Binder System Conversion at Magotteaux Pulaski

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INTRODUCTION

The Pulaski plant is one of 15 production sites in the Magotteaux family. Standardization of product and processes is part of the company discipline to provide the customer a consistent quality part independent of production facility. As part of the continuous improvement journey to improve in-house casting surface quality, a review of the sand binder system indicated that a change that had already occurred at other production sites could also aid the Pulaski operation. The Pulaski team initiated a capital project and after justification, the conversion process began.

The Binder Systems

Phenolic Acid-Cure

A phenolic acid-cured system was the incumbent. This binder system, developed in the 1950's, became popular in the 1970's. Phenol and formaldehyde react to form the polymer bond. An acid catalyst completes the reaction. Resin contents typically range from 0.8% to 1.5%. The acid addition, based on resin content, ranges from 20% to 40%. Standard acid catalysts are TSA (toluene sulfonic acid) or BSA (benzene sulfonic acid). Much like a furan system, the mold cures from the outside surface in contact with the air inward. Acid selection determines the curing time and a short plastic stage exists prior to the completion of the reaction. Resin storage life is limited and is two to three months in ideal conditions. High temperatures shorten the shelf life as viscosity increases with age and temperature making mixing and coating difficult.

Phenolic Urethane

A phenolic urethane system was selected to replace the phenolic acid-cured system. This binder system, developed in the 1970's uses a phenol resin, a poly-isocyanate, and a derivative of pyridine as a catalyst make up this three part chemical system. Binder contents vary between 0.7% and 2.0%. The ratio of Part I to Part II ranges from 50/50 to 60/40. The catalyst, Part III, ranges from 2% to 10% and its selection is based on the desired work and strip times. The poly-isocyanate, Part II, is hydroscopic and needs protection from moisture. Iron oxide or an iron oxide replacement is added to the sand to prevent gas and expansion type defects. A feature of this system is an expanded work time in the curing reaction. The cure rate is constant throughout the mold and is independent of contact with air. There is an additional potential of casting defects with a phenolic urethane system including veining and nitrogen porosity.

