time of the investment. The working time is a bit subjective in that it is the time from when the powder is added to the water until the investor feels as though the material is too viscous to continue to work or manipulate.[3] This maximum viscosity depends on the user's preference and the application. However, as defined in the R&R ISO 9001 procedures, the pour time (PT) and set time (ST) tests are less subjective.

In brief, the pour time procedure is as follows. As soon as all the powder is added to the water, a timer is started. The powder is wet-out by hand with a spatula and then mechanically mixed for 20 seconds. The mixed investment is then poured from one bowl to another every 15 seconds. The timer is read when the investment has become so thick that it will not pour out of the bowl. This time is then recorded as the pour time. This test has a margin of error of +/-15 seconds.[4]

The procedure for determining the set times measures the amount of time it takes from when all the powder is added to the water until the investment reaches a defined hardness. This hardness is measured with a vicat. When the investment is just hard enough to keep the vicat needle from penetrating more than one millimeter, it is considered set. At this point in the setting process, the investment is not strong enough to use; but will continue to strengthen with time. This test also has a margin of error of +/-15 seconds.[4] For more details on the vicat set time refer to the American Society for Testing and Materials (ASTM) designation C 472-20.

The following data was obtained from a premium gypsum-based jewelry investment. This provides an idea of the magnitude of dependence the pour time and set time have on the starting temperature of both the water and powder.

Table 1: Gypsum Investment

Temperature (°F)	**65**	**70**	**75**	**80**	**85**
Pour Time (min)	11.50	10.75	10.25	9.75	9.50
Set Time (min)	19.50	18.25	17.50	16.75	16.25

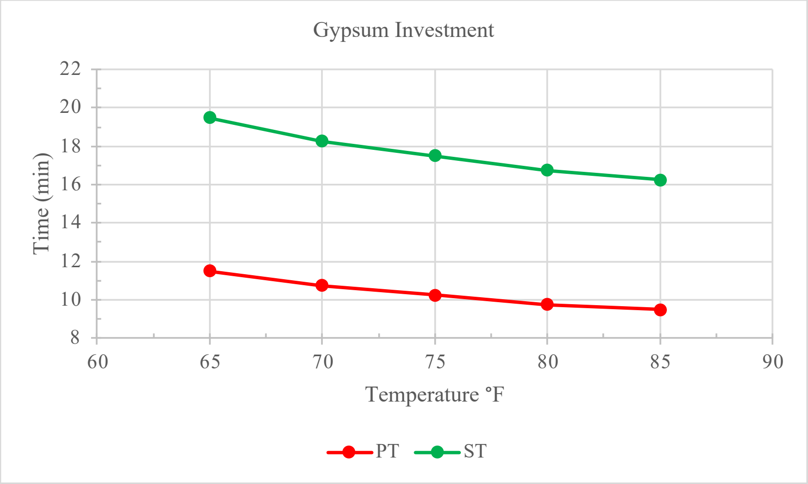


Figure 1: Gypsum Time/Temp

Below is data obtained from a phosphate-based investment. Compared to the gypsum-based investment the phosphate investment is more sensitive to the starting temperature of the water and powder.

Table 2: Phosphate Investment

Temperature (°F)	**55**	**65**	**70**	**75**	**80**	**85**
Pour Time (min)	11.50	7.75	6.50	5.00	4.50	3.00
Set Time (min)	28.25	13.00	10.50	7.75	7.75	12.00

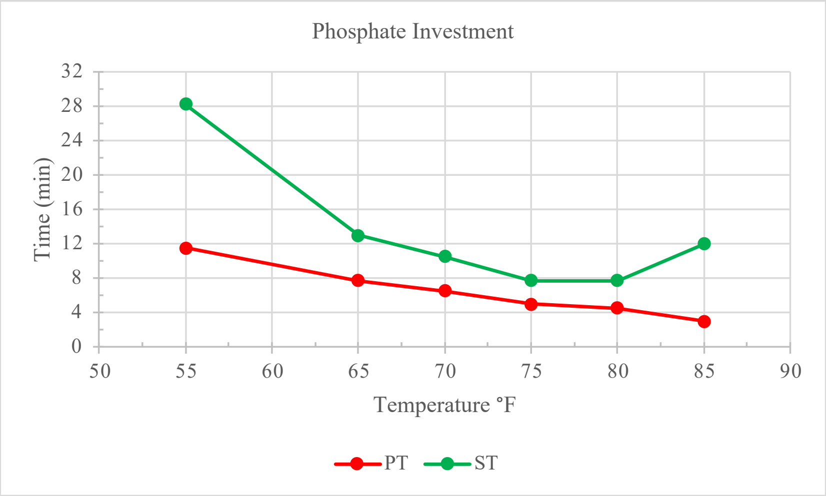


Figure 2: Phosphate Time/Temp

In Figure 2, the set time actually stayed the same at 75°F (23.8°C) and 80°F (26.6°C) and then increased above 80°F. Suspecting that pouring from bowl to bowl had an influence on the set time, a set of measurements were done without pouring at all. Table 3 and Figure 3 contain those results.

