Reducing Molding Sand Variation at a Job Shop Casting Facility

Kuldeep Agarwal and Ashley Folden-Ecker
Department of Automotive and Manufacturing Engineering Technology
Minnesota State University Mankato
Mankato, MN 56001, USA
Kuldeep.agarwal@mnsu.edu, Ashly.folden-ecker@mnsu.edu

Abstract

A job shop casting facility in Southern Minnesota utilizes the green sand molding process in the production of ductile iron castings. The foundry's green sand is produced by mixing recycled molding sand with water, clay, seacoal, and other ingredients in a muller. Maintaining consistent sand properties through the molding process is critical to the production of quality iron castings. One of the primary measured and controlled characteristics of which indicates molding sand quality is compactability. Compactability is measured in-line automatically on every batch of sand; the results are used as the sole factor to determine water additions for the subsequent batch of sand. While this formula frequently produces sand that is sufficient for molding, various factors exist outside of this calculation that can affect the outcome of the next sand batch. These factors are currently not accounted for in the calculation of water additions and as such, some amount of inconsistency is generated by the current process. Inconsistent molding sand may result in the production of scrap castings as well as downtime at the molding machines. This project utilizes the DMAIC improvement process to reduce variation in molding sand by measuring, analyzing, and improving upon the parameters used in the green sand control process. The desired outcome of the project is to produce consistently stable sand by predicting and controlling water addition rate (therefore resulting compactability) based on the measured inputs. Reducing batch-to-batch and overall variation in molding sand will lead to a reduction in sand-related scrap and downtime.

Keywords

Casting, Sand Compactability, Variation, DMAIC, Data Analysis.

1. Introduction

A job shop casting facility in Southern Minnesota utilizes the green sand molding process in the production of ductile iron castings. The foundry's green sand is produced by mixing recycled molding sand with water, clay, seacoal, and other ingredients in a muller. Maintaining consistent sand properties through the molding process is critical to the production of quality iron castings. One of the primary measured and controlled characteristics of which indicates molding sand quality is compactability.

Compactability is defined as the percent change in height of a given volume of loose molding sand when compacted under an established force. Compactability is measured in-line automatically on every batch of sand; the results are used as the sole factor to determine water additions for the subsequent batch of sand. A 1% increase in compactability will results in a 0.1-gallon decrease in water addition for the next batch of sand made (and vice-versa). While this formula frequently produces sand that is sufficient for molding, various factors exist outside of this calculation that can affect the outcome of the next sand batch. These factors are currently not accounted for in the calculation of water additions and as such, some amount of inconsistency is generated by the current process.

Inconsistent molding sand may result in the production of scrap castings as well as downtime at the molding machines. When sand is dryer than desired, sand is easily washed or broken away from the mold during pouring, resulting in sand inclusion defects. Wet sand can lead to pinhole defects and soft molds resulting in poor surface finish. Extremely dry sand can result in molds that will crack or fall apart during transport or pouring, while very wet sand can also stick to tooling, mold jackets, etc. and cause further issues. Sand-related downtime can occur when sand is produced outside of the set parameters (too dry or too wet). Molds cannot be made with this sand, so operators must recycle the sand

and wait for new batches of properly mixed sand to be made. A single muller (mixer) feeds all three molding lines and as such, any downtime at molding can impact connected operations both up and downstream.

This project utilizes the DMAIC improvement process to reduce variation in molding sand by measuring, analyzing, and improving upon the parameters used in the green sand control process. The desired outcome of the project is to produce consistently stable sand by predicting and controlling water addition rate (therefore resulting compactability) based on the measured inputs. Reducing batch-to-batch and overall variation in molding sand will lead to a reduction in sand-related scrap and downtime.

