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Optimizing Clay Addition to Reduce Variability in Green Sand Compactability, Moisture, and Strength

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ABSTRACT

Green sand strength is provided by the bonding strength produced by the water activation of bentonite clay. Maintaining the proper proportion of clay, moisture, and other green sand components is critical for casting quality and is made challenging since material losses during each casting cycle are highly variable. If compactabilities of different samples match, then a comparison of sample moisture and strength can reveal green sand composition changes. Control strategies are applied in automated production systems to adjust bond additions to minimize variations in moisture. Application of optical moisture sensor measurement and understanding of the fundamental relationships between clay, moisture, compactability, and strength form the basis of this control strategy. Clay addition optimization resulted in improved compactability control and reduced variability in moisture and strength.

Keywords: green sand, moisture, compactability, bond, available bond, bond control, sand system control, control tools, green sand properties

INTRODUCTION

Green sand molding is the common method for high production casting operations. Bentonite clay activated by water absorbed inside its structure provides most of the strength in a green sand mold. To provide stable strength properties, the water needs to be in a precise ratio with the clay and other moisture adsorbing materials in the green sand mold. Water impacts most every property of green sand during both molding and casting. High or low moisture is responsible for most sand-related casting defects.[1] Other moisture absorbing materials include cereal or wood flour and the actual sand grains. A significant amount of water is needed to cover the large surface area around finer sand particles. While the clay's water requirement is the largest, the term bond is employed to encompass all the green sand constituents' water requirements.[2]

The proportion of each green sand component lost during the casting process differs from their target proportion in the green sand. Also, losses will differ with different casting products. During each casting cycle, roughly 60 to 90 percent of the water is lost due to evaporation

depending upon the metal temperature, the sand-to-metal ratio, the casting surface area, and other product specific characteristics. Similarly, roughly 5 to 10% of the green sand clay, coal, and other premix materials are lost to burnout or extraction by the dust collection system. Furthermore, sand enters the system from the breakdown of cores and direct new sand additions. These variable losses and additions make adding clay premix into the system to maintain the proper green sand balance a challenging problem. Any green sand composition changes require an adjustment in the moisture level to maintain the proper balance to minimize changes in the sand properties.[1] Finally, the green sand must be fully mixed and mulled with the new additions to maximize the strength of the water-clay bond.

The relationships between water addition, moisture, and compactability are non-linear because the bonding strength between the water and the solid surfaces is variable. Water can be both absorbed onto the outer surface or within a variety of particles with differing chemistries.[1] Research results[3] in Figure 1 show three separate regions where the relationship between compactability and moisture have different slopes. Shih et al.[4] discussed that the inflection points at ~30% and 47.5% compactability are believed to indicate clay layer saturation at 3 and 4 molecular water layers, respectively. Compactability is most sensitive to moisture changes in this region between 30 and 48%.

Compactability is a measure of the water to bond ratio. Thus, in foundry sand processing, a constant compactability with a decrease in moisture suggests an increase in new sand or core sand dilution, while an increase in moisture suggests an increase in clay added.[3] A green sand with matching compactabilities but different moistures must have a different composition in some way.

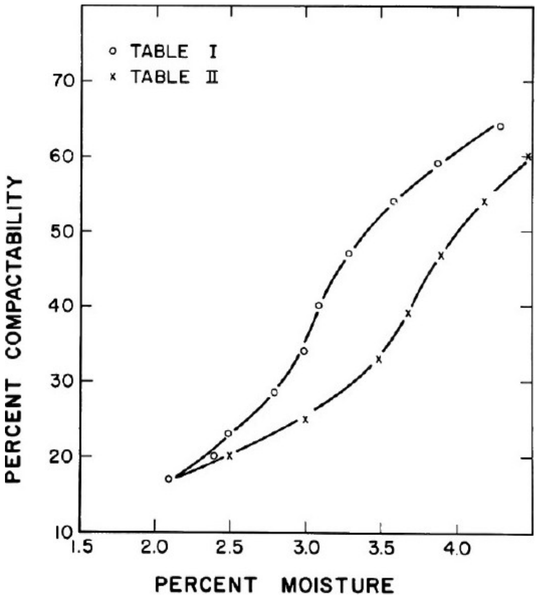

Figure 1. The relationship of compactability to moisture from Heine and Schumaker.[3] (o-sodium/calcium bentonite blend, x-sodium bentonite)

Compactability, moisture, and green compressive strength measurements have been used to determine the bond content and mulling quality using the available bond, working bond, and mulling efficiency calculations.[3,5-9] Frequently, the available bond calculation is used to adjust the clay premix. These measurements can be made quickly and are easily automated, allowing for a more rapid response to sand system changes as compared to a methylene blue (MB) clay test. The relationships between bond, strength, and moisture only apply when the sand is fully mixed and mulled and thus is a necessity for this type of control. A fully mulled sand as one where additional mulling time will have no impact on strength properties.[10]

$$Working\ Bond = \frac{15.29 \times GCS}{(132.1 - Comp)} \quad \text{Eqn. 1}$$

$$Available\ Bond = 0.105 \times GCS + 1.316 \times MST \quad \text{Eqn. 2}$$

$$Mixing\ Effectiveness = \frac{100 \times Working\ Bond}{Available\ Bond} \quad \text{Eqn. 3}$$

GCS is green compressive strength.
MST is percent moisture.
Comp is percent compactability.