Table 3: Phosphate Investment No Pouring

Temperature (°F)	55	65	70	75	80	85
Set Time (min)	76.00	53.00	34.50	28.50	25.75	20.50

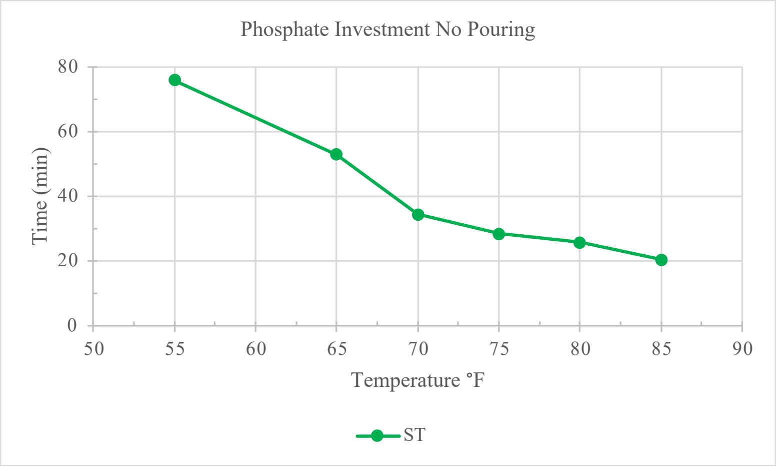


Figure 3: Phosphate Time/Temp, No Pouring

By not pouring back and forth from bowl to bowl, the change in trend at the higher temperatures disappeared. In addition, the set times without pouring are two to four times longer. This indicates how much the set time is influenced by the pouring. Pouring is rather gentle compared to mechanical mixing. Imagine how much of an influence mixing intensity and mixing time has on phosphate investments. Design changes in mixing equipment as well as changes due to wear can impact the set time of phosphate investments.

The impact of temperature is often observed by operators when the seasons change. In colder months they may have enough time to invest a certain number of flasks, then in warmer months they are surprised to see that they are lacking enough time. Storing the investment in a constant-temperature area can avoid this variable. Many foundries will also use temperature-controlled water to reduce seasonal fluctuations. The recommended temperature for water and powder is 72-85°F (22-29°C).

WATER QUALITY

Investments are used all over the world with water from many different sources and many different compositions. To eliminate the effects that each water source will have on the rate of reaction, the investment manufacturers simply suggest that the investor use de-ionized water. De-ionized water is water that has had virtually all the interfering ions removed. A common way to determine if water has been de-ionized is to measure its conductivity. This is a measurement of the water's ability to conduct electricity. Conductivity is the reciprocal of resistivity. When compounds dissolve in water they disassociate to ions. Ions carry a charge and give water the ability to conduct electricity. As the number of ions present in water is reduced, so is the water's ability to conduct electricity and thus its conductivity goes down.

A variety of water samples were collected from various sources to observe the effects that they have on an investment's pour time and set time. Also included was the investment's mixed fluidity as measured by the R&R slump test. These water sources include tap water from various cities around the world as well as lake water, river water, swimming pool water and field run-off. The data is presented in the following table and figures. De-ionized water is used as the standard and the results from the various water sources are reported as a difference from de-ionized water. All tests were performed at the same temperature and with the same mixing time and intensity.

Table 4: Water Source

Water Source	1	2	3	4	5	6	7	8	9	10	11
Δ Pour Time (min)	0.75	2.25	1.75	2.25	3.25	3.75	5.00	6.25	0.75	6.75	5.75
Δ Set Time (min)	0.75	1.75	1.75	2.00	3.50	3.50	4.75	5.75	2.00	7.25	6.00
Δ Slump (in)	0	0	- 1/4	- 1/8	- 3/16	- 1/4	3/16	- 1/16	- 1/16	0	1/16