2. Literature Review

Antony and Banuelas (2002) underscore the pivotal ingredients for effective Six Sigma implementation, highlighting DMAIC's role in the process. Harry and Schroeder's seminal work (2006) offers a comprehensive guide, elaborating on Six Sigma's breakthrough strategies and DMAIC's significance. Pyzdek and Keller (2014) provide a detailed handbook catering to Green Belts, Black Belts, and managers, elucidating the DMAIC process's integration with Six Sigma tools. Eckes (2001) delves into sustaining Six Sigma's impact, shedding light on cultural and technical adjustments with DMAIC. Linderman et al. (2003) contribute a goal-theoretic perspective on Six Sigma, emphasizing DMAIC's structured process towards desired outcomes. Antony (2004) critically evaluates Six Sigma's pros and cons, addressing the challenges tied to DMAIC integration. Rungtusanatham and Ussahawanitchakit (2007) provide empirical evidence of Six Sigma and DMAIC's application in Thai industries, showcasing practical insights. Kumar et al. (2006) explore Six Sigma's influence on Indian organizational performance, focusing on DMAIC's effects. Rath & Strong's pocket guide (2000) serves as a quick reference to Six Sigma principles, including DMAIC's stages. Breyfogle III (2014) offers an in-depth exploration of statistical methodologies within the DMAIC framework. This review concludes that while Six Sigma and DMAIC offer substantial benefits, organizational transformations and implementation intricacies remain crucial aspects to consider in achieving continuous improvement.

3. Methods

3.1 Measure Phase

Figure 1 shows the cycle of green sand during the casting process at the foundry. Sand is added simultaneously from two cooled sand storage tanks by plate feeders into a clam-shell style hopper above the muller. The sand is weighed by load cells on the hopper and the batch weight is set manually and seldom changed from approx. 4,000 pounds. Sand temperature is measured here, but this data is not currently utilized in the control process. When sand is requested by the molders, sand will be dropped into the muller and the muller cycle is initiated. A premixed blend of clay, sea coal, and other ingredients is added to the sand pneumatically. The premix is weighed in a hopper on load cells at a weight set by the process control team based on results of a methylene blue active clay test performed every 4-6 hours. Water is added to the batch at a volume determined by the compactability results from the previous batch. Water added can either be water enriched with clay and carbonaceous materials (referred to as enriched water) or city water. The enriched water is treated with wash water used to clean the clay and coal from the recycled sand for reuse in the core making process.

Additional variables at the muller include the moisture and temperature of the incoming sand. The temperature and moisture of the sand is heavily dependent on the sand to metal ratio, which is ratio of sand volume to metal volume in each mold. This will impact the maximum temperature of the sand mold and dictate how quickly the casting and sand will cool, impacting the temperature and residual moisture content of the return sand. Production rates also impact the rate of sand use and cooling time and therefore return sand temperature and moisture. The muller is designed to mix the sand, premix, and water and to optimally activate the clay in the premix. The action of the vertical muller wheels is critical to the activation of clay by water in the mixture. Overall cleanliness of the muller and the settings of the wheels from the muller shell will impact how much water is bound to the clay.