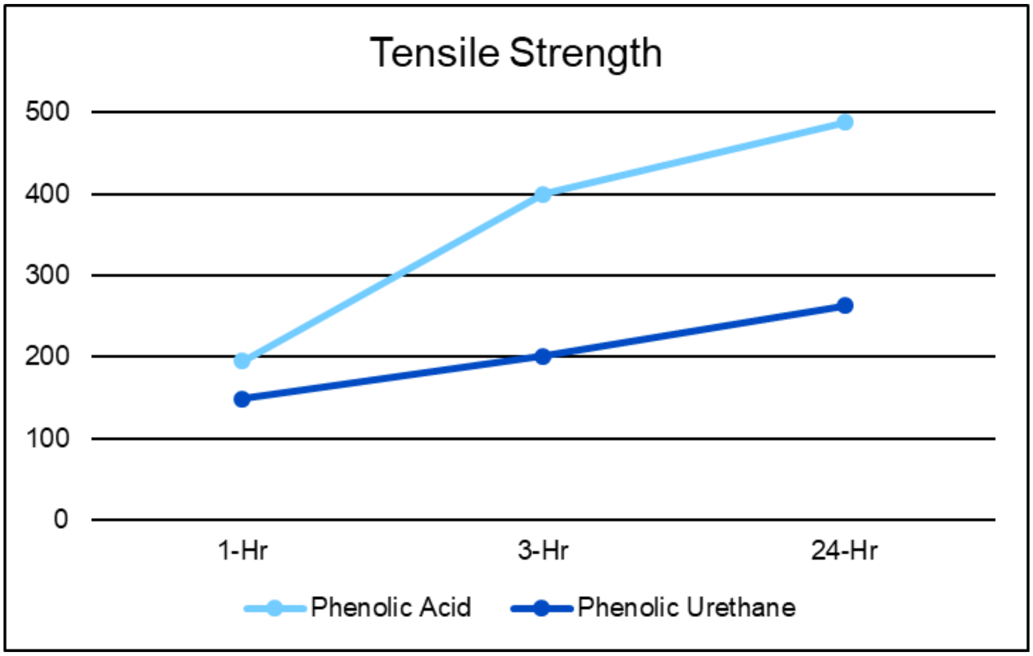
Comparison of Binder Systems

Justification for the project was based on cost savings in the cleaning room. How much savings could be anticipated? This estimation can be determined if looking at sand testing data that is available on the two different systems from previous research. Not a lot of recent data can be found for the acid cured phenolic system as use of this binder system has decreased over the years. There is data from 2002 that ran these two systems, as well as several others, side by side.[1] Various tests were run to compare properties of the binder systems. Information on work time / strip time ratio and tensile testing are in Table 1. It is seen from the work time strip / strip time ratio that there is far more work time available on the proposed phenolic urethane system. If a ten-minute work time is needed at the mixer, the phenolic acid system requires the strip time to be over 21 minutes. The phenolic urethane system requires less than 13 minutes. The advantage for the work time / strip time ratio is in favor of the phenolic urethane. This would be advantageous to speeding up the operation and increasing capacity if the strip time is the constraint in the system. This potential increase in capacity was not included in the justification, but is available. When reviewing tensile strength results at three different times, the phenolic acid is considerable stronger than the phenolic urethane. The tensile strength data is presented in Table 1 and Figure 1.

Table 1: Comparison of tensile strengths and work time strip time ratio for phenolic acids and phenolic urethane systems.[1]

	Work Time Strip Time Ratio	1-Hr	3-Hr	24-Hr
Phenolic Acid	0.47	195	400	488
Phenolic Urethane	0.80	149	201	263

Figure 1: Comparison of tensile strength developed over time for a phenolic acid cured system and a phenolic urethane system.[1]