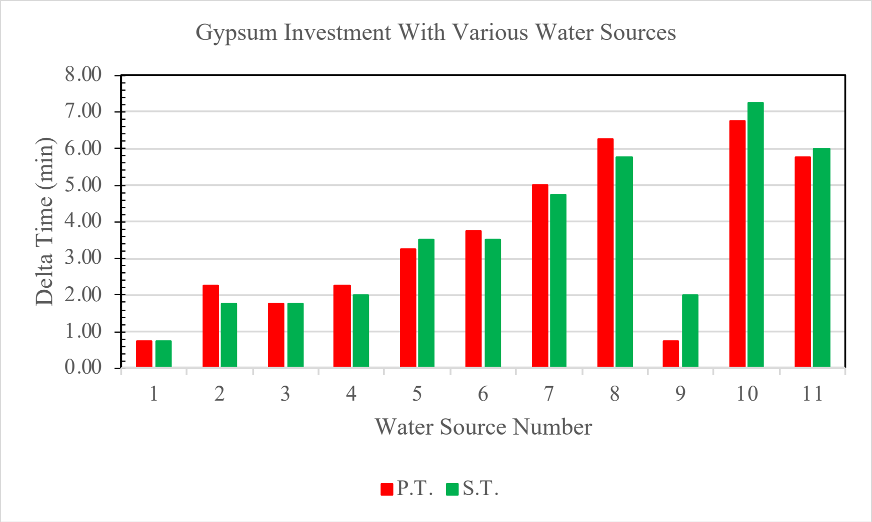


Figure 4: Gypsum Water Source Time

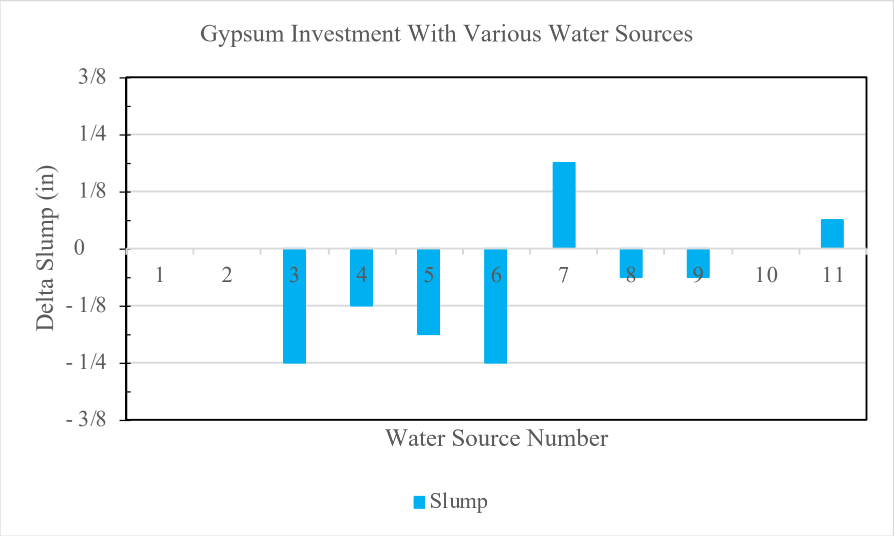


Figure 5: Gypsum Water Source Slump

This demonstrates that each water source affected the setting reactions of the gypsum investment. Each water source causes the pour time and set time to be longer than the standard. Some water sources had a greater effect than others. The fluidity was unaffected by some sources, while many made the slump smaller, and some made the slump larger. Notice what happens to these differences once each water source is de-ionized. This data is found in the following table and figures. The variance from the standard drops to essentially zero. That means that once the water is de-ionized every water source will behave the same. This demonstrates that the water quality is a source of variability in the working properties of investments. However, this variability can be eliminated simply by de-ionizing the water.

Table 5: Water Source

Water Source	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Δ Pour Time (min)	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Δ Set Time (min)	0.00	0.00	0.00	0.00	0.25	0.25	0.00	0.00	0.00	0.00	0.00
Δ Slump (in)	0	- 1/16	1/16	1/8	- 1/8	0	1/16	0	0	0	0

