

Effects of water quality and temperature on investment casting powders

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Introduction

In each step of manufacturing jewelry castings, there are many factors that can adversely affect quality. Because of this, process control is very important. Investing is one of those steps in which control of process variables is vital. Most jewelry investment manufacturers help the investor control process variables by providing a consistent product, user instructions and technical support.

Investment manufacturers ensure that investment properties such as compressive strength, set expansion, thermal expansion, particle size, working time, setting time and fluidity will always be the same batch after batch and drum after drum. However, all of these efforts can be destroyed if the investment is not used properly.

Two factors that are thought to influence investment performance are the quality and temperature of the water that is mixed with the investment. Investment manufacturers suggest that all water be de-ionized to remove interfering compounds. They also suggest that the investment and the water both be used at a consistent temperature, typically 70-75°F (21.1-23.9°C). Two questions that are commonly asked are, how much do these factors really affect the investment and is it really necessary to control these variables?

This paper explores how dependent both gypsum based and phosphate based investments are on water quality and temperature. Possible reasons why water quality and temperature are important variables to control will be discussed.

Background

Jewelry investment powders consist

of three types of materials. These are refractory materials, bonding materials and controlling chemicals. Refractory materials can withstand high temperatures without decomposing. 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 industry two types of investments are commonly used. These are gypsum based and phosphate based investments. The type indicates the material that is used to bond refractory materials together (i.e. either gypsum or phosphate). Gypsum investments initially contain calcium sulfate hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$), 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 ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which is gypsum (1). Phosphate investments are a more diverse group of investments. These investments contain one or more phosphorous containing materials.

Each type of investment undergoes a chemical reaction during the setting process. The rate at which the chemical reaction progresses will determine how much time it takes the investment to 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 done by adding various controlling chemicals, keeping the reactants within a tight particle size range and recommending specific mixing methods. However, compounds that affect the rate of reaction are often found naturally in water. These interfering compounds can negate the effort manufacturers put towards making a consistent product.

Investments are used worldwide with water from many different sources and of 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 from which virtually all the interfering compounds have been 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.

Most rates of reaction are very dependant on temperature. A common rule, which should be used with caution, is that the rate of reaction near room temperature will double with a 10°C rise in temperature (2). Because of this, investment manufacturers test their investments within a specific

temperature range. If the investments are used at a temperature outside that range, the rate of reaction can be changed. Investment manufacturers recommend that the water and the investment be used at the same temperature each time to eliminate the temperature variable.

Procedures

Three properties of a gypsum and a phosphate based investment were investigated using various water sources and temperatures. These three properties are the pour time, set time and slump. Ultra-Vest® investment was the gypsum based investment used, while Astro-Vest™ investment was the phosphate based investment. It should not be assumed that all gypsum and phosphate based investments would behave in the exact same manner as these two; although a brief and preliminary comparison did indicate that two other well known brands of gypsum investment behave in at least a very similar manner. Ultra-Vest and Astro-Vest investments were chosen for this study simply because of familiarity and convenience.

Pour time is similar to working time; but there is a subtle difference. The working time is the amount of time from when all the powder is added to the water until the investor feels that the mixture is too viscous to continue to work or manipulate (3). This maximum viscosity depends on the user's preference and the application; therefore it is subjective. However, as defined in the R&R ISO 9002 procedures, pour time is less subjective.

The procedure for determining the pour time 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 sec. The mixed investment is then poured from one bowl to another every 15 sec. 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 sec (4).

The R&R procedure for determining set time 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 hard enough to use;

but will continue to harden until it is. This test also has a margin of error of ± 15 sec (4). For more details on the vicat set time refer to the American Society for Testing and Materials (ASTM) designation C 472-90a.

The R&R slump test is a measure of the mixed investment's fluidity. After the investment is mixed as described above, it is poured into a cylinder that is resting on a glass plate. The cylinder is 2" (5.1 cm) tall and has an inner diameter of 1 3/8" (3.5 cm). The investment is "struck-off" level with the top of the cylinder. When the timer reads exactly two minutes, the cylinder is raised off of the glass plate about 1" (2.5 cm). The investment is allowed to drain from the cylinder for 15 seconds. The investment will spread out onto the plate in the shape of a disk. The more fluid the investment is, the larger the diameter of the resulting disk. The diameter of the disk is measured in inches with a ruler. This test has a margin of error of $\pm 1/16$ " (± 1.6 mm) (4). Figure 1 shows the equipment used.

For this study the pour time, set time and slump of both types of investments were tested several times varying only the source of water used in the mixture. Water samples were collected from several sources including a Midwestern USA residential tap, a fresh water lake, a river, a West coast USA city tap and a farm well. For a complete identification of each sample, refer to Appendix A. The pour time, set time and slump were obtained with each of these various water samples and were compared to those obtained using de-ionized water from R&R's Maumee, Ohio research lab.

The water used at R&R's research lab was de-ionized using two Barnstead/Thermolyne combination cartridges in series. See Figure 2. Using the pressure from the tap, the water is forced counter to gravity through the two cartridges and finally into a holding bottle. This water was used as the standard to compare all the results throughout this study. The results obtained while using R&R's de-ionized water were subtracted from the results obtained from other water sources. This allows for a convenient comparison of the difference in pour time, set time and slump caused by each of the various



Figure 1 - A) Investment and scale, B) Thermometer, C) Rubber Bowls, D) Slump Ring, E) Mixing Head, F) Vicat, G) Timer



Figure 2 - De-ionised water system at R&R

water sources. During this portion of the investigation all tests were performed at a constant temperature.

The pH and conductivity are two properties that give some indication to the condition of water. Conductivity is used to determine the amount of total dissolved solids (TDS) in the water (5). Pure water has a pH of 7 and a conductivity of 0 millimhos. These two properties of the various water sources were measured to determine a possible correlation between the various water sources and their effects on the investments. Four water samples were sent to Culligan USA (Illinois EPA Approved) laboratory at Northbrook, IL for a more extensive analysis (see Appendix B). Each water sample was also de-ionized and the pour time, set time and slump of the investments were tested again. After de-ionization the pH and conductivity were also tested again. By doing this, the effect of de-ionizing could be determined.

De-ionizing cartridges, if used properly, remove ions from water. There are certain ions that are commonly found in most water sources. These are Na^+ , Ca^{+2} , Mg^{+2} , SO_4^{-2} , Cl^- , HCO_3^- and CO_3^{-2} (6). To understand how these various ions affect the setting reactions of investments, the standard de-ionized water was intentionally contaminated with various minerals that contain these ions. The pour time, set time and slump of the investments were then tested using the contaminated water. The minerals used were table salt (NaCl), road salt (CaCl_2), Epsom salt (MgSO_4), magnesite (MgCO_3) and slaked lime (Ca(OH)_2). Each mineral was used individually at a concentration of 1gm/liter in the standard de-ionized water except MgCO_3 , which due to its limited solubility, was used only at 0.04gm/liter.