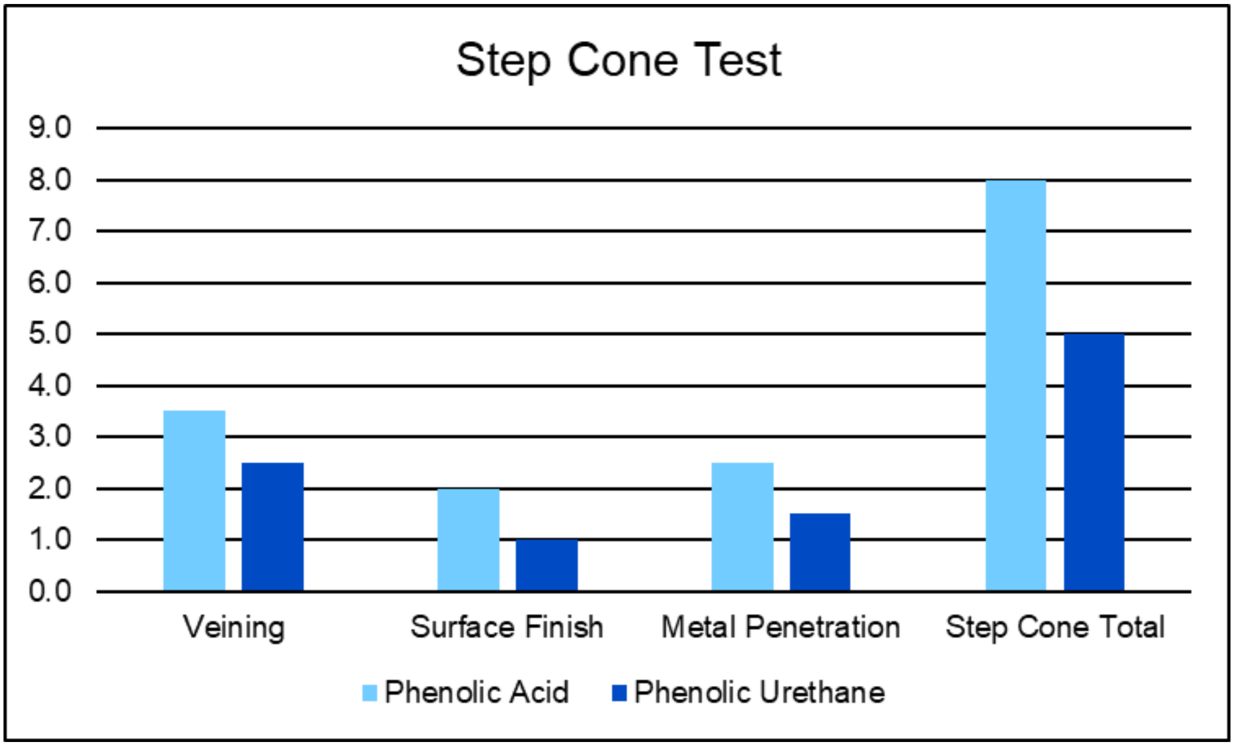


Step cone tests were graded on veining, surface finish, and metal penetration. The grading system gave a value of one for excellent up to five for very poor. Results of this testing are presented in Table 2 and Figure 2. The phenolic urethane system outperformed the acid cured system in all three areas graded in the testing. All three of the areas graded have a direct impact on the grinding time per casting. The lower numbers indicate that the phenolic urethane system will reduce the amount of time in the cleaning room.

Table 2: Step cone test results comparing a phenolic acid- cured system and a phenolic urethane system.[1]

Step Cone Test Results				
	Veining	Surface Finish	Metal Penetration	Step Cone Total
Phenolic Acid	3.5	2.0	2.5	8.0
Phenolic Urethane	2.5	1.0	1.5	5.0
Ratings: 1=Excellent / 2=Good / 3=Fair / 4=Poor / 5=Very Poor				

Figure 2: Comparison of test results from the step cone test.[1]