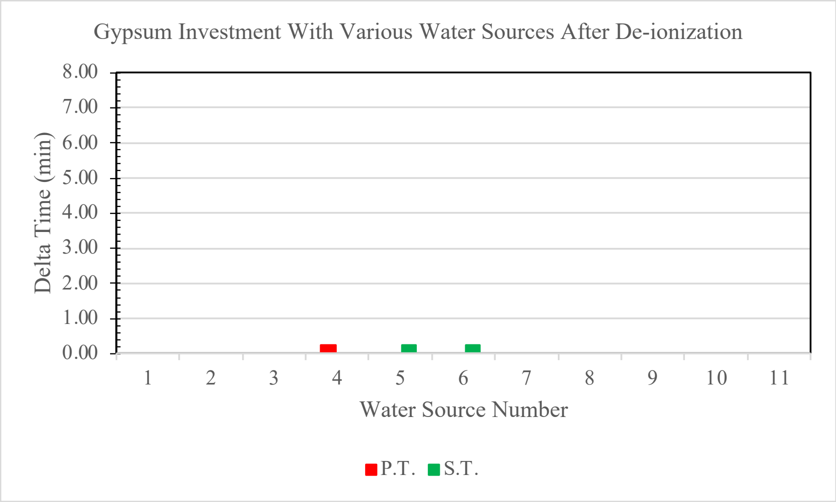


Figure 6: Gypsum De-ionized Water Time

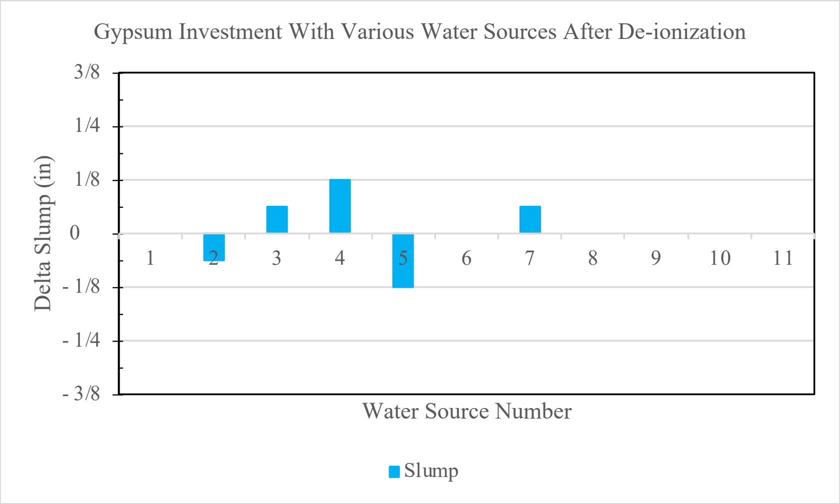


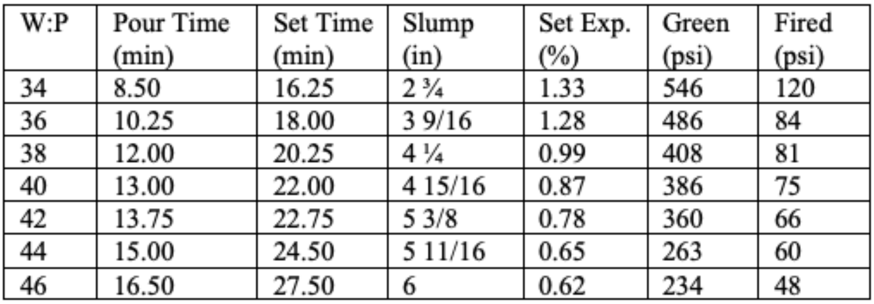
Figure 7: Gypsum De-ionized Water Slump

WATER-TO-POWDER RATIO

The ratio of the amount of water to the amount of investment powder is commonly expressed as the water-to-powder ratio (w:p), having units of milliliters of water per 100 grams of powder. A w:p of 40 ml water per 100 g powder is sometimes written as 40/100 or simply as 40 or even 0.40.

When an operator observes a change in the working time or fluidity of the mixed investment they might be tempted to change the water-to-powder ratio to return to what they are used to seeing. This can have some unintended effects including the strength, working time, setting expansion, permeability, thermal expansion, casting surface smoothness, creating watermarks and investment removal.[5,6,7] To gain an idea of the magnitude of change, many of these properties were measured with a gypsum investment at various w:p's. The results are shown in the following table and subsequent figures.

Table 6: W:P



W:P	Pour Time (min)	Set Time (min)	Slump (in)	Set Exp. (%)	Green (psi)	Fired (psi)
34	8.50	16.25	2 ¾	1.33	546	120
36	10.25	18.00	3 9/16	1.28	486	84
38	12.00	20.25	4 ¼	0.99	408	81
40	13.00	22.00	4 15/16	0.87	386	75
42	13.75	22.75	5 3/8	0.78	360	66
44	15.00	24.50	5 11/16	0.65	263	60
46	16.50	27.50	6	0.62	234	48