The pour time, set time and slump of the investments were also tested at various temperatures. For this part of the study only the standard de-ionized water was used. Both the water and the powder were carefully brought to the same starting temperature. Variables, such as mix time, mixing intensity and room temperature, were all held constant throughout this study.

Results & Discussion

The data is presented as a difference and not the actual pour time, set time and slump. For example, if with R&R's de-ionized water, the standard used throughout this study, the pour time was 10 min and a particular water source resulted in a 13 min pour time, a difference of +3 min was reported. This was done for convenience, because what is of interest in this study is how each result differed from the standard. To provide perspective, the pour time, set time and slump of Ultra-Vest investment is controlled, at the point of manufacturing, to be 10-10.5 min, <20 min and 4 3/8-4 5/8" (11.1 cm - 11.7 cm) respectively. Astro-Vest investment is controlled to a pour time of 5-5.5 min, a set time of 8-12 min and a slump of 5-6" (12.7 cm - 15.2 cm).

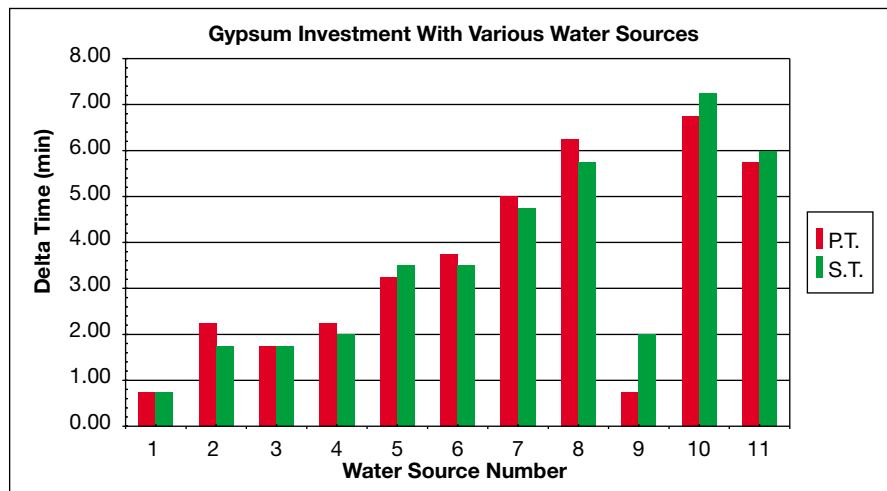
Table 1 displays the variance for the gypsum investment properties as a function of water source. Figures 3 and 4 are the corresponding graphs. It can be easily seen that each water source affected the setting reactions

of the gypsum investment. Each water source caused the pour time and set time to be longer than the standard. Some water sources had a greater affect than others. The slump was unaffected by three of the sources and while most of the other sources made the slump smaller, two actually made the slump larger.

Table 1. Gypsum Investment Variance From De-Ionized Water Standard

Water Source	1	2	3	4	5	6	7	8	9	10	11
Δ Pour											
Time minutes	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 minutes	0.75	1.75	1.75	2.00	3.50	3.50	4.75	5.75	2.00	7.25	6.00
Δ Slump	0	0	-1/4	-1/8	-3/16	-1/4	3/16	-1/16	-1/16	0	1/16
inches (mm)	(0)	(0)	(-6.4)	(-3.2)	(-4.8)	(-6.4)	(4.8)	(-1.6)	(-1.6)	(0)	(1.6)

Note: Each test was performed at the same temperature and with the same mix time.



Note: P.T. = Pour time; S.T. = Set time

Figure 3

Table 2. Gypsum Investment Variance From De-ionized Water Standard

De-ionized Water Source	1	2	3	4	5	6	7	8	9	10	11
Δ Pour											
Time minutes	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 minutes	0.00	0.00	0.00	0.00	0.25	0.25	0.00	0.00	0.00	0.00	0.00
Δ Slump	0	-1/16	1/16	1/8	-1/8	0	1/16	0	0	0	0
inches (mm)	(0)	(-1.6)	(1.6)	(3.2)	(-3.2)	(0)	(1.6)	(0)	(0)	(0)	(0)

Note: Each test was performed at the same temperature and with the same mix time.