The understanding of compactability, moisture, strength, and clay relationships in the operating region is key to optimizing sand system control. Below ~2.5% moisture, the relationship between strength and moisture is close to linear, Figure 2.[11] Above 2.5% moisture, the strength increases with moisture becomes more gradual until it hits a peak and then starts decreasing gradually. A foundry might find it attractive to operate in this flatter region so that moisture variations have a smaller impact on the sand strength.

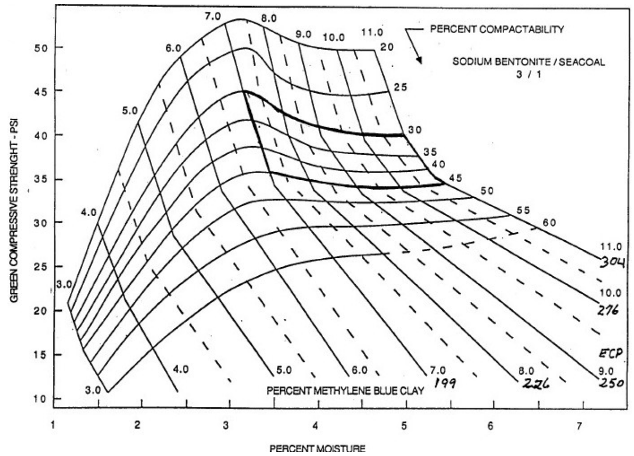

Figure 2. The relationship of green compressive strength, moisture, compactability, and MB clay in fully processed sodium bentonite green sand from Heine.[11]

At a constant compactability, the relationship between strength and clay is close to linear when the clay content is below ~6%, Figure 3.[10] Above ~6% clay, the strength increases with clay becomes more gradual and the strength becomes insensitive to clay content when its concentration is above ~7%. Operating the green sand system such that clay content variations have a small impact on strength may also be attractive. Above 7% clay, strength does remain sensitive to changes in compactability. Consequently, if operating in these regions, clay content will have little impact on strength and controlling bond addition based on the strength or available bond can be troublesome.

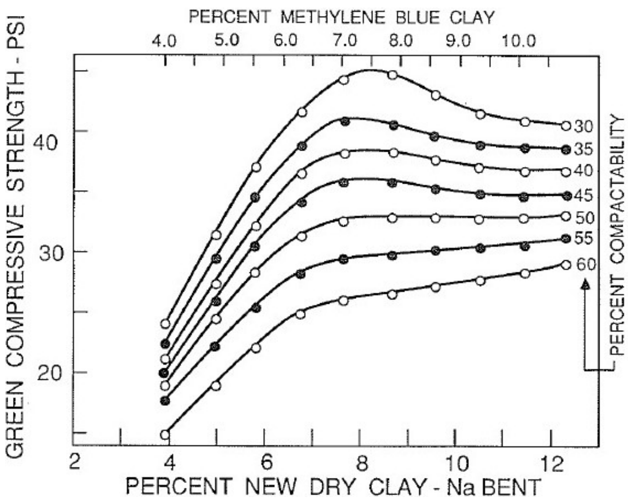

Figure 3. The relationship between green compressive strength, dry sodium bentonite, and MB clay in green sand at constant compactability from fully processed sodium bentonite green sand from Heine and Green.[10]

Quality moisture measurement is crucial. In a previous case,[12] optical moisture measurement exhibited a different sensitivity to moisture changes than conductivity-based measurement (Figure 4[12]) and a sensitivity similar to thermal mass loss moisture measurement. At a fixed compactability, the optical moisture also tracked with changes in clay addition and clay content. At this facility, a different moisture technique offered a more responsive moisture measurement to use for control.

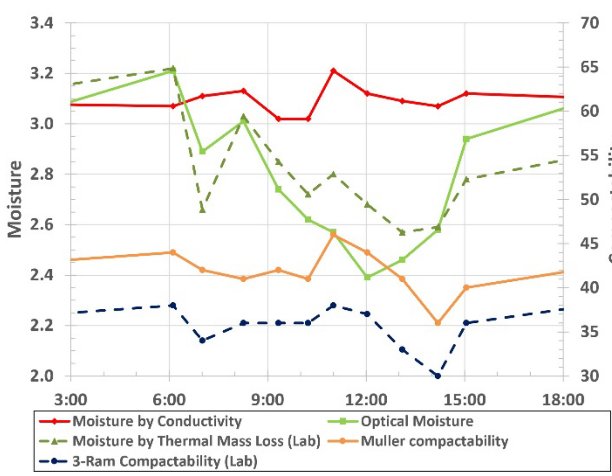

Figure 4. Moisture method comparison at production foundry.[12]

This paper presents the results for production sand mulling operations where water addition is adjusted in a typical method to maintain a compactability target and the bond pre-mix is slowly adjusted to maintain a constant target available bond or moisture. Bond pre-mix adjustment is done slowly by averaging results from many batches and uses only results when the compactability measurement is at or close to its target.