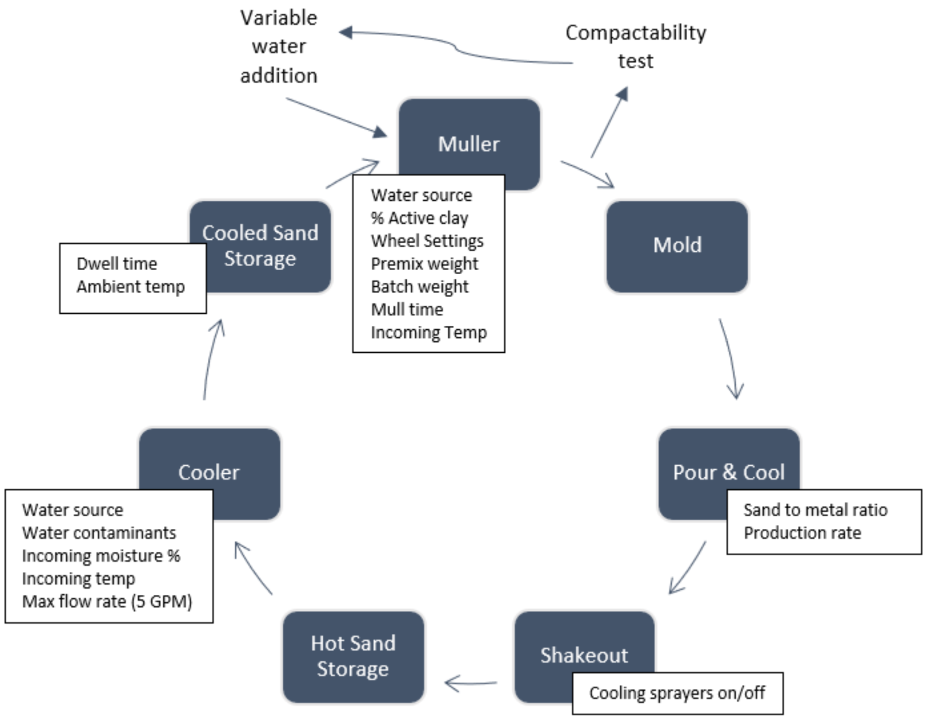

Figure 1. Process and Variable Map

Once sand is mulled, it travels through a series of hoppers and belts where it is consumed by the mold machines. If a batch of sand is produced that is outside of the desired compactability range, operators can choose to return sand back to the system without being used to produce mold. This adds another variable to the system as this sand was not exposed to molten metal and will be of a very different moisture level and temperature than the rest of the return sand. Molds are pushed into a turntable and poured per the job requirements. Cooling time varies depending on the rate of production and castings weight and/or geometry. Once cooled for an appropriate amount of time, molds travel through a series of shaking conveyors and a rotating drum screen which is where sand is recollected for reuse in the system.

Sand that is recollected for reuse in the system goes through a screen and is temporarily dropped into a hot sand storage tank above the sand cooler. Sand temperature is measured as sand is fed through the sand cooler. The cooler agitates sand while adding water and air to help reduce the sand temperature and increase the sand moisture. The source of water can be either enriched water or city water and is added based on the conductivity of the sand, which is measured by probes inside the cooler. Typical moisture levels coming from the cooler during normal operation is 1.6-1.8% while outbound temperature varies more and depends on the incoming temperature and the time spent inside the cooler. From the cooler, sand is transported to one of two cooled sand storage tanks for reuse in the muller. Overall time of the return sand loop is a variable and is dictated by many factors.

Table 1. Variables and their measurement methods

Variable Factor	Measurement Method	Data Use	Notes
Sand Temperature (muller-incoming)	Infrared	NA	Data is measured and collected, but not used
Sand Moisture (muller-incoming)	NA	NA	Not currently measured
Sand Moisture (cooler-outbound)	Conductivity	Controls water addition rate	Data is measured, but not collected

Sand Temperature (cooler-inbound)	Infrared	Controls if water is used; rate of use	Data is measured, but not collected

Among the variables discussed in Figure 1, those with the highest impact on controlling sand compactability were identified as moisture and temperature of the sand coming out of the cooler and going into the muller. Measurement methods, current and potential data collection and analysis points are summarized in Table 1.

In theory, the ability to measure and account for sand temperature and moisture data at either of these points will allow improved control of the subsequent compactability. Incoming sand moisture is not currently measured at the muller, so the first focus will be on collecting and analyzing the cooler moisture and temperature data for variation. Results of this analysis will help determine whether there is a need to measure the moisture of the incoming sand at the muller, or if additional programming controls can be added to improve control.

3.2 Measurables and Goals

Compactability was the primary measurement used to determine improvement. Currently, sand produced falls within the desired compactability range (setpoint +/-3%) only 87% of the time. The aim of this project was to improve that overall number to 97%. Sand related downtime and scrap data can be anticipated secondary improvements if the project is successful in reducing variation in the sand properties.