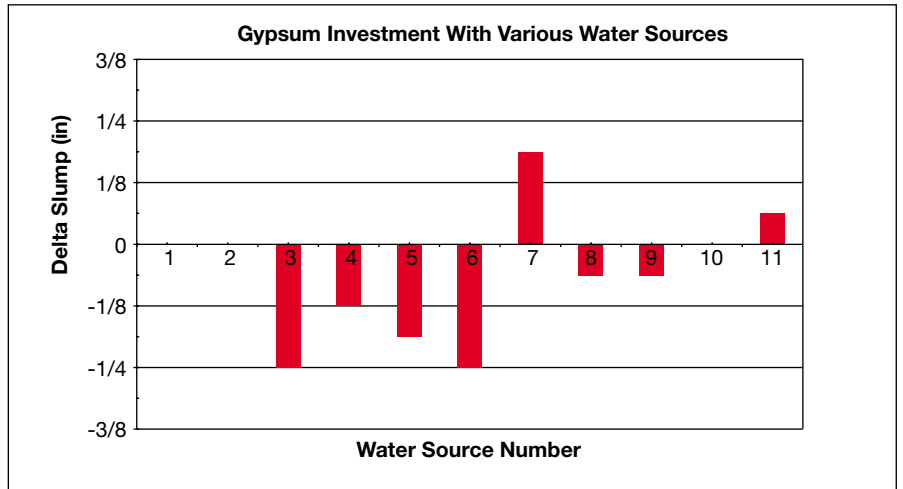


Figure 4

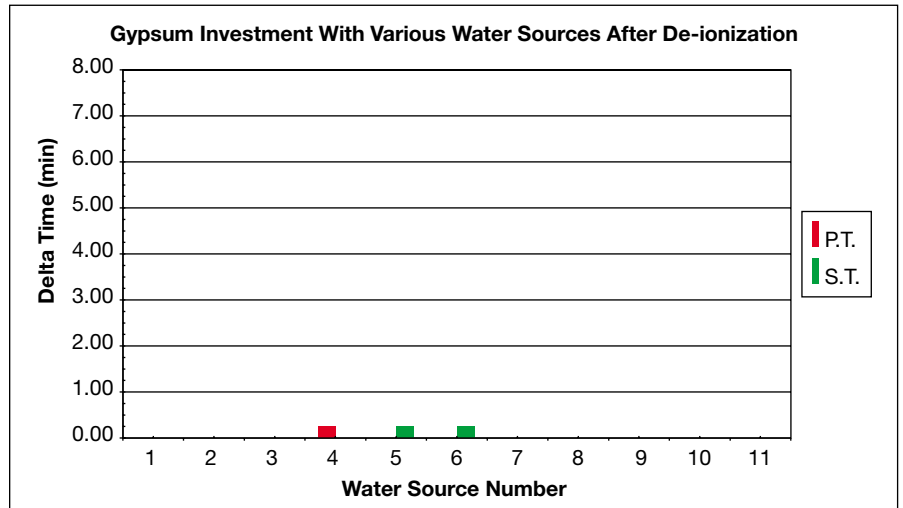


Figure 5

Each water source was de-ionized using a Barnstead/Thermolyne combination cartridge and the properties of the gypsum investment were tested again. Table 2 and corresponding Figures 5 and 6 show the resulting variance. The scales on both of these charts were kept the same as Figures 3 and 4 to help in visualizing the difference. By de-ionizing the water, the variations

dropped to zero in most cases. Some water sources still showed a small variation from the standard; but when considering the margin of error associated with each test, these variations are negligible. For example, water source number four caused the pour time to be 15 sec longer than the standard. As stated before, the pour time and set time can only be measured to ± 15 sec. Therefore this

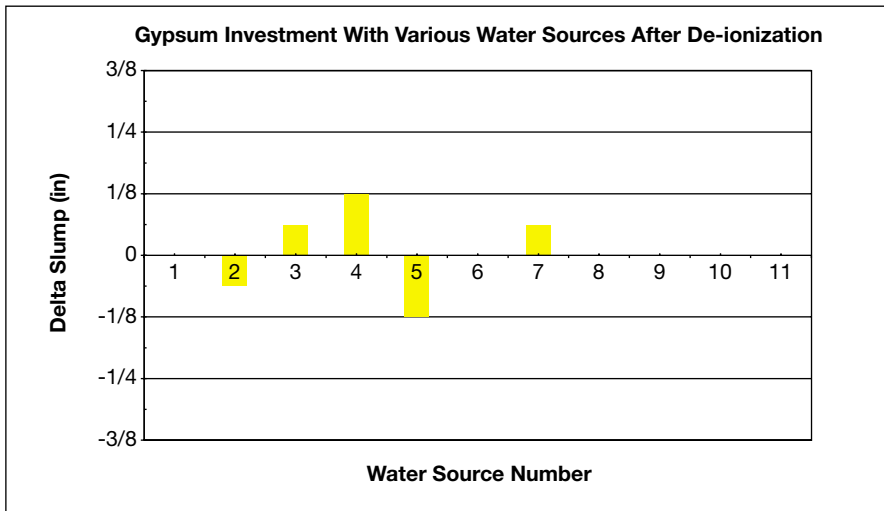


Figure 6

Table 3. Phosphate Investment Variance From De-Ionized Water Standard

Water Source	1	2	3	4	5	6	7	8	9	10	11
Δ Pour											
Time minutes	-0.50	-0.75	0.00	0.00	0.00	-0.25	-0.25	-0.25	-0.50	0.25	0.50
Δ Set											
Time minutes	-0.75	-1.00	0.00	0.25	0.25	-0.25	-1.00	-0.75	-0.50	0.00	0.75
Δ Slump	0	-3/16	5/16	-1/16	-1/16	3/8	0	0	0	3/16	1/16
inches (mm)	(0)	(4.8)	(7.9)	(-1.6)	(-1.6)	(9.5)	(0)	(0)	(0)	(4.8)	(1.6)

Note: Each test was performed at the same temperature and with the same mix time.

small variation is insignificant. Source four also caused the slump to be 1/8" (3.2 mm) larger than the standard. Considering that the margin of error associated with the slump test is $\pm 1/16$ " (± 1.6 mm), this difference also is insignificant. A slump that varied by more than 1/8" (3.2 mm) would, however, be significant.

By comparing Tables 1 and 2 and their corresponding graphs, it is clear that de-ionizing the water samples had a significant impact. This suggests that, unless de-ionized, the water can introduce significant, unwanted, process variables when using a gypsum investment.

Table 3 displays the variance for the phosphate investment properties as a function of various water sources. Figures 7 and 8 are the corresponding graphs. The variations were less with the phosphate investment than with the gypsum, so the scales on the charts were made smaller. Unlike the gypsum investment, not every water source caused the pour time and set time to increase. Instead some sources caused an increase and some a decrease. Only water source number two significantly shortened the pour time. Water sources one, two, seven and eight significantly shortened the

set time. Given that with phosphate investments these properties are already short, this is not a desirable effect. Water source number eleven was the only one to significantly increase the set time.

By de-ionizing the water sources, the variations in the phosphate investment's properties were reduced. This is shown in Table 4 and corresponding Figures 9 and 10. The scales on both of these charts were kept the same as Charts 7 and 8 to aid in visual comparison. The few slight variations that remain are negligible considering the margin of error associated with the tests. This shows the importance of de-ionizing water before it is used in the phosphate investment.

Table 4. Phosphate Investment Variance From De-Ionized Water Standard

De-Ionized Water Source	1	2	3	4	5	6	7	8	9	10	11
Δ Pour											
Time minutes	0.25	0.00	0.00	0.00	0.00	0.25	-0.25	0.00	0.00	0.50	0.25
Δ Set											
Time minutes	0.00	-0.25	0.25	0.25	0.00	0.50	-0.25	-0.50	0.00	0.50	0.25
Δ Slump	1/8	0	0	0	0	1/8	0	0	0	1/8	1/8
inches (mm)	(3.2)	(0)	(0)	(0)	(0)	(3.2)	(0)	(0)	(0)	(3.2)	(3.2)

Note: Each test was performed at the same temperature and with the same mix time.