METHODS

Unless specified otherwise, the data reported are from automated sampling and measurement systems standardly provided with muller control systems. Conductivity measures the resistance between two probes immersed in the sand to provide a continuous moisture measurement. The optical moisture measurement method uses the absorbance of near infrared light to determine the moisture levels. This measurement is obtained automatically and continuously with a sensor positioned four to six inches above the green sand moving on a conveyor belt exiting the muller. The thermal mass loss measurement is done in the foundry's laboratory by heating a sample to 220-230F (105-110 C) until the sample weight is constant per AFS 2216-19-S.[13]

Both the conductive and optical moisture measurement instruments are calibrated by using results from thermal mass loss measurement. Conductivity and infrared absorbance changes both correlate to moisture changes. However, as green sand composition changes, the sensitivity of these measurements to moisture changes can be affected. Since these are different techniques, sand composition changes will affect the sensitivity of the moisture correlation differently. Understanding the measurement technique is important because fundamentally the results provide different information.[12]

RESULTS AND DISCUSSION

Proper mulling and good compactability control come first as a necessity to good green sand properties and stability but are not sufficient to maintain consistent strengths and moisture. Foundry X uses traditional compactability control for its water adjustment and automatically adjusts its bond pre-mix addition to an available bond target calculated from the control system's measurement of strength and moisture (conductivity method). The muller batch size is 3100 pounds with a mulling time of 95 seconds. The bond adjustment rate is at its slowest setting. During the period depicted in Figure 5, compactability control was 77% +/-1, 94% +/2, and 98% +/3. The change in bond addition is gradual enough that the water addition adjusts to the different bond content well and good compactability control is maintained. However, the bond addition amounts alternate between the extremes of 1 and 7 resulting in green strength measurements ranging between ~17 and 25. The minimum and maximum additions resulted in associated large changes in the green strength. At this facility, it takes ~1 day for the strength to respond to bond addition changes at the typical production rate of ~140 batches per day.

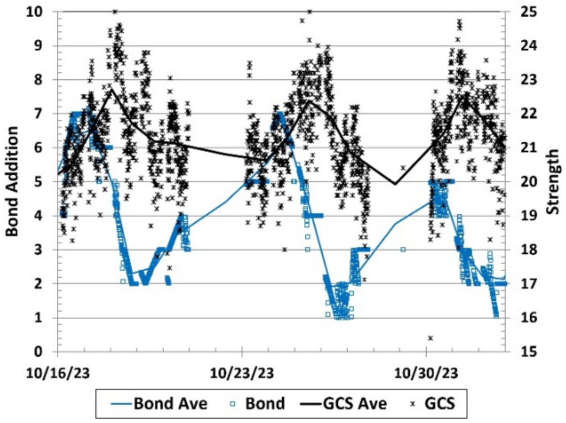

Figure 5. Bond additions and strengths at foundry X with averages representing 100 batches.

The overcorrection could possibly be attributed to insensitivity of the conductive-based moisture and/or the strength measurements being insensitive to the bond concentration in this operating region. Only when the bond and/or moisture move well outside the design parameters do these measurements change enough to trigger adjustments in the bond addition. Adding to these control difficulties is the long time it takes for the sand to go through the casting cycle and return to the muller. Like most foundries, the sand batch represents a small fraction of the total sand in the system, so any change in the bond pre-mix addition takes a long time to change the green sand bond content. Without adjusting the logic of control, the strength variation could be mitigated by narrowing the range between minimum and maximum bond additions after analyzing system operation. Foundry X could be better served by restricting the bond additions between 3 and 5.

Two different approaches to adjusting bond addition were used to improve green sand control. In the first case (Y), the system still adjusts bond to an available bond target but used the optical moisture measurement in calculating available bond. In the second case (Z), the bond adjusts to a moisture target for a given compactability after determining that the green sand is operating where strength is insensitive to changes in bond. In both cases, the manager will adjust targets according to laboratory results (MB clay, strength, etc.) and according to casting part requirements.

Foundry Y uses traditional compactability control for its water adjustment and automatically adjusts its bond pre-mix addition to an available bond target calculated from the control system's measurement of strength and conductivity-based moisture. The muller batch size is 4700 pounds with a mulling time of 50 seconds. In its available bond calculation, Foundry Y switched from the conductive moisture to an optical moisture measurement resulting in improved compactability control (Figures 6 and 7), reduced moisture variability (Figures 8 and 9), and reduced strength variability (Figures 10 and 11). Representative one-week production periods of 2000 batches are compared in these Figures and improvements were maintained after the reported period.