4. Results and Discussion

4.1 Analyze Phase

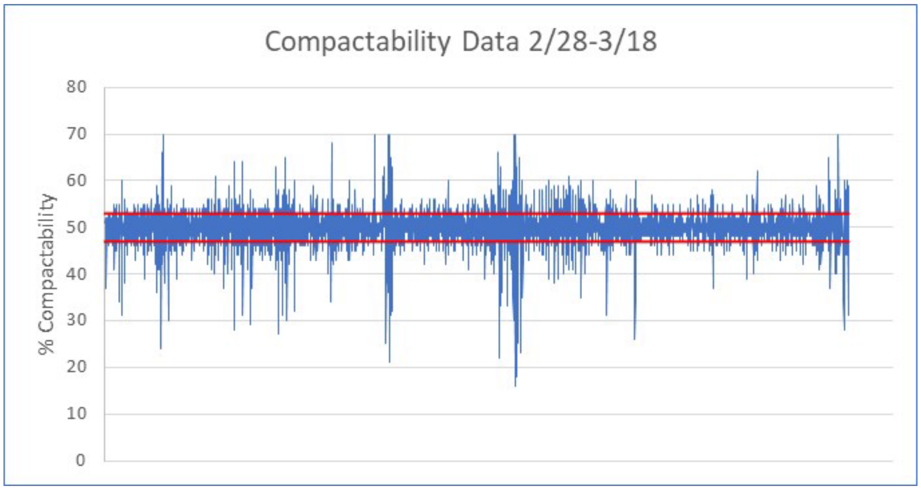

Figure 2. Compactability Data

Figure 2 shows the range and distribution of compactability readings over the course of several weeks. The graph displays the +/-3 range as the upper and lower control limits, with frequent swings outside of the range which can be accounted for by some of the variables in the process map in Figure 1. Data was analyzed to identify those variables with the biggest impact on the variation in compactability. Multiple factor analysis of variance was used to determine which measured variables have a significant impact on the amount of water required to reach the desired setpoint of compactability.

4.2 Data Analysis

Results of the ANOVA analysis are shown in Table 2, showing that temperature, measured bond addition, and water source are all significant factors on the amount of water required to reach desired compactability. Figure 3 shows a main effects plot for temperature impacts on the resulting compactability. It was noted that the mean deviation is greatest at the highest and lowest temperatures and most stable within the temperature range of 80°-115°F. This is consistent with past observations and suggests that adjusting water addition based on compactability alone without accounting for the changes in temperature limits control at those most extreme temperature conditions. It should also be noted that the biggest deviations in compactability tend to occur during periods of time where the sand temperature is increasing or decreasing significantly. An example can be seen in the data from March 2022, in figure 4. The largest swings in compactability coincide with segments of temperature change; both increasing and decreasing temperature shifts tend to cause this variation.

Table 2. ANOVA results

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Temp Avg/6	57	5833.7	102.346	11.72	0.000
MBond	32	1016.9	31.779	3.64	0.000
Seconds	14	190.2	13.584	1.56	0.084
BW=1	1	121.6	121.564	13.92	0.000
Error	4617	40321.6	8.733		
Lack-of-Fit	2166	24632.9	11.373	1.78	0.000
Pure Error	2451	15688.8	6.401		
Total	4721	48195.9			