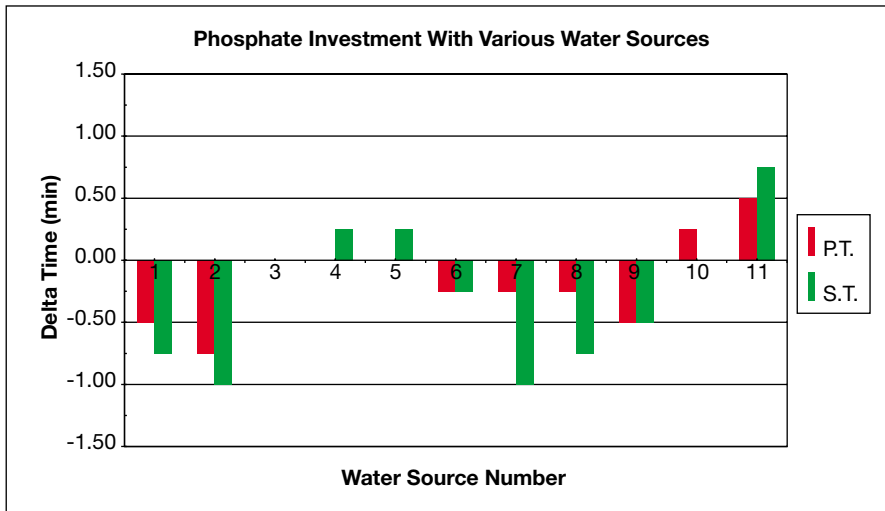


Figure 7

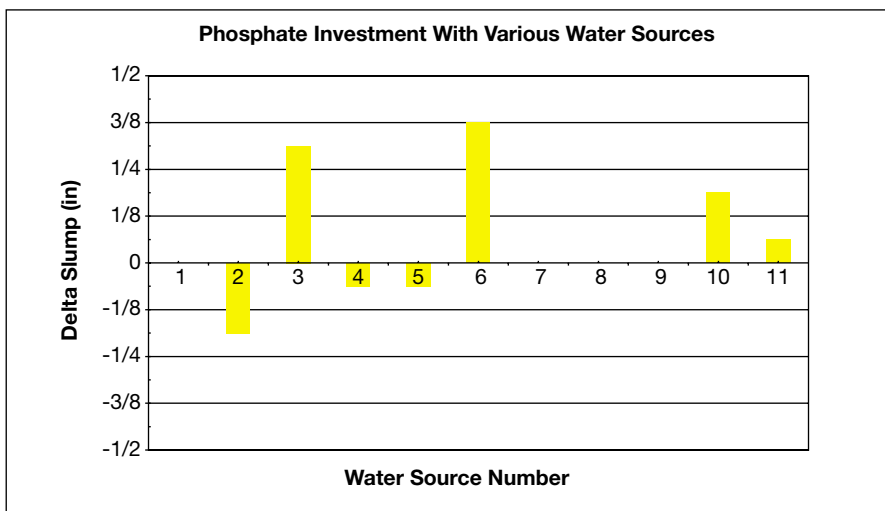


Figure 8

Table 5 shows the pH, conductivity and TDS of each water source. Each water source has significant amounts of TDS. There does not appear to be any continuous relationship between the conductivity or TDS with the variances observed in Tables 1 and 3. Because of this, it might be possible that the type of compound in the water is also a factor and not simply the amount.

Table 6 shows that after the de-ionization process all the water

sources' conductivity and TDS went to zero and the pH's decreased. This table shows that characteristics of the water sources were actually changed. This is not surprising; because this is exactly what the de-ionizing cartridge is designed to do. The lack of variation in the investment properties observed in Tables 2 and 4 correspond to water with a conductivity and TDS of zero. Testing the water for conductivity may be a good way to predict if the water would introduce unwanted variables. If the water has a conductivity greater than 0.0millimhos, then it probably will change the investment's properties.

Table 7 and corresponding Figures 11 and 12 indicate what certain known contaminants do to the properties of the gypsum investment. This part of the study was done to search for a connection between compounds commonly found in water and the variations observed in Table 1.

From Table 7 it is seen that the variation caused by the NaCl contamination had the opposite effect as CaCl₂. This is also true when comparing the variation observed by MgSO₄ and MgCO₃. The variation caused by MgCO₃ is more like the variations observed in Table 1 than the other known contaminants. This may be an indication of what compound is causing the variations observed in Table 1.

The Ca(OH)₂ contamination reduced the pour time greatly and increased the set time. This is interesting because the pour time and set time previously have varied in the same direction. The Ca(OH)₂ also caused the slump to be reduced greatly. Because of the amount of thickening that this contaminate caused, the investment could not be poured even immediately after mixing.

Table 8 and corresponding Figures 13 and 14 show the variations

Table 5. Water Characteristics as Sampled

Water Source	1	2	3	4	5	6	7	8	9	10	11
pH	9.61	7.93	7.66	8.31	8.43	7.52	8.19	7.80	7.70	7.99	7.62
Conductivity (milli-mhos)	0.18	0.64	1.5	0.25	0.58	1.55	0.4	0.69	0.1	0.66	0.55
TDS (mg/l)	90	320	750	125	290	775	200	345	50	330	275

Table 6. Water Characteristics After De-Ionized

Water Source	1	2	3	4	5	6	7	8	9	10	11
pH	6.16	6.05	5.80	5.96	5.90	5.86	5.51	6.00	6.50	5.76	5.75
Conductivity (milli-mhos)	0	0	0	0	0	0	0	0	0	0	0
TDS (mg/l)	0	0	0	0	0	0	0	0	0	0	0

Table 7. Gypsum Investment Variance From De-Ionized Standard

Contaminant	NaCl	CaCl ₂	MgSO ₄	MgCO ₃	Ca(OH) ₂
Δ Pour					
Time minutes	-1.75	0.50	-0.80	3.25	-10.25
Δ Set					
Time minutes	-1.50	1.00	-0.50	3.75	6.75
Δ Slump					
inches (mm)	-1/16 (-1.6)	-1/8 (3.2)	-1/16 (-1.6)	-1/2 (-12.7)	-4 (-114.3)

Note: Each test was performed at the same temperature and with the same mix time.

Table 8. Phosphate Investment Variance From De-Ionized Standard

Contaminant	NaCl	CaCl ₂	MgSO ₄	MgCO ₃	Ca(OH) ₂
Δ Pour					
Time minutes	-0.25	-0.50	-0.50	-0.50	-1.00
Δ Set					
Time minutes	-0.25	-0.75	-0.50	-0.25	-1.25
Δ Slump					
inches (mm)	-1/8 (-3.2)	-3/16 (-4.8)	-3/16 (-4.8)	-3/16 (-4.8)	-1 3/8 (-34.9)

Note: Each test was performed at the same temperature and with the same mix time.

set time of the gypsum investment. With the phosphate investment, there is not such an obvious trend.

The actual results from testing the gypsum investment with de-ionized water at various temperatures are shown in Table 9. Figures 15 and 16 are the corresponding graphs. The temperatures stated apply to both the water and investment. The pour time and set time are dependent on the starting temperature, as the investment manufacturers claim. The amount of dependence on temperature may not seem to be very significant; however this temperature dependence may allow some investors to change the amount of time used to invest. An extra minute may be needed in certain applications or possibly the investor would like to speed up the setting slightly. An investor could do this by simply changing the starting temperature of the investment and the water. As seen in Figure 16, these changes could be made without affecting the fluidity much. This may be due to the fact that the slump is measured at two minutes, which is several minutes before the reaction has come to completion.