The reduced moisture and strength variability suggests that a more consistent sand composition may have made it easier to adjust water to maintain compactability. In contrast to the reduced strength variability, the MB clay (Table 1) did not see a significant change in variability which may be a result of the inherent variability of the MB clay test, infrequency of testing, operating where strength is insensitive to MB clay, or some other factor.

Table 1. MB Clay at Foundry Y (20 samples each period)

	June 12-16,2023	December 4-8, 2023
Minimum	8.3	8.3
Maximum	10.0	9.5
Average	9.00	9.07
Std. Deviation	0.376	0.359

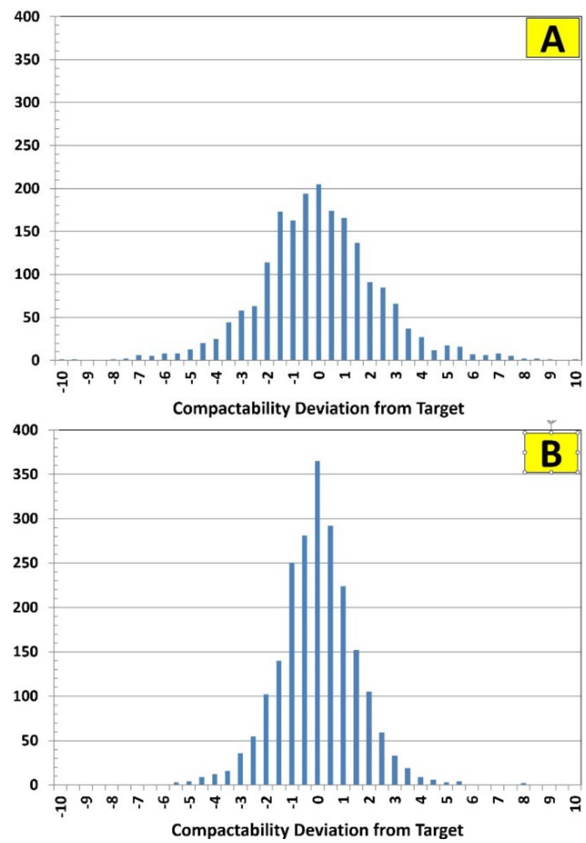

Figure 6. Compactability control histograms comparing one-week periods before (A: June 12-16, 2023) and after (B: December 4-8, 2023) control change at foundry Y.

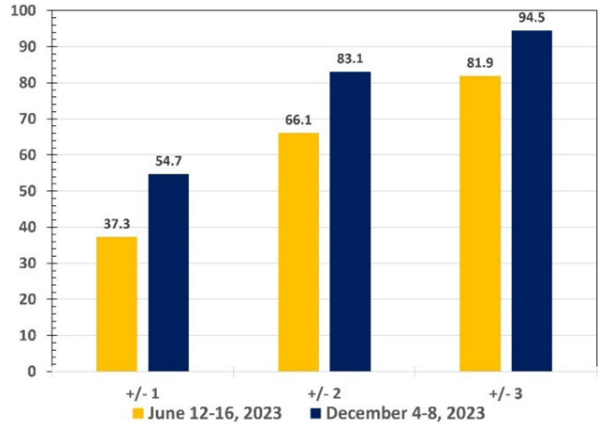

Figure 7. Compactability control comparison summary at foundry Y.

Bond additions range from 10 to 60 pounds per batch during both periods with the strength range narrowing after the control adjustment (Figure 12). The strength reacts ~4 hours after a bond addition change.