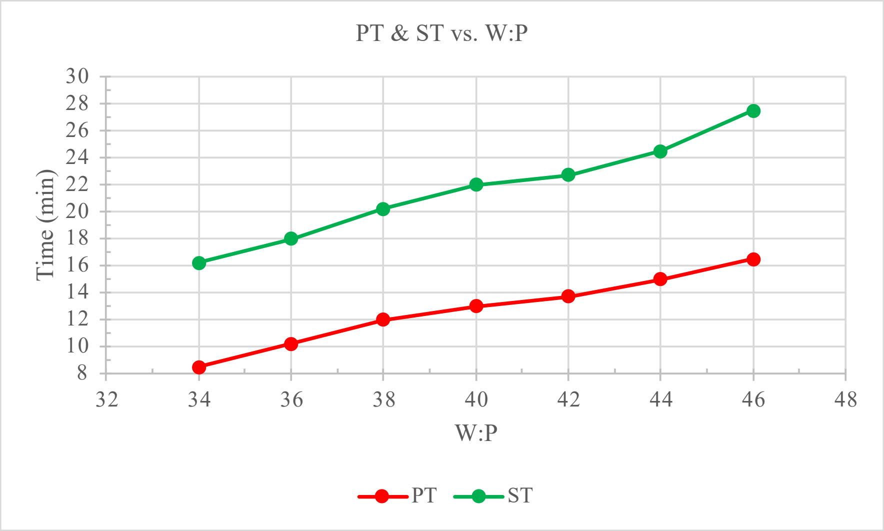


Figure 8: Pour and Set Time vs Water:Powder

In almost a linear fashion the pour time and set time have a direct dependence on the w:p. As the w:p is increased so is the pour time and the set time. Within the commonly recommended w:p range of 38 to 42, the pour time changed 1.75 minutes. This should allow for enough flexibility to the investor, without risking other properties by going outside the commonly recommended w:p range.

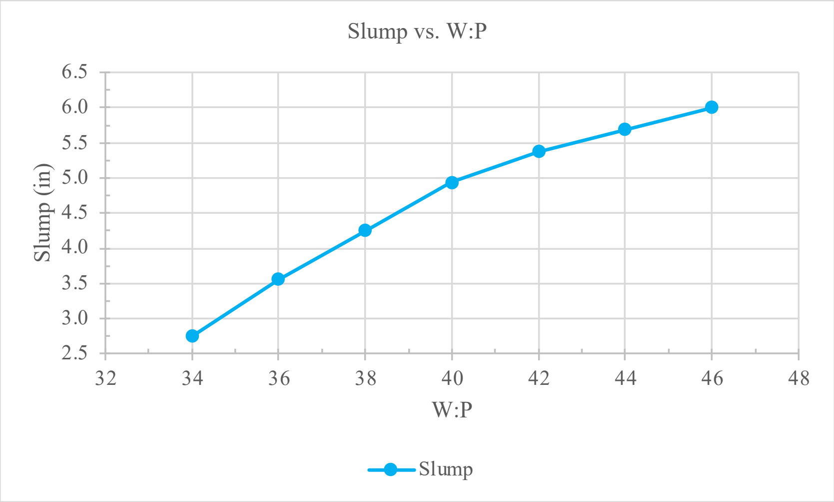


Figure 9: Slump vs Water:Powder

Figure 9 shows that the slump is also directly dependent on the w:p. As expected, the investment gets thinner with increased w:p. What is more interesting is the magnitude of the change within the commonly recommended w:p range. Between 38 and 42 the slump changes 1-1/8 inches. This is certainly more than enough flexibility to satisfy the investor's preferences in fluidity.

Below a w:p of 38, the fluidity becomes thick and is not easy to work with. It is easy to understand how air could become trapped next to the wax patterns and cause defects.

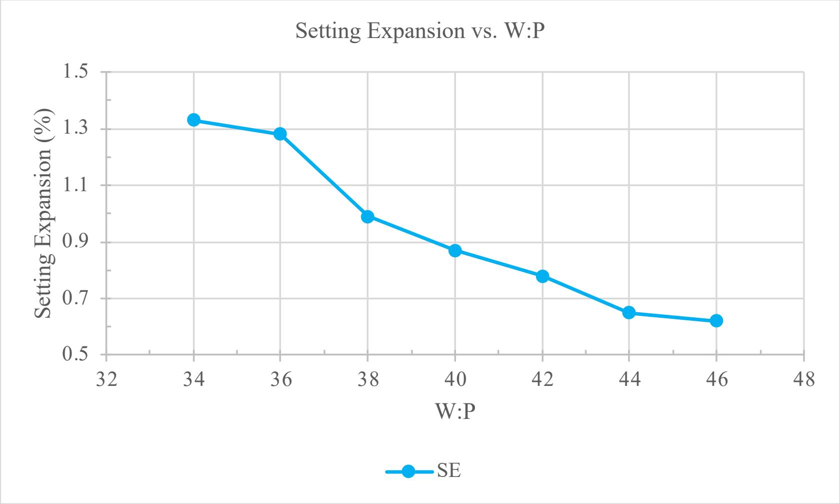


Figure 10: Setting Expansion vs Water:Powder

Figure 10 shows that the setting expansion is inversely dependent on the w:p. This property is important for dimensional precision of the casting. When contemplating changing the w:p, it is prudent to consider that the dimensions of the finished piece could adversely be affected.