Temperature dependence could be a reason why some investors notice

observed with the phosphate investment while using de-ionized water altered with known contaminants. Except for Ca(OH)₂, these contaminants did not affect the properties very much. Each property was only slightly reduced. Possibly at greater concentrations there would be greater variations.

The contaminants did not have as drastic effect on the phosphate investment as they did on the gypsum. Therefore, the gypsum investment is more sensitive to the interfering compounds than the phosphate investment. When comparing Figures 3 and 7, the same trend is observed. The variations obtained with the gypsum investment using various water sources (Figure 3) are much larger than those with the phosphate investment (Figure 7). Both investments were greatly influenced by the Ca(OH)₂ contamination.

In Appendix B are the results of more extensive analyses of water source four, six, eight and also source eight after de-ionization. The analysis

of source eight before and after de-ionization confirm that de-ionizing results in the removal of ions and a reduction in pH, conductivity and TDS. According to the results in Appendix B, water sources four, six and eight are in sequence of increasing amounts of Mg⁺² and HCO₃⁻. According to Figure 3, these sources are also in sequence of increasing variance of pour time and set time for the gypsum investment. This indicates a correlation between the concentration of Mg⁺² and HCO₃⁻ with the variation in pour time and

Table 9. Gypsum Investment Using De-Ionized Water Standard

Temperature °F (°C)	65 (18.3)	70 (21.1)	75 (23.9)	80 (26.7)	85 (29.4)
Pour Time minutes	11.50	10.75	10.25	9.75	9.50
Set Time minutes	19.50	18.25	17.50	16.75	16.25
Slump inches (mm)	4 7/16 (112.7)	4 9/16 (115.9)	4 9/16 (115.9)	4 9/16 (115.9)	4 1/2 (114.3)

Note: This is the starting temperature of both the water and investment.

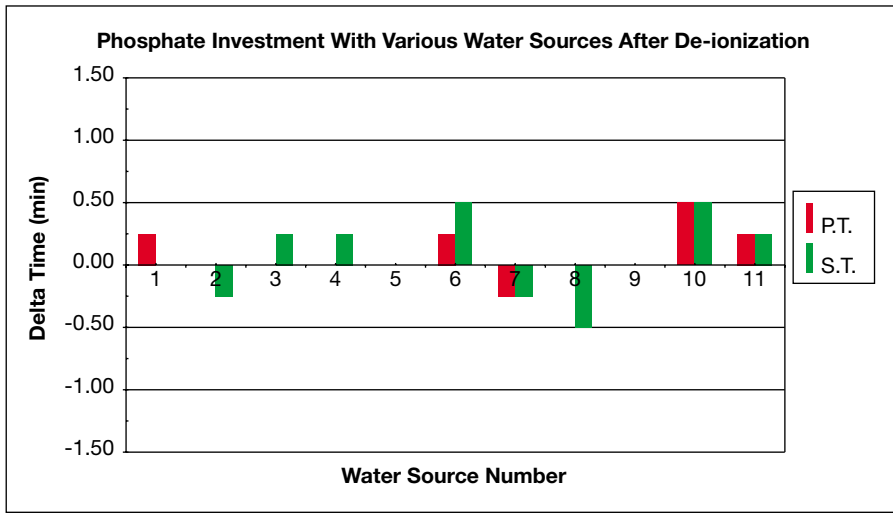


Figure 9

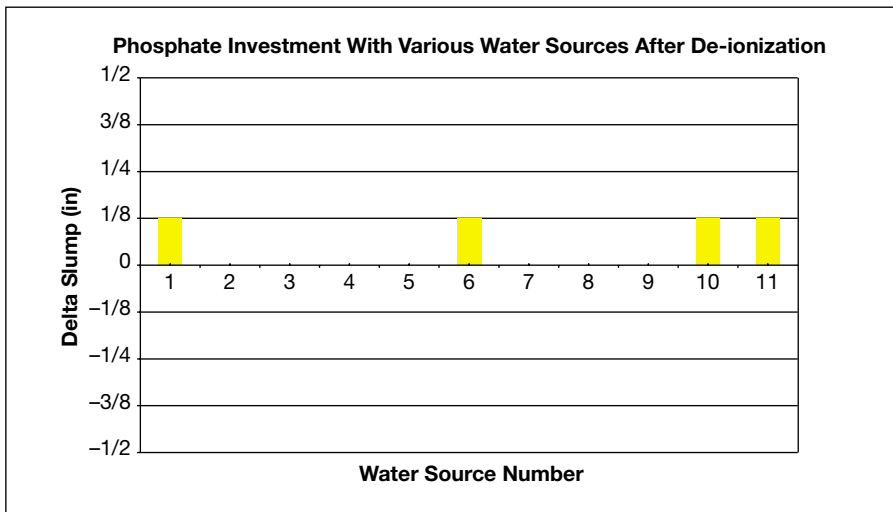


Figure 10

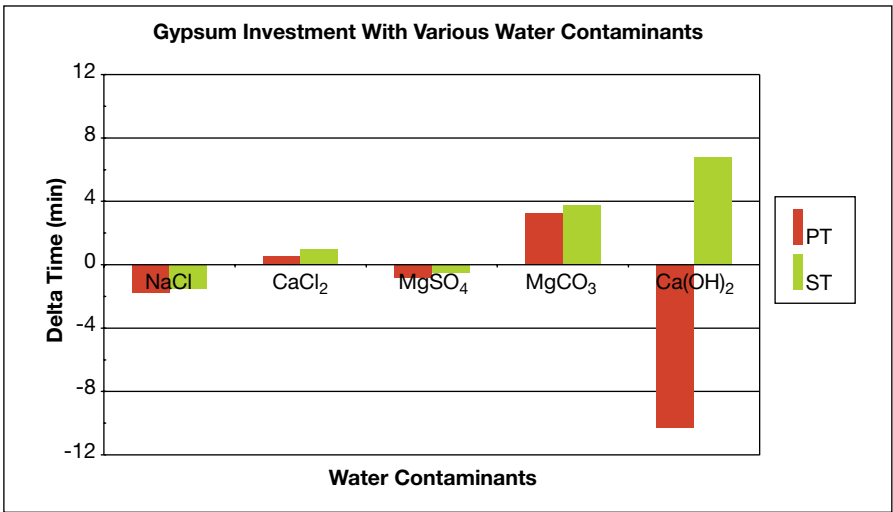


Figure 11

investment. Storing the investment and water in a constant-temperature area can avoid this variable.

The actual results from testing the phosphate investment with de-ionized water at various temperatures is shown in Table 10. Figures 17 and 18 are the corresponding graphs. The temperatures stated apply to both the water and investment. The pour time and set time of the phosphate investment are a bit more sensitive to the temperature than the gypsum investment. As with the gypsum investment, the investor could possibly change these properties by changing the temperature of the water and investment.