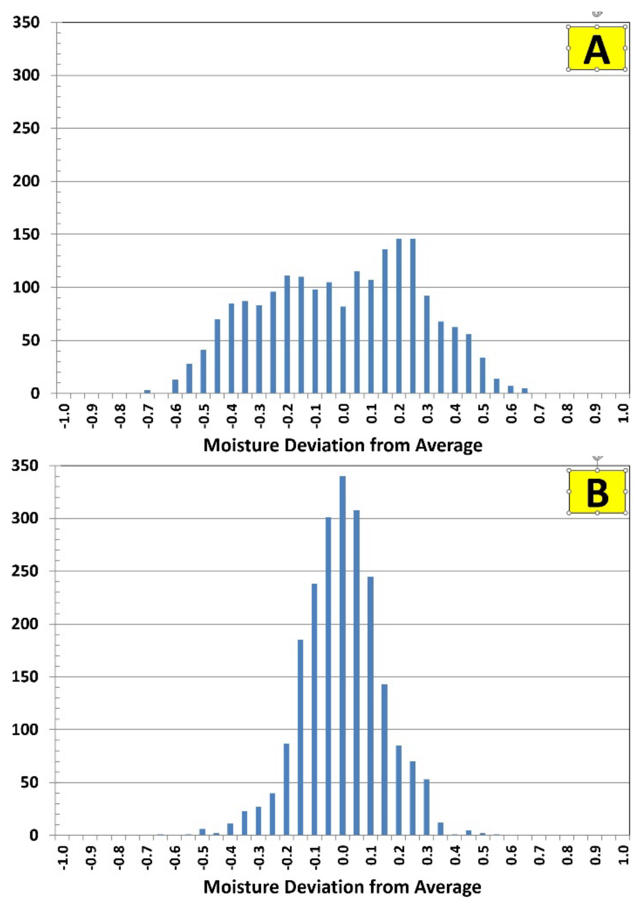

Figure 8. Moisture histograms comparing one-week periods before (A: June 12-16, 2023) and after (B: December 4-8, 2023) control change at foundry Y.

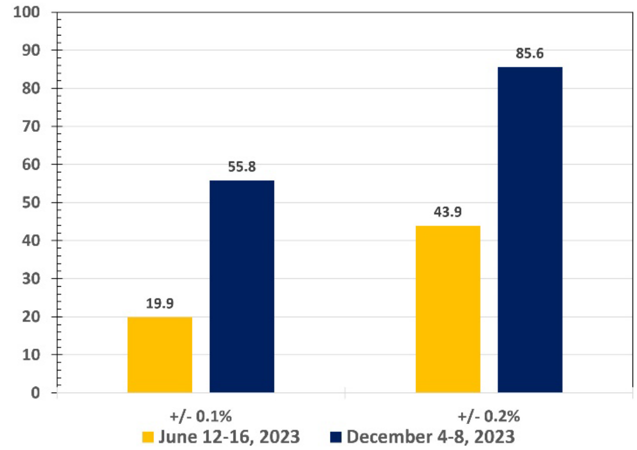

Figure 9. Moisture variation from average comparison summary at foundry Y.

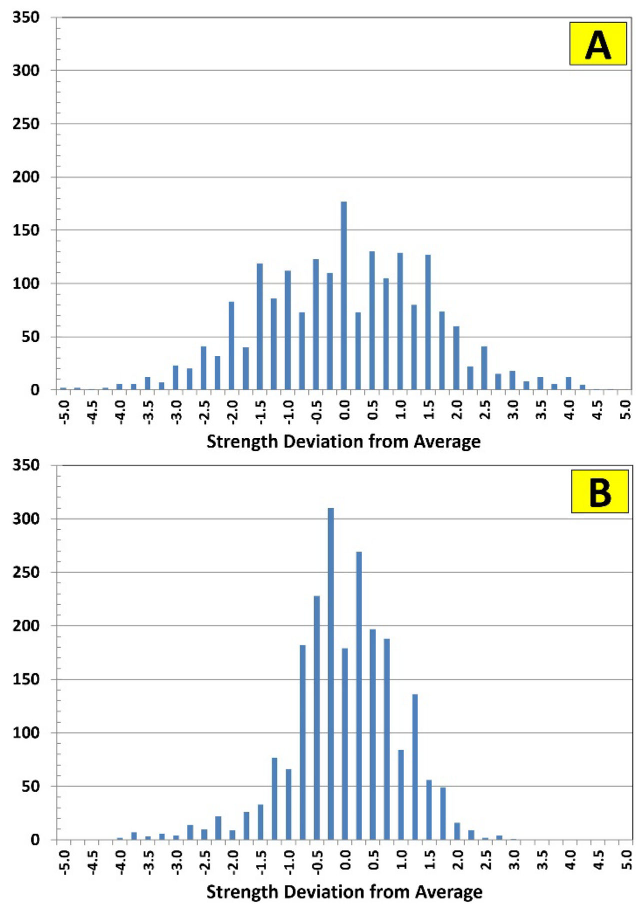

Figure 10. Strength histograms comparing one-week periods before (A: June 12-16, 2023) and after (B: December 4-8, 2023) control change at foundry Y.

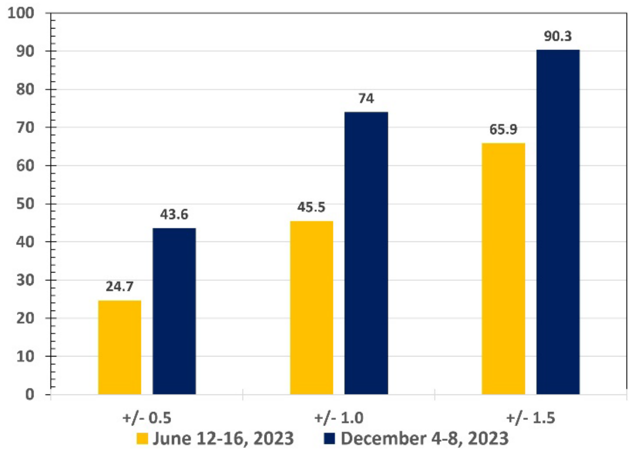

Figure 11. Strength variation from average comparison summary at foundry Y.