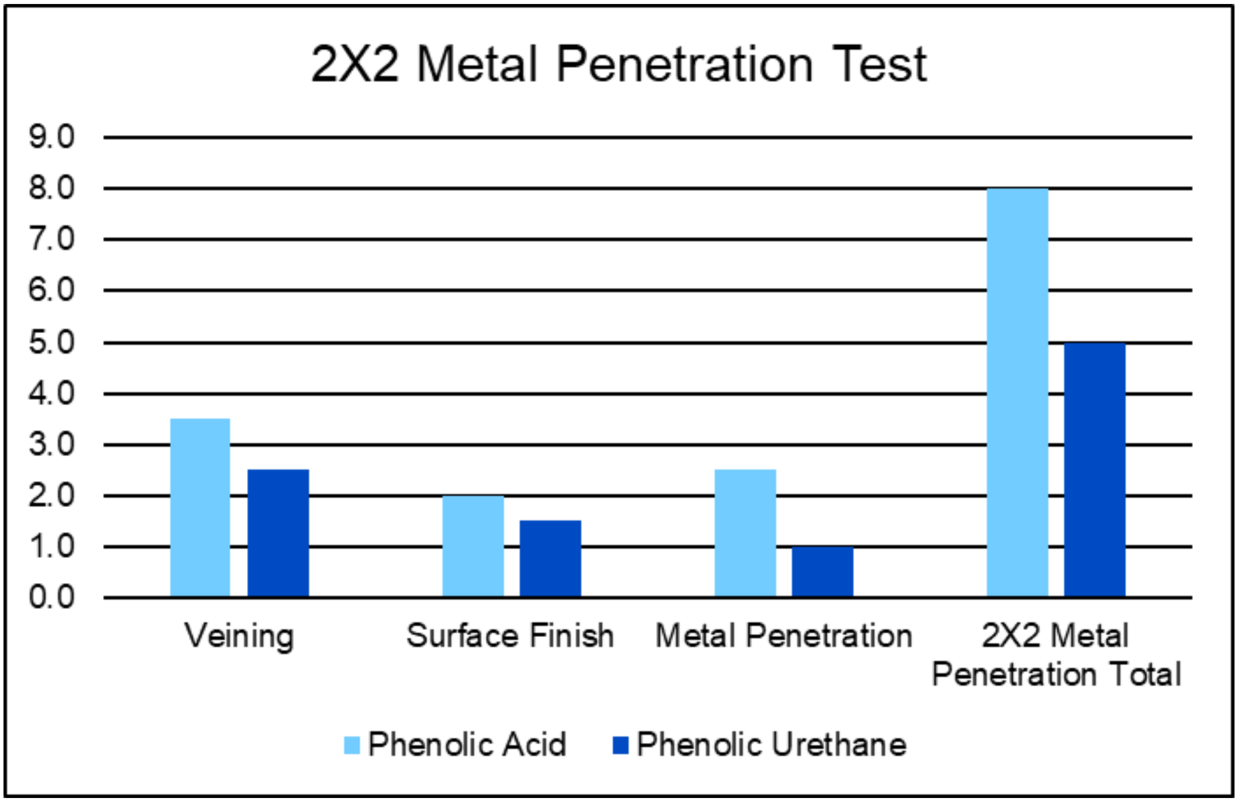


Further testing comparing the binders on a 2X2 Metal Penetration Test was also performed. Veining, surface finish, and metal penetration of the samples were graded in the same manner as the step cone test. Again, the phenolic urethane outperformed the phenolic acid binder system.

Table 3: 2X2 Metal Penetration test results comparing a phenolic acid- cured system and a phenolic urethane system.[1]

2X2 Metal Penetration Test Results				
	Veining	Surface Finish	Metal Penetration	2X2 Metal Penetration Total
Phenolic Acid	3.5	2.0	2.5	8.0
Phenolic Urethane	2.5	1.5	1.0	5.0
Ratings: 1=Excellent / 2=Good / 3=Fair / 4=Poor / 5=Very Poor				

Figure 3: Comparison of test results from the 2X2 metal penetration test.[1]