In Figure 18 it is seen that the slump had a sharp reduction at 85°F (29.4°C). This coincides with a very short pour time. The small slump might be due to the reaction having progressed so far by the time the slump is measured that thickening of the investment had already begun. Because the pour time and set time of phosphate investments are so short to begin with, it is unlikely an investor would want to shorten them even more by increasing the temperature. Instead, an investor may be more concerned with what happens at the cooler temperatures. This data may be helpful to investors as they troubleshoot problems with phosphate investments.

It is interesting to see in Figure 17 that the set time actually stayed the same at 75°F (23.9°C) and 80°F (26.7°C) and then increased above 80°F (26.7°C). This was a bit surprising so the entire set of tests was repeated. The same results were obtained. This indicates that there is a variable that is not being held constant which is influencing the set time. Two other variables known to affect rates of reaction are mixing time and mixing intensity; but the initial mixing for each test was done the same way and for the same amount of time. Therefore, the initial mixing cannot be the cause of this upswing. It cannot be forgotten that pouring from bowl to bowl during the pour time test also creates a mixing action. At higher temperatures, the pour time is reduced and because there is less pouring, there is less mixing caused by pouring. If there is less mixing

changes in working times as the seasons change. If the investment or water comes from an area that is

affected by the temperature outside, then this would affect the pour time and set time of the gypsum

there are fewer opportunities for the reactants to come in contact and the reaction occurs slower. This could possibly be the uncontrolled variable that caused an upswing in the set time.

To test this theory, the set time was measured again at various temperatures. Although, this time, after the initial mixing, the investment was not poured from bowl to bowl. This removed the suspected variable. Table 11 and Figure 19 show the results. The surprising upswing at the higher temperature is gone. The set times in Figure 19 are considerably longer than those in Figure 17. This demonstrates how much the set time was being affected by the pouring of the investment as well as the starting temperature. This also indicates that changes in mixing have a significant impact on the phosphate investment. If an investor has difficulties with the phosphate investment, mixing method is another variable to be concerned about.

Conclusions

Jewelry casters have a number of variables that need to be monitored during production. Controlling and reducing these variables will improve product quality. While investing, water quality and temperature are two variables that can affect investment properties. To control these variables, investment manufacturers suggest that the water be de-ionized and the temperature be held constant. This investigation was intended to explore the importance of following these suggestions.

It is clear that contaminants in water have a significant impact on the pour time, set time and slump of both gypsum based and phosphate based investments. This was found to be true whether contaminants occurred naturally in the water or were deliberately introduced. The contaminants deliberately introduced were used in this study because they are commonly found in most water sources worldwide. Regardless of the water source and its composition, simply by de-ionizing the effect it had on the investments was removed.

Temperature was also found to impact the properties of mixed investments. This is mainly due to the temperature influence on the rate of