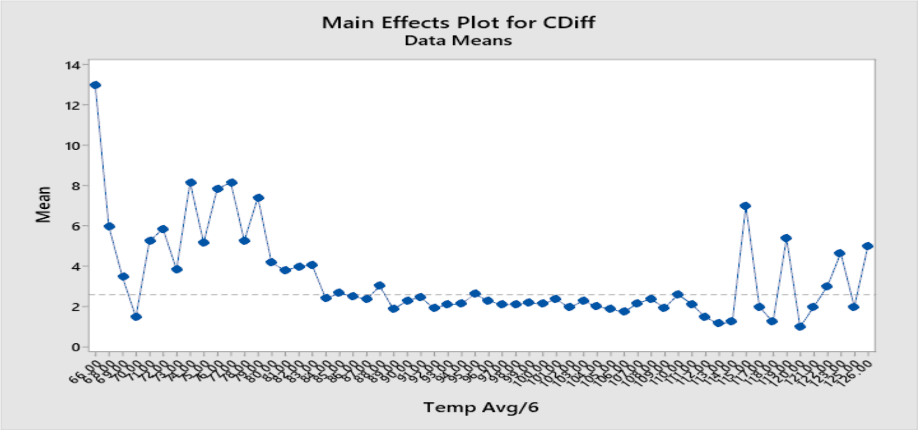

Figure 3. Main Effects Plot

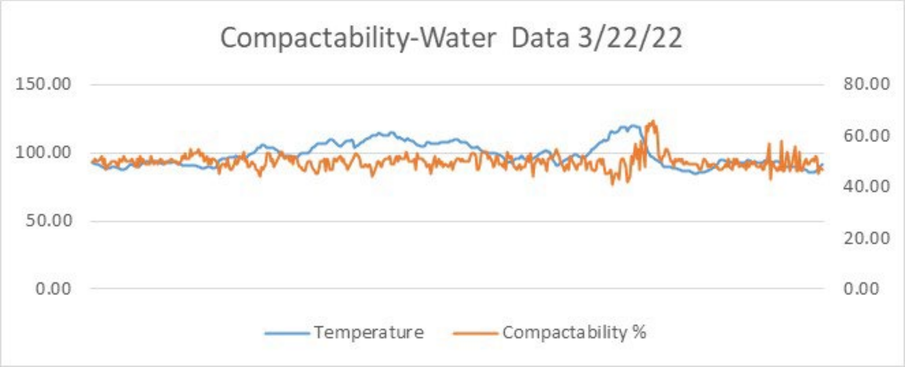

Figure 4. Compactability Water Data

4.3 Variation Analysis

Throughout the course of this project, variation in the ability to hit the target compactability setpoint was observed under varying circumstances. During the analysis of the data, several issues related to equipment malfunctions were noticed and corrected. These were determined to be special causes of variation which could be traced to a particular time and condition of the system. Two of these issues will be discussed within the scope of this project.

Special Cause Variation: It was noted during the month of March that compactability deviation was increasing and compactability was skewed higher on average than the setpoint (Figure 5). Further data analysis showed the incoming sand temperature at the muller was running higher than average and often above the acceptable threshold of 120 degrees Fahrenheit. It was determined that the deviation from the compactability setpoint was highest during times when the temperature increased or decreased rapidly, or when the sand temperature at the muller was greater than 120 degrees Fahrenheit. A closer look at the conditions during these timeframes showed that the higher sand temperature at the muller was occurring due to little to no water addition at the cooler. This was causing the muller and compactability tester to unsuccessfully attempt to control additional variation due to the lack of proper water addition and cooling at the sand cooler.

Proper water addition at the cooler is critical to ensure sand is cooled to a temperature which allows for reuse in the system. While this is a critical function of the system, there is no alarm, only a display, to indicate whether the system is achieving its goal.

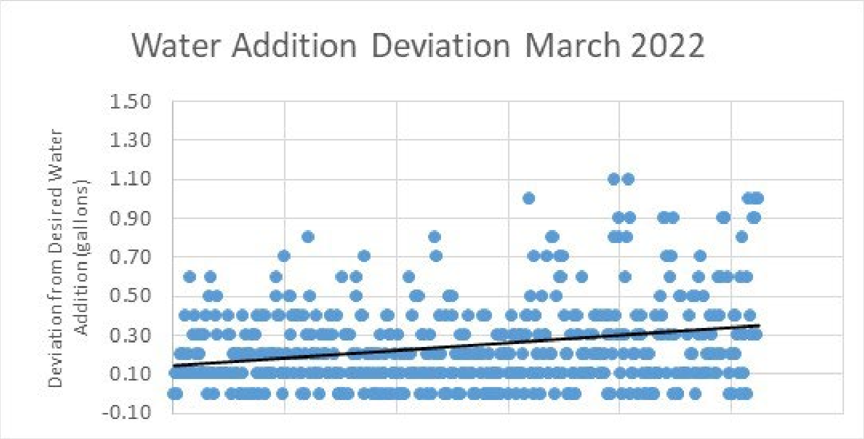

Figure 5. Water Addition Deviation from norm

Another instance of special cause variation that continued to come up throughout the data analysis was during weekly startup of the system. Foundries notoriously dread “Monday morning sand” as it is associated with poor moldability and excess defects in castings. Looking at the incoming sand temperatures at the muller during a startup phase (Sunday night each week), there is a sharp decline in temperature followed by a sharp increase up to “normal” mean operating temperature (Figure 6). This is due to the surge of hot sand from the previous week’s casting process followed by the sand that has cooled over the weekend shutdown, all of which is inconsistent in moisture content.

Figure 6. Temperature during a typical week

The Hartley system cannot properly account for and adjust water additions based on compactability alone in these circumstances, which is apparent in the resultant deviation from the target setpoint during these timeframes. These wild swings in temperature and moisture content of the incoming sand are not currently controlled nor accounted for in the startup process.