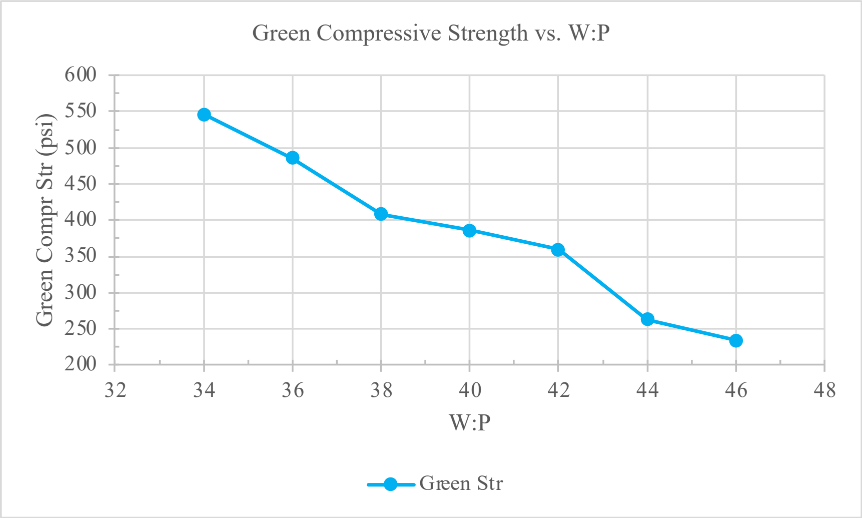


Figure 11: Green Compressive Strength vs Water:Powder

Figure 11 indicates that the green compressive strength is inversely proportional to w:p. There is a modest (48 psi) change in the green strength within the commonly recommended w:p range. This stability can be helpful if a higher w:p is desired for something like fluidity, but losing mold strength is a concern. Outside the recommended w:p range, the strength changes more dramatically. A high w:p could weaken the investment too much, which would increase the probability of small cracks forming in the mold, which could result in finning. A rough surface may also be observed if the investment is weakened too much.[5,6,7]

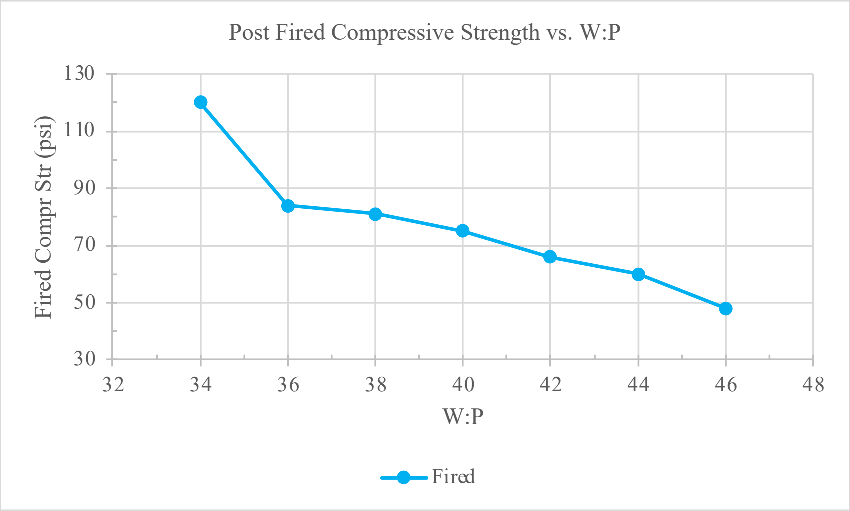


Figure 12: Post-Fired Compressive Strength vs Water:Powder

The post fired compressive strength is also inversely proportional to the w:p. The slope is fairly consistent, except for the lowest w:p. This will result in more energy being required to remove the casting. This is, of course, not the only factor affecting the ease of casting removal. There are formulation factors as well as raw material quality factors, for the investment manufacturers to consider, which affect casting removal.

The permeability is also affected by the w:p. Using a w:p of 38 a premium gypsum jewelry investment was measured to have a permeability of 0.0287 Darcy. While at 42 the permeability is increased to 0.0392 Darcy. That is a 37% increase and can help with complete metal fill.[11] Here in Figure 13 the permeability difference can be seen.