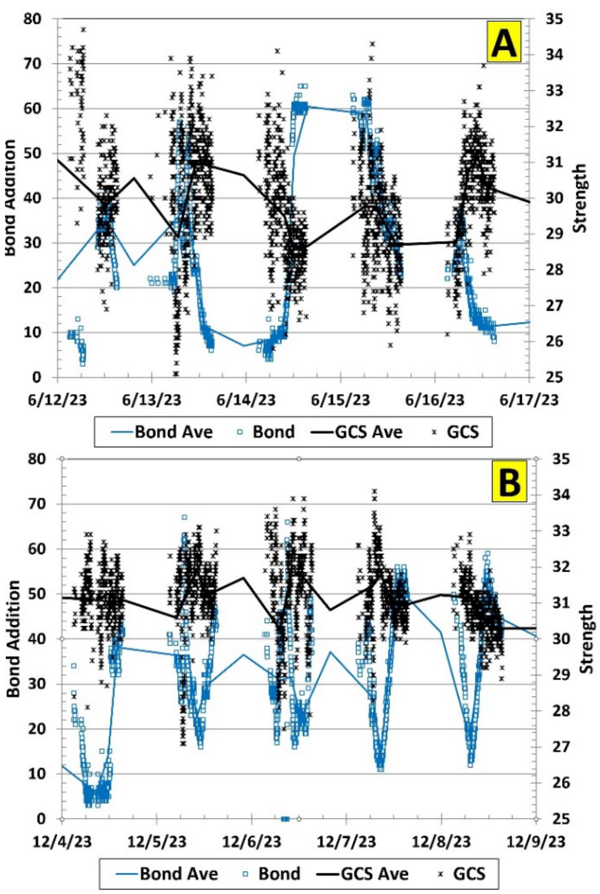

Figure 12. Bond additions and strengths at foundry Y with averages representing 100 batches.

Foundry Z uses compactability control for its water adjustment and was automatically adjusting its bond pre-mix addition to an available bond target calculated from the control system's measurement of strength and conductivity-based moisture. For the February and October 2023 data, the batch weight was 4500 pounds with an 80 second mull time. Subsequently, the batch weight was increased to 5000 pounds with the same 80 second mulling time (August 2024 data).

Figures 13 and 14 show the improvement in compactability control at foundry Z. Initially, Foundry Z improved its compactability control by simply slowing the bond adjustment (February to October 2023). In the next step, the system adjusted bond addition to a moisture target based upon averaging the optical moisture measurements. The minimum bond addition was also raised from 10 to 30 pounds per batch. Representative one-month production periods of 1000 batches are compared in these Figures with histograms only comparing the period before and after the conceptual change in the second step.

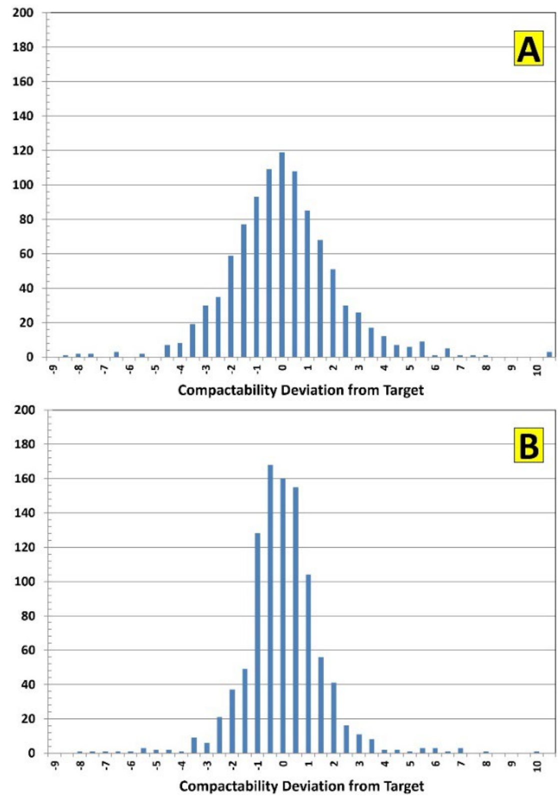

Figure 13. Compactability control histograms comparing one-month periods before (A: October 2023) and after (B: August 2024) conceptual control change at foundry Z.

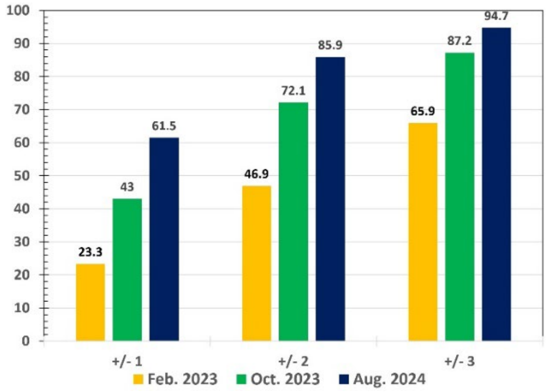

Figure 14. Compactability control comparison summary at foundry Z.