Common Cause Variation: Despite other recent changes which adjusted the water correction factor based on the temperature range, which resulted in some level of improvement, sand properties continued to be inconsistent in times of big temperature swings. Figure 7 shows that the largest compactability deviations occur when the sand temperature peaks. These grossly deviated batches produce very wet sand, which has downstream process impacts that result in downtime and scrap castings. Hot, dry sand which has not been properly cooled for re-mulling is the cause of such batches. Currently, the cooler is targeting a specific setpoint of conductivity, regardless of sand temperature, and is allowed to operate and process sand whether the setpoint is met or not. Sand that has not been properly cooled will flow through without issue (until it gets to the muller), while sand that is over-cooled and over-wetted will cause the system to plug up at some stage and result in downtime.

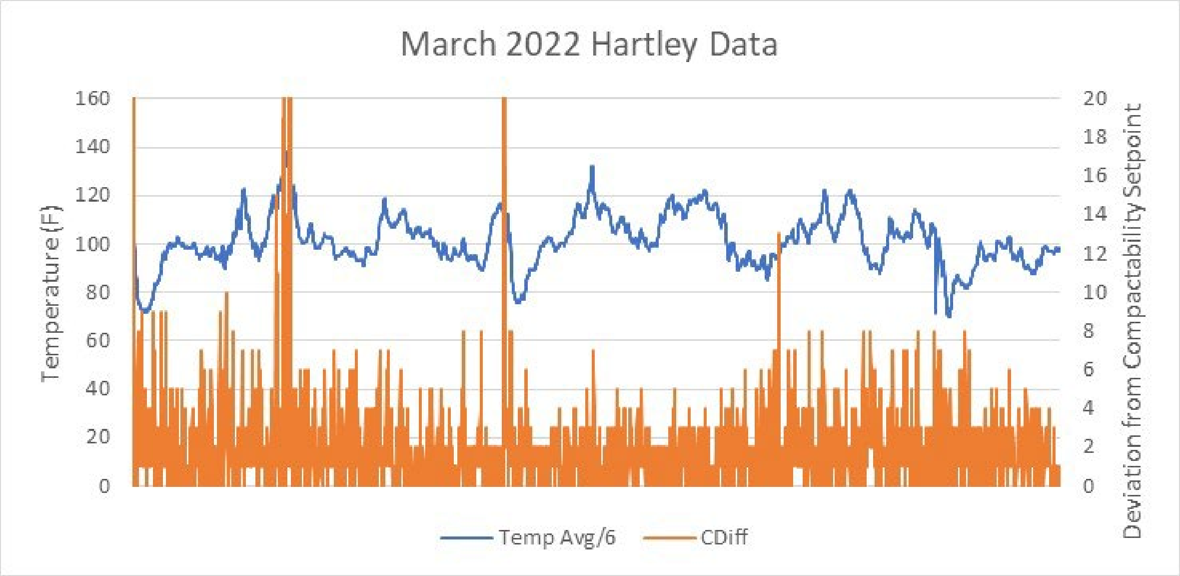

Figure 7. Temperature data and deviation from compactability setpoint

Determining a correct water addition protocol at the cooler is critical to eliminating the downstream hot and cold sand incoming to the muller. Additional adjustments can be made at the muller to incrementally improve the outbound molding sand as well.

4.4 Improve

One of the first changes made was to eliminate the issue of no water flowing to the cooler and implement an alarm system when there was a water flow issue. An investigation by the maintenance team determined that debris from the sand system was the most common reason for the water valves plugging up. This debris would occasionally get into the pipe for the cooler water pump and partially or fully block the valves that add water to the cooler. The cause of the debris getting into the system was undetermined; contaminants were random such as pieces of wood pallets. In order to prevent the debris from entering the water add system for the cooler, a screen was put over the end of the pipe where water is drawn from the tank to feed the cooler.

This screen was set up in the preventative maintenance system to be checked weekly for blockages and damage. In addition to the engineered change, a “low flow to cooler” alarm was put in place to alert users on the HMI that there is an issue with water flow to the cooler. Training was performed with the maintenance team to make them aware of what the alarms mean and how to troubleshoot an alarm if there is an issue. These two changes will help improve the stability of the proper water addition to the sand cooler and therefore condition the sand better, improving the consistency of sand coming into the muller.