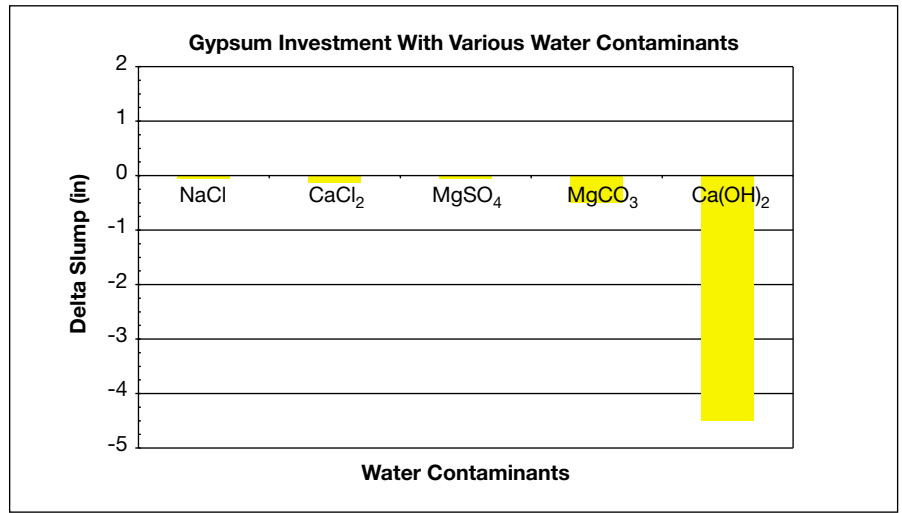


Figure 12

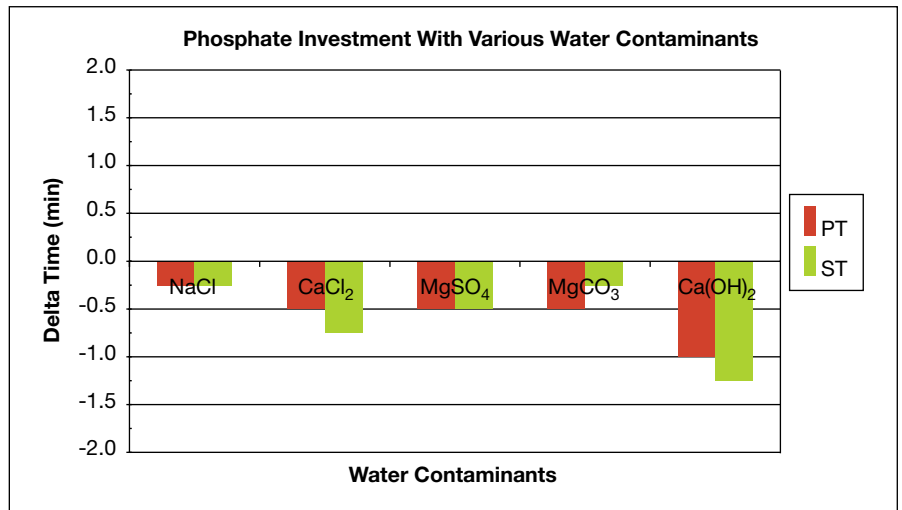


Figure 13

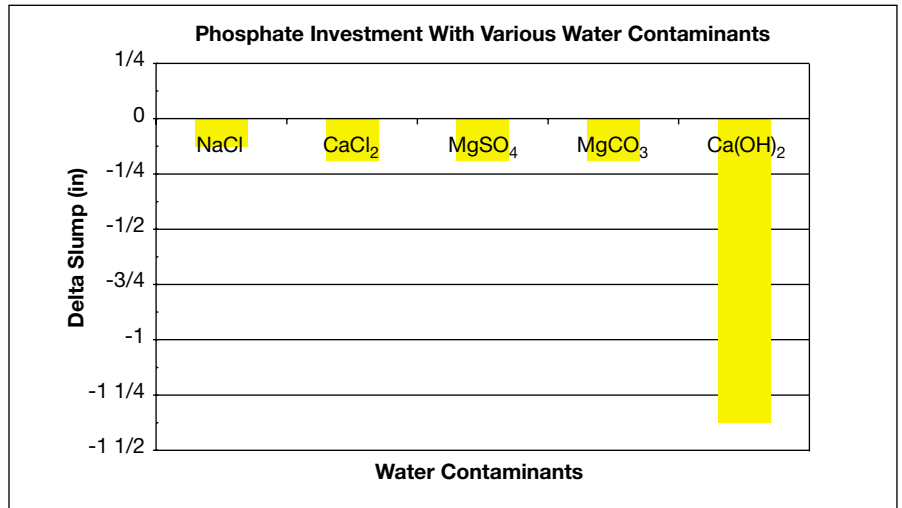


Figure 14

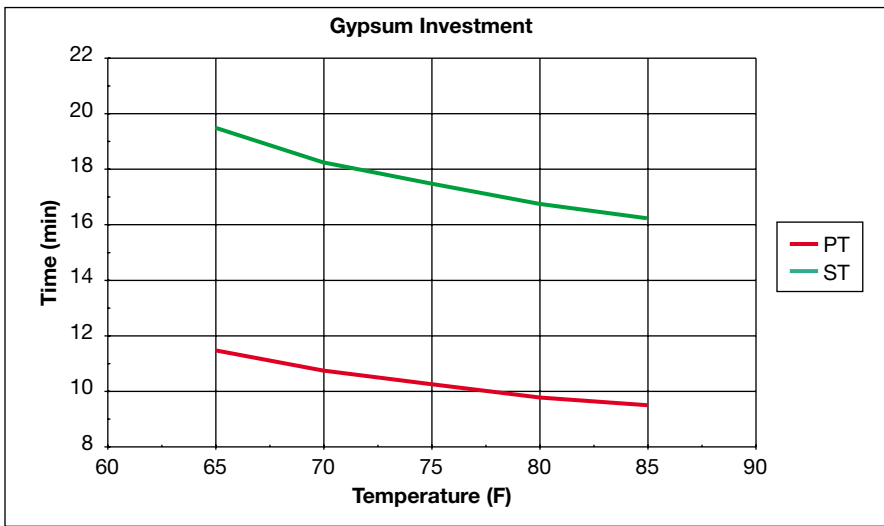


Figure 15

Table 10. Phosphate Investment Using De-Ionized Water Standard

Temperature °F (°C)	55 (12.8)	65 (18.3)	70 (21.1)	75 (23.9)	80 (26.7)	85 (29.4)
Pour Time minutes	11.50	7.75	6.50	5.00	4.50	3.00
Set Time minutes	28.25	13.00	10.50	7.75	7.75	12.00
Slump inches (mm)	6 (152.4)	5 7/8 (149.2)	5 11/16 (144.5)	5 13/16 (147.6)	5 5/8 (142.9)	4 9/16 (115.9)

Note: This is the starting temperature of both the water and investment

Table 11. Phosphate Investment Using De-Ionized Water Standard

Temperature °F (°C)	55 (12.8)	65 (18.3)	70 (21.1)	75 (23.9)	80 (26.7)	85 (29.4)
Set Time minutes	76.00	53.00	34.50	28.50	25.75	20.50

Note: This is the starting temperature of both the water and investment.

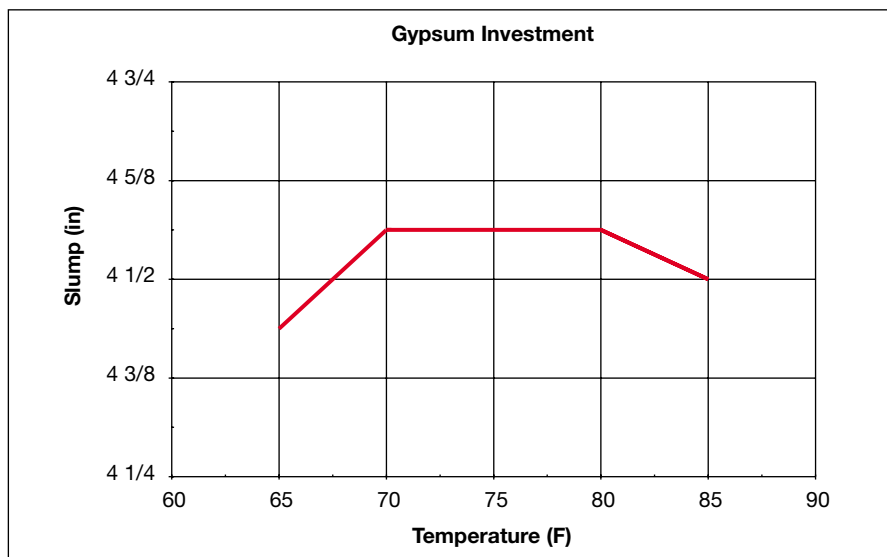


Figure 16

reaction. By maintaining a constant temperature of the water and investment, process variability is eliminated. However, the temperature may be deliberately altered to change the working time to fit a particular application.

This study clearly shows that, by following the investment manufacturer's suggestion to de-ionize the water and control temperature, process variability can be reduced.

Recommendations

Based upon the results of this study, it is recommended that water used in investing both gypsum based and phosphate based investments be de-ionized. It is also recommended that the temperature of both the investment and water be controlled. Attention to these two variables should aid in obtaining consistent results. To further help in obtaining consistent results follow the investment manufacturer's user instructions.

Acknowledgments

I would like to thank Mike Hendricks, R&R's Director of Technology, for coming up with this idea for a research project. I would like to thank R&R for allowing me the opportunity to do this study. I would like to thank Sam Mihailoff of Culligan Industrial Water Systems, Inc. He was very informative in his efforts to help me analyze the water samples.

Appendix A

Water Sources

- 1 City tap water, Maumee, Ohio, USA, sampled on 8/2/99.
- 2 City tap water, Los Angeles, California, USA, sampled on 7/15/99.
- 3 University of Toledo Recreation Center pool water, Toledo, Ohio, USA, sampled on 8/25/99.
- 4 Lake Erie surface water at the East Harbor State Park of Lakeside-Marblehead, Ohio, USA, sampled on 8/25/99.
- 5 Maumee River surface water at Perry's landing of Perrysburg, Ohio, USA, sampled on 8/25/99.
- 6 Agricultural field run-off water, off of Scott Rd just south of Old State line Rd in Lucas county Ohio, USA, sampled on 8/25/99.