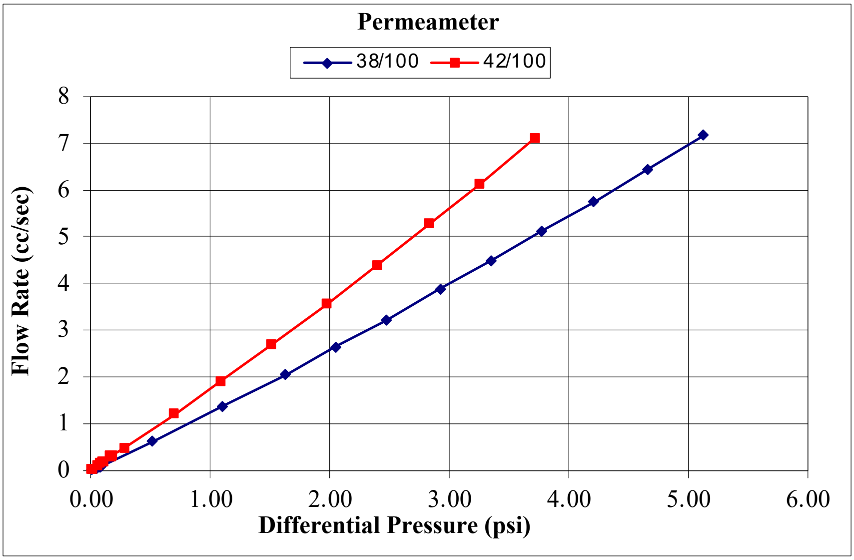


Figure 13: Permeameter

MIXING

Mixing the water and powder together is important. There are many mixers that are commonly used to accomplish this task. Not that long ago it was common to use planetary style mixers like a Hobart or Kitchen Aid. However, they have become less common compared to mixers that can also draw a vacuum during the mixing process.

It is still important to follow the recommended mixing time to activate the various controlling chemicals. The idea is to mix vigorously to get each particle intimately wet with water. Simply stirring together will not suffice. As the mix size increases, more energy needs to be imparted to the mix. This can happen through increasing the mix time, increasing mixing speed or even changing the mixer design.

A comparison of Figures 2 and 3 showed how sensitive the set time of a phosphate investment is to the gentle mixing created by pouring. The mixing time has an influence on the setting time, setting expansion and strength of plaster. As the mixing time is increased the set time is decreased, but the setting expansion and strength are increased.[1]

BENCH CURING

Likely the most important step to take is the bench cure time. Unfortunately, it likely is the one most overlooked for the sake of saving time. When the investment looks and feels set, many people assume that it is ready to move to the oven. However, it is not even close to being ready. At the point in time when it becomes set, it is only about 20% of its full strength.[3] Time is needed for the mold to reach greater strength to endure the stresses of burnout. This is the reason for the recommendation of a two-hour cure time.

To have a proper curing period, the flasks need to be transferred to a disturbance free area while the investment is still fluid. If the investment is already transitioning from liquid to solid, this is the worst time to move the mold. This is because the investment is no longer fluid enough to flow back together to “heal” any fissures or separations that are created by movement and vibrations.

The area needs to be vibration free. The molds need to be left and not moved around. Over the years there have been foundry observations of molds being placed on carts and the carts often being repositioned during this crucial curing phase. There have also been observations of molds receiving vibrations from a nearby train traffic. Even the removal of collars and bases can damage the mold if done at the wrong time.[6] Once these sources of vibrations were eliminated at the various casting shops, the incidence of flashing was dramatically reduced.

BURNOUT

Following the recommended burnout cycle for the investment being used is important. Short hold times and fast ramp rates will create mold cracks and even mold explosions. There are three main phases of most burnouts. The first one is drying, followed by pattern burnout and finally bringing the mold to the desired casting temperature.

The goal of the drying phase is to eliminate the water in a manner that will not crack or explode the mold. Obviously, slower is gentler. Having good air flow through the oven is helpful. On more than one occasion, there have been reports of electric ovens being so air-tight that the hot moist air cannot escape. Therefore, the mold does not dry out. Make sure the vent holes are open when using an electric oven.

Related to good air flow is propping the molds up off the oven floor. This is done with refractory bricks or a high temperature metal grate. The goal is to expose more surfaces from which moisture can be carried away from the mold. Also, having the pattern material drain out and away from the mold is helpful. Pattern materials that become trapped inside a mold can deform the mold when they boil inside the mold.

The amount of time needed to dry a given mold depends on a lot of factors including mold size, air flow through the oven, temperature of the oven, number of molds in the oven, etc. In the green state, the mold will contain close to 30% water (40/140*100%=28.6%). Simply put, time is needed for all this water to migrate to the outside surface of the mold, vaporize and then be carried away by the air flow. Attempts to speed this up by increasing the oven temperature beyond the recommendations, risks vaporizing water inside the mold and therefore cracking the mold.

Figure 14 contains an example of a gypsum-based mold drying in a gas oven at 400°F (204°C). What is interesting is the internal temperature reveals the stages in which interstitial water and later the chemical water leaves. The amount of time to remove all the water was close to 7 hours. Roughly half of that time was needed for the interstitial water to leave. The chemical water, which is only about 5% of the mold weight, took the latter half to exit.