To further improve the consistency of the sand coming out of the cooler, the current cooler water addition settings were evaluated. The cooler was not receiving any water when the incoming sand temperature was below 100°F as it was assumed any sand below 100°F did not have the capacity to evaporate water in the system and would lead to the cooler plugging up with wet sand. Small incremental changes were made which allowed the reduction of this baseline temperature down to 80°F. This change has the potential to improve the overall sand properties, with early conditioning of the clays, less dust in the area due to higher moisture sand, and more consistency of the sand arriving at the muller.

In order to control the variation induced by the sand temperature incoming at the muller, two additional options were discussed. The relationship between temperature and water addition rates was determined to be non-linear. A fourth order polynomial trendline was used to generate a quadratic equation with an R^2 value of 0.946 which was highly representative of the water use over the temperature range (Figure 8).

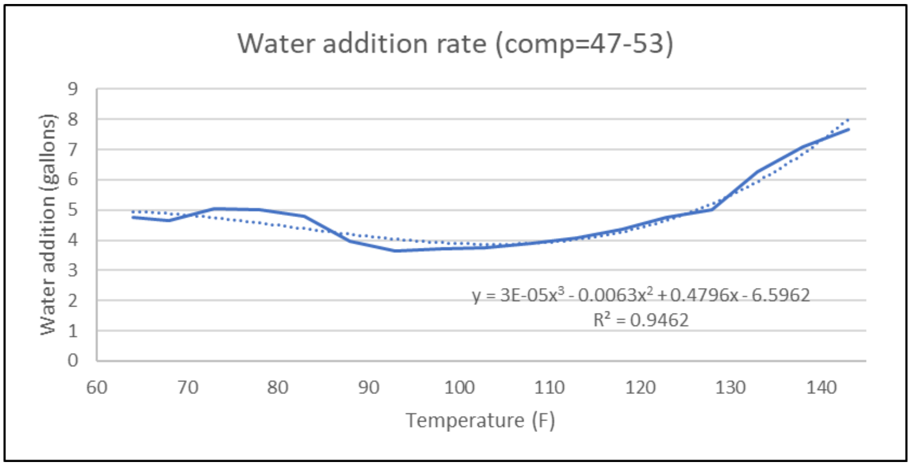

Figure 8. Regression analysis for Water addition and temperatures

The first option for controlling variation due to sand temperature was to update the logic using the above quadratic equation. While this would be the most accurate solution, the programming time required to develop and implement the logic may be beyond the current team’s capabilities. A second solution was discussed which involved adjusting water additions based on the temperature range during each phase (cold/dry, tempered, and hot/dry). Table 3 breaks down the temperature data into four individual ranges, with their corresponding water addition trend, and the proposed water adjustment which was calculated through linear regression.

Table 3. Programming ranges

TEMP	TREND	ADJUSTMENT
<79	STABLE	0.1 GALLON PER 1% COMP
80 TO 90	DECREASING	.144 GALLON PER 1% COMP
91 TO 119	STABLE	0.1 GALLON PER 1% COMP
120+	INCREASING	0.154 GALLON PER 1% COMP

The programming required to implement the proposed water adjustment calculations described in Table 3 was determined to be straightforward compared with the current logic and sufficient to provide additional control over sand output. This will improve the startup sand issue as well as overall sand consistency by accounting for extreme temperatures.

5. Conclusions

5.1 Control

As changes were implemented to the process, percent compactability and deviation from the setpoint were monitored and trended as the most immediate indicator of the success of the changes. This data is collected in real time on every batch of sand made and logged on to an internal server. The feedback is also utilized to determine water additions for the next batch of sand per the new adjustment chart in Table 3. Run charts are available to display data and deviation from the setpoint will trigger alarms and email alerts if there are more than three instances of the result being at least three points from the setpoint. An overview in Figure 9 shows the current typical spread of compactability, a drastic improvement from the compactability percent prior to the implementation of the aforementioned improvements.