- 7 Farm well water from 13949 Lockwood Rd, Sherwood, Ohio, USA, sampled on 8/28/99.
- 8 City tap water, Hicksville, Ohio, USA, sample on 8/28/99.
- 9 City tap water from Birmingham, UK, sampled before 9/28/99.
- 10 City tap water from East London, UK, sampled before 9/28/99.
- 11 City tap water from Dartford in Kent, UK, sampled before 9/28/99.

Appendix B

Chemical Species mg/l	Water Source #8	Water Source #8 after de-ionized	Water Source #6	Water Source #4
Calcium (Ca)	58.5	N.D.	86.2	34.3
Magnesium (Mg)	54.9	N.D.	24.9	9.6
Sodium (Na)	33.4	N.D.	230	9.1
Potassium (K)	2.2	N.D.	11.4	1.7
Strontium (Sr)	8.36	N.D.	0.9	0.2
Barium (Ba)	70.77	N.D.	71.24	21.52
Iron (Fe)	N.D.	N.D.	0.28	N.D.
Manganese (Mn)	N.D.	N.D.	0.28	N.D.
Copper (Cu)	0.047	N.D.	0.098	0.006
Zinc (Zn)	N.D.	N.D.	N.D.	N.D.
Chloride (Cl)	9.6	N.D.	382	16.6
Nitrate/Nitrite (N)	N.D.	N.D.	1.1	0.5
Sulfate (SO ₄)	137	N.D.	84	26
Bicarbonate (HCO ₃)	311.2	N.D.	222.1	89.9
Carbonate (CO ₃)	11.5	N.D.	N.D.	N.D.
Fluoride (F)	1.2	N.D.	0.3	0.1
Silica (SiO ₂)	18	N.D.	1.95	2.38

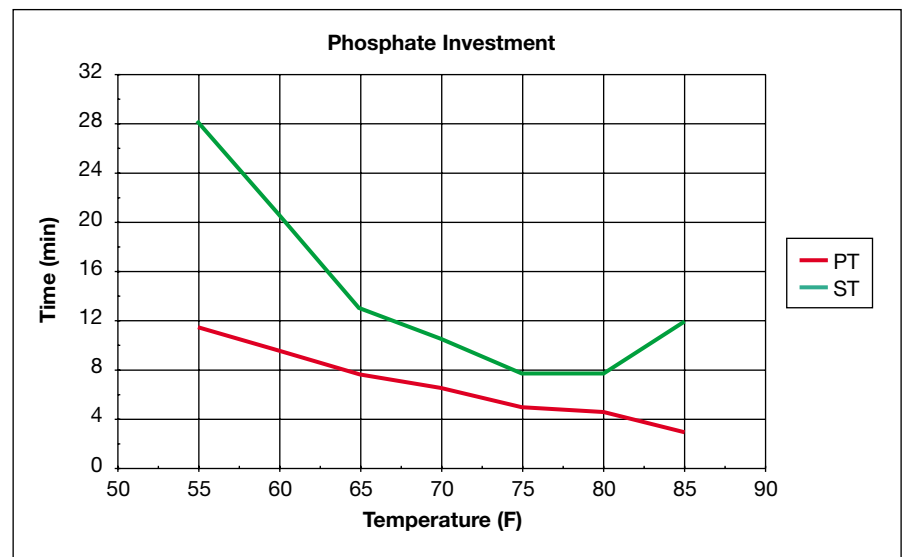


Figure 17

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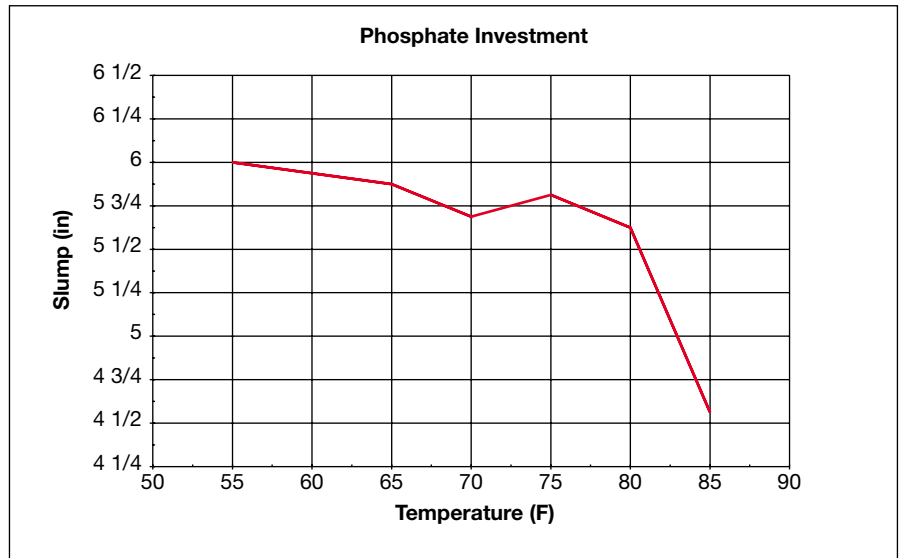


Figure 18

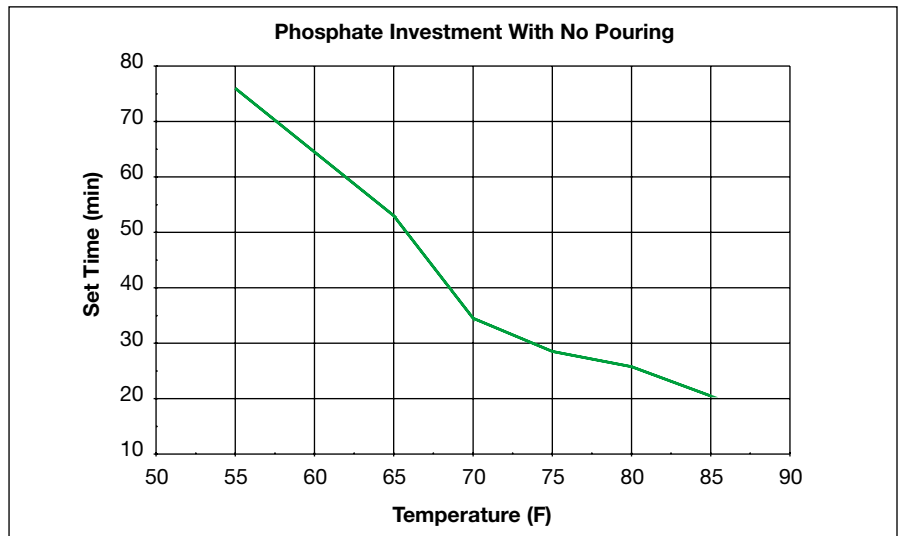


Figure 19

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