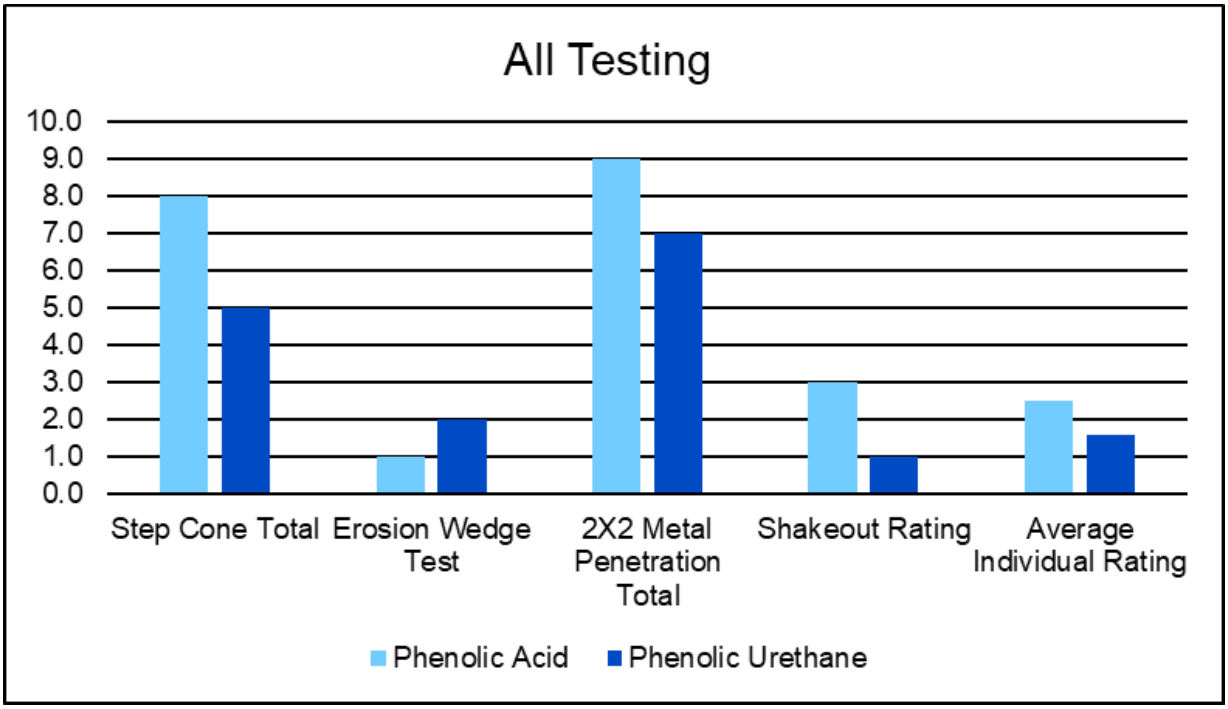


Additionally, an erosion wedge test and shakeout ratings were used for comparison purposes. Using the same rating scale as the other tests, the phenolic acid system, scoring one, outperformed the phenolic urethane system in the erosion test, scoring two on the erosion wedge test. The phenolic acid system outperformed the phenolic acid system in the shakeout rating with a score of one compared to three. A summary of the test data is presented in Table 4 and Figure 4.

Table 4: Comparison of the phenolic acid and phenolic urethane sand binder systems ability to prevent sand related defects and ease of shakeout using various test methods.[1]

	Step Cone Total	Erosion Wedge Test	2X2 Metal Penetration Total	Shakeout Rating	Overall Rating	Average Rating
Phenolic Acid	8.0	1.0	9.0	3.0	20	2.5
Phenolic Urethane	5.0	2.0	7.0	1.0	13	1.6
Ratings: 1=Excellent / 2=Good / 3=Fair / 4=Poor / 5=Very Poor						

Figure 4: Overall comparison of test results. The average phenolic urethane binder system results are 18% better.[1]



A review of the testing that took place in 2002 reveals that the phenolic urethane binder would outperform the phenolic acid binder in all but the erosion test. Any improvements made to veining, metal penetration, and surface finish would decrease cleaning room time. The reduction of cleaning room time was used to justify this project.

Cost of Necessary Changes

The proposal to switch from a two-part system to a three-part system would require additional equipment as listed in Table 5. The mechanical operation of the mixer was capable of the conversion with no changes. The most important additions would be mass flow meters with temperature bias capability and the iron oxide delivery system. An evaluation of the day tank and bulk tank requirements for the project indicated that they would need to be cleaned or replaced. It is noted that the cleaning or replacement of the tanks could be worked out in the binder pricing. The current sand in the system was not compatible the proposed binder system. The current sand would need to be removed from the system. Rather than disposal, it was determined to empty the system, put this sand aside, and slowly reintroduce this sand into the system through the thermal reclaimer for minimal impact. New sand would need to be purchased to fill the system, but this cost was not included in the project as it is an upfront cost that will counteracted in the future with the addition of the old sand back into the system. If any cost had been associated to this, it would have been the cost per pound to thermally reclaim the sand multiplied by the total pounds of sand removed from the system.

Table 5: Estimated total project cost for equipment. In-house labor costs not included.

Description	Justification	Cost (less labor)
Iron oxide feeder and handling equipment.	Necessary due to binder differences to minimize casting defects.	$51,000
Pump system (Reuse existing pump system as much as possible)	Needed for conversion from two part binder system to three part binder system.	$65,000
Mechanical Installation	Modifications required for access and platforms to the additional equipment necessary and replacement of tubing.	$9,500
Electrical Installation	Needed to install any additonal control and power circuitry.	$2,500
Replace pumps from bulk tanks.	Required for pumping new chemicals from the bulk tanks to the day tanks.	$7,000
Replace piping from outside to bulk tanks and from bulk tanks to day tanks	Existing piping is not compatible with the existing binder system and must be replaced	$11,500
Cleaning or replaceing of bulk tanks	Change of binder system requires either new bulk tanks or cleaning of existing bulk tanks. May be able to negotiate into binder price with supplier	$46,000
Replace day tanks with modified totes and plumb.	Change of binder system requires new day tanks.	$2,000
Tote heater for part one day tank	The new binder requires a consistent temperature to maintain viscosity.	$2,000
	Total	$196,500