This second change reduced the variability in moisture (Figs. 15 and 16) and provided further compactability control improvements. The reduced moisture variability is a direct result of deliberately adjusting bond to a target moisture and makes these results a simple confirmation that the control system is working as designed. Nonetheless, maintaining a tighter moisture window is attractive for reducing moisture variability at casting. The strength variability did not change significantly (Figs. 17 and 18). Note that before any changes were made, the strength variability for foundry Z was already low relative to the other foundries studied.

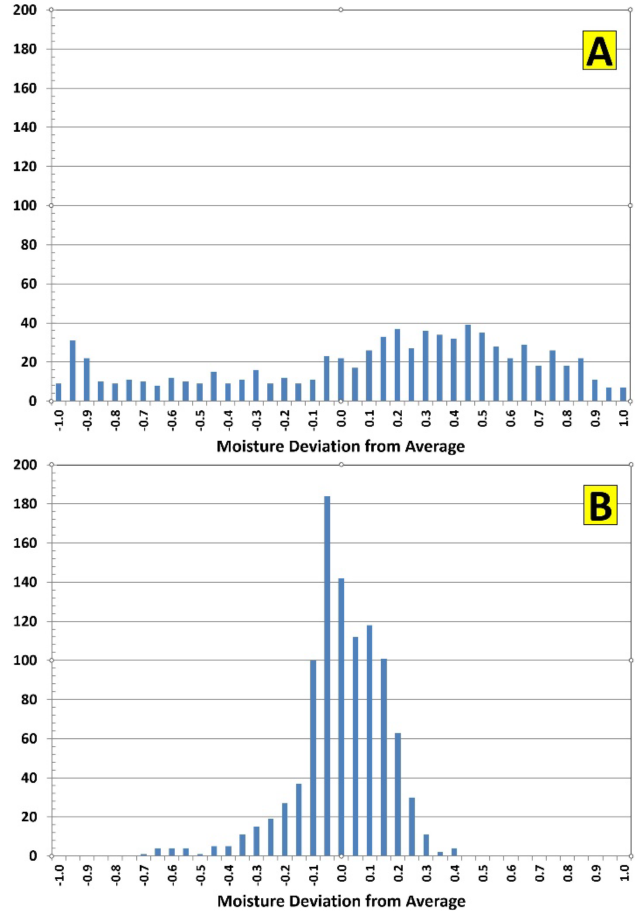

Figure 15. Moisture histograms comparing one-month periods before (A: October 2023) and after (B: August 2024) conceptual control change at foundry Z.

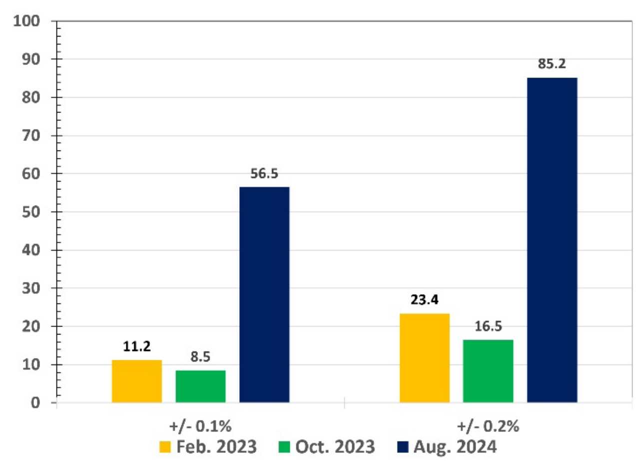

Figure 16. Moisture variation from average comparison summary at foundry Z.