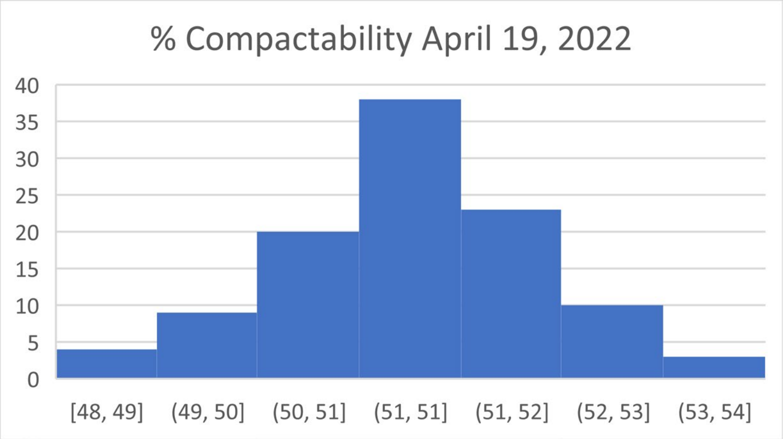

Figure 9. Spread of Compatibility after improvements

Overall system stability was improved, and sand properties have continued to be more stable thanks to the improvements made to eliminate excess variation in the sand cooling and mulling processes. Accounting for the additional variations in incoming sand temperature and moisture have proven to stabilize the percent compactability of sand produced at the muller. Ongoing monitoring through X-bar and R charts as shown in Figure 10 allows us to further narrow down additional factors that can impact sand, some of which are discussed in the future improvements below. The ongoing use of alarms and email alerts has increased the awareness of sand properties among operators and maintenance technicians and allowed issues to be resolved before they lead to excessive downtime or scrap.

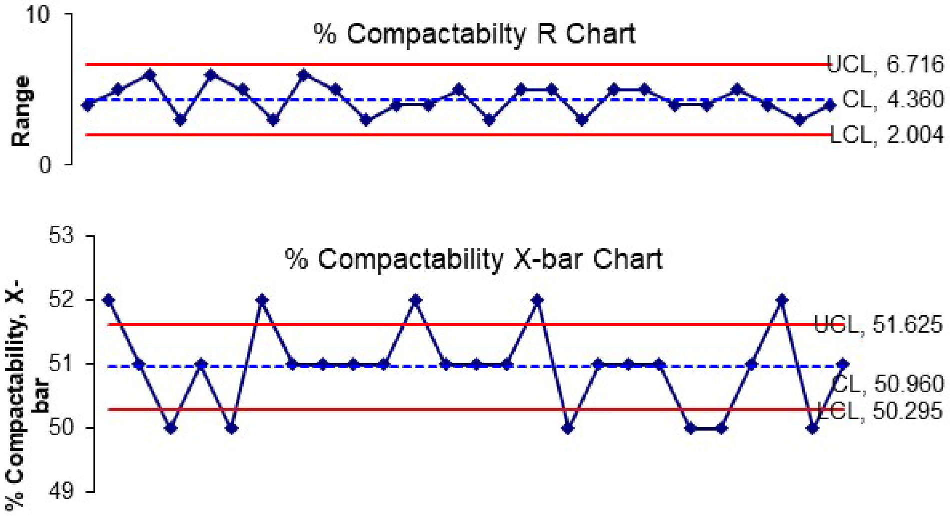

Figure 10. X bar and R charts after the improvements

5.2 Future Improvements

While significant long-term improvements in sand consistency and availability are expected as a result of the changes made, this project helped to identify more variables that could be further controlled. Currently, compactability is tested just after sand is produced. The timeframe between point of sand production and point of use vary depending on rate of production and this impacts the final properties of the sand at the point of use, since sand is losing moisture over time at varying rates depending on the temperature of the sand and the ambient conditions. Other additional variables to consider are the amount of clay added per batch, water temperature, ambient temperature and humidity, and moisture (conductivity) of the incoming sand. Future improvements should consider measuring and controlling these additional parameters which could result in an even higher level of consistency and increased availability.

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Biographies

Ashley Folden-Ecker is working as Process Control Manager at Dotson Iron Castings. She holds a bachelor's degree in chemistry from Minnesota State University Mankato and Master's degree in Engineering Management from

Minnesota State University Mankato. Her research interests are quality management systems, process development, design validation and lean practices.

Dr Kuldeep Agarwal is a professor in the Department of Automotive and Manufacturing Engineering Technology at Minnesota State University Mankato. His research is in the areas of Additive manufacturing, metal forming, process improvements, and robotic welding. He is the graduate coordinator and works with local industries on lean, project manufacturing, and six sigma methodologies.