Project Justification

The sand testing described in the previous sections indicates that there should be savings in the cleaning room with a reduction in grinding times. The sole basis of project justification was on this reduction in cleaning room costs. There was an estimated total savings of $150,000 through head count reduction, grinding stone reduction, and grinding tool reduction. Other benefits such as better surface appearance in the eyes of the customer had no value assigned to them. Other savings were not included in the overall justification of the project but anticipated. The previously mentioned increased capacity due to faster curing of molds was not included because in order to recognize this, the pouring and shakeout staging areas would need to be addressed to ensure that any increased capacity can be realized.

Analysis of Binder Costs

Even though it was not included in the project justification, binder costs have a significant impact on operations when over 35,000 tons of sand are mixed per year in this area of the operation. The phenolic acid system was running at 1.1% resin with 40% acid based on resin. There were no additional products being added to the sand system for defect prevention. Wanting to stay as close to neutral impact on binder cost as possible, it was calculated that a 0.86% phenolic urethane resin level with a 55/45 ratio of part I to part II, using 5% catalyst, and 2% iron oxide would be around break even. This was adding the iron oxide to 100% of the sand mixture and not just the facing sand. By having the iron oxide feeder only running for the facing of the pattern, about 50% of the mix, the phenolic urethane system could be run at a 1.1% binder level for a break even analysis in binder cost.

Current operating parameters in the system have improved upon that initial break even analysis. Resin percentage is at 0.93%, a 5% catalyst level, and 4% iron oxide additive for 33% of the mix. This current analysis saves $70,000 per year. A next step will be to test running the system at 3% iron oxide for an additional savings of $57,000 per year. This data is presented, in Table 6, with the dollar value normalized so that the base phenolic acid system is one. Values less than one are savings and values greater than one would be a cost increase. When reviewing these calculations, it is interesting to see that a 0.1% change in binder consumption is the same as a of 1% change in iron oxide consumption. Future investigation may also include looking at the balance between the iron oxide additive percentage, binder percentage, and casting quality for further savings.

Table 6: Detailed cost of incumbent phenolic acid system, current state phenolic urethane system and goal phenolic urethane system. Base cost per ton of phenolic acid system is valued at one with no units. Sand cost is not included as it is neutral to all three situations.

Phenolic Acid		
SAND WEIGHT	2000	lbs
RESIN PERCENT	1.1%	
TOTAL RESIN/TON	22.0	lbs
ACID PERCENT (BOR)	40%	
TOTAL ACID/TON SAND	8.8	lbs
TOTAL RESIN COST	0.63	
TOTAL ACID COST	0.37	
SYSTEM COST/TON SAND	**1.00**	

Est. Current Savings / year	$70,000
Est. Goal Savings / year	$127,000

Phenolic Urethane - Current		
SAND WEIGHT	2000	lbs
RESIN PERCENT	0.93%	
TOTAL RESIN/TON	18.5	lbs
PART 1 RATIO	55%	
PART 2 RATIO	45%	
TOTAL PT1/TON	10.2	lbs
TOTAL PT2/TON	8.3	lbs
CATALYST PERCENT	5.0%	BO Pt I
TOTAL CATALYST/TON	0.51	lbs
IRON OXIDE ADDITION %	4.0%	1/3 of sand
TOTAL PT 1 COST	0.33	
TOTAL PT 2 COST	0.31	
TOTAL CATALYST COST	0.05	
IRON OXIDE COST	0.24	
SYSTEM COST/TON SAND	**0.93**	

Phenolic Urethane - Goal		
SAND WEIGHT	2000	lbs
RESIN PERCENT	0.93%	
TOTAL RESIN/TON	18.5	lbs
PART 1 RATIO	58%	
PART 2 RATIO	42%	
TOTAL PT1/TON	10.7	lbs
TOTAL PT2/TON	7.8	lbs
CATALYST PERCENT	5.0%	BO Pt I
TOTAL CATALYST/TON	0.54	lbs
IRON OXIDE ADDITION %	3.0%	1/3 of sand
TOTAL PT 1 COST	0.35	
TOTAL PT 2 COST	0.29	
TOTAL CATALYST COST	0.05	
IRON OXIDE COST	0.18	
SYSTEM COST/TON SAND	**0.87**	