Once the mold is dry, the second main stage of the burnout can begin. That is the burnout of the pattern material. To accomplish this, the oven will need to ramp up to a high enough temperature to oxidize the pattern material. This temperature is commonly around 1250-1350°F (675-730°C). The ramp rate to get there needs to be slow enough not to thermally shock the mold, which will be going through an expansion. Often the investment manufacturers recommend that the ramp rate be less than 180°F/hr (100°C/hr). The molds will lag behind the oven. The amount of lag will depend on oven type, oven loading, mold size, etc.

Once the oven reaches the temperature needed to burnout the pattern, then the oven needs to hold there until all the pattern is combusted. The amount of time is dependent on the same sort of factors mentioned earlier, oven type, oven loading, mold size, air flow, etc. When the pattern is not completely burned away, the area in the central sprue will appear grey, yellow or brown.[6]

Once the pattern material is burned away, then the oven can be cooled to the temperature desired for the molds when casting. Because this depends on the alloy type, the alloy suppliers have recommendations for this temperature. The oven will need to hold at this temperature long enough for the molds to achieve the oven temperature throughout. Again, this depends on oven air flow, loading, mold sizes, etc.

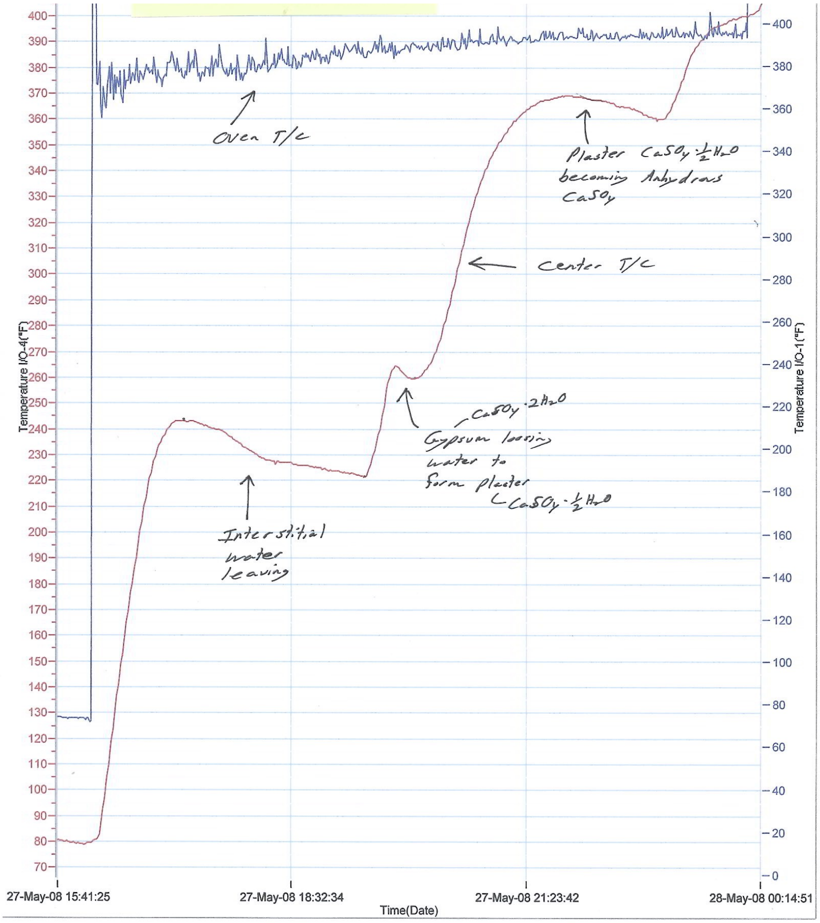


Figure 14: Gypsum-based Mold Drying

Wax is a common and traditional pattern material. It is a great material in that it has very little ash content, 0.003-0.007%. However, today there are many other materials used. These often have a much greater amount of ash content, 0.1%. This can be about thirty times more ash than wax. This ash consists of oxidized components of the pattern, which are solids. Many pattern materials have components that no matter how they are burned up will always be solid and not gas and therefore leave ash behind. Sometimes this ash interferes with the detail replication when alloy flows into the mold and sometimes it does not. People have tried many techniques to deal with the ash but few deliver satisfactory results consistently.

SUMMARY

With many manufacturing processes there is a fast way and then there is the right way. This paper walked through the jewelry investment casting process from storage through burnout, sharing properties of jewelry investment. Once one understands the investment properties, the instructions will make greater sense and mean more. The best practice is to follow the instructions to obtain the best jewelry investment performance. Deviating from the recommendations runs the risk of generating more defects on the finished pieces that will eat up a lot of time to finish, repair or even re-cast.

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