Unexpected Challenges / Opportunities

Not long after the conversion, it was discovered that the time savings were not being realized in the grinding operation. The reality indicated an increase in grinding time. The surface finish on the castings was better but inconsistent at this point, but the grinders were removing more metal. The castings had grown with the binder system conversion. All products are gauged for fit and the increased dimensional size led to increased grinding on the four sides and machine time for the other two for the largest product line. From dimensional layout information all three axis of the casting measured larger than with the previous binder system. The increase in length was relative to the size of the dimension. It was determined after this that the difference was due to the difference in binder systems. The phenolic acid system grows approximately 0.1% while the phenolic urethane system shrinks about 0.1%[2]. Lowe and Showman presented information on phenolic urethane binder systems in 2011 that indicates that the overall amount of shrinkage is related to the time between the molding and pouring operations. The bulk of the shrinkage is due to the evaporation of the solvents. It has not yet been concretely determined if this relationship to time will affect dimensions in production as it is desired to have all molds poured off within 24-hours of production in Pulaski. It also showed that higher volatility solvents had produced higher shrinkage rates.[3] The effect of the higher volatility solvent increased the shrinkage 50% to 0.15%. Thiel surmised that the effect of binder systems on dimensional accuracy is not thoroughly understood.[4]

Discussion

The physical changes to the plant needed for the conversion of binder systems occurred with minimal issues. A difficulty was encountered in setting up the additive feeding system as the previous infrastructure presented problems with location and method of transportation to the mixer. These limitations have only allowed a consistent addition of the anti-veining agent at 2% maximum until this time. The necessary feeding equipment has been determined to allow additions of 3-4%. There is still veining present at the 2% addition level. Since the initial installation, the calibration of the mixer and pumping systems has shown that it is very stable with minimal adjustments needed. Overall, surface finish has improved over the previous binder system though no side-by-side comparisons can be made.

Cleaning the phenolic acid sand out of the bulk sand system was labor intensive. All parts processed through shakeout so that no molds remained. The shop was then completely cleaned and swept prior to starting to mold with the phenolic urethane sand system. The initial molds in the phenolic urethane system were made using 100% virgin sand. The binder and catalyst percentages were different using the virgin sand and needed to be adjusted as the shop generated reclaimed sand. The system dialled in to the current settings once the desired sand blend of 70% mechanically reclaimed and 30% thermally reclaimed was achieved and stable.

The unexpected change in dimensional results have affected the cleaning room negatively. This is being corrected through pattern alterations. These alterations are being made so that a minimal amount of grinding is needed for individual parts to pass the gauging tests. It has been determined through measurement that there is a variability in the dimensional results on the same part from one mold to another. No definitive root cause has been defined, but the possibility of the time between molding and pouring can vary enough to correlate with the Lowe and Showman information. As a greater number of patterns are resized, grinding times will be reduced.

Conclusion

The change of binder type systems is significant in the way it affects a foundry operation. This one was not a simple plug and play type operation as expected. Data indicates that even changes in a phenolic urethane binder system's solvents have an impact on results obtained on larger dimensions. Lower cleaning room times have not been achieved due to the dimensional changes that took place. Once the dimensional corrections are made to the patterns, the cleaning room improvements are expected to be realized. The additional benefit of binder cost savings is being recognized.

References

1. J. J. Archibald; "Benchmarking the Nobake Binder Systems," AFS Transactions, 2002.
2. J. A. Otte (Personal communication 2021)
3. K. E. Lowe, R. E. Showman; "Dimensional Changes in Chemically Bonded Molds and Cores," AFS Transactions 2011.
4. J. Thiel; "Thermal Expansion of Chemically Bonded Silica Sands," AFS Transactions, 2011.