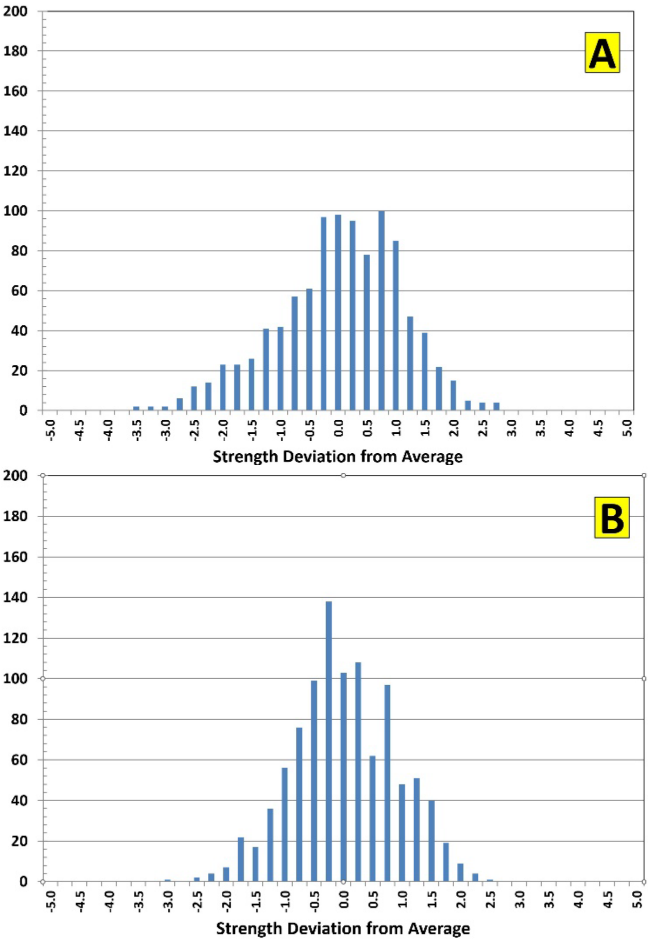

Figure 17. Strength histograms comparing one-month periods before (A: October 2023) and after (B: August 2024) conceptual control change at foundry Z.

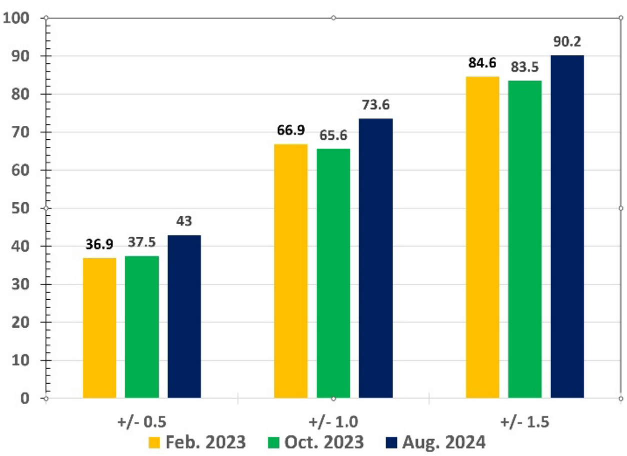

Figure 18. Strength variation from average comparison summary at foundry Z.

Foundry Z tested MB clay once per week which was deemed too infrequent to assess any variability changes. Over a one-year period, Foundry Z's MB clay averaged 8.75 with a standard deviation of 0.729.

Bond additions at foundry Z range from 10 to 90 pounds per batch prior to control change and from 30 to 90 pounds per batch after control change. (Figure 19). The strength reacts ~1 to 2 days after a bond addition change reflecting a much slower processing rate of ~60 batches per day at foundry Z

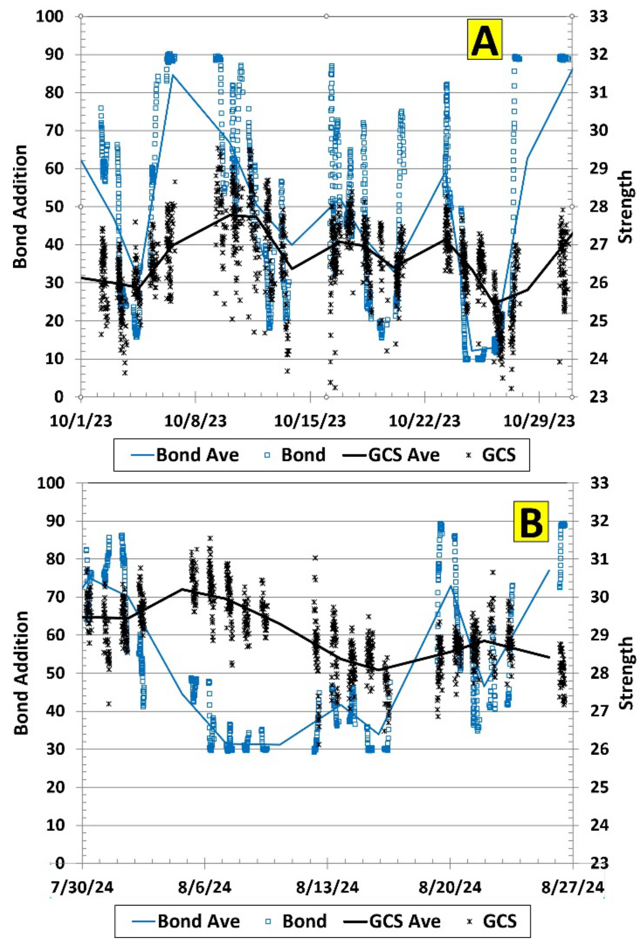

Figure 19. Bond additions and strengths at foundry Z with averages representing 100 batches.

CONCLUSIONS

Good compactability control can be achieved with proper adjustment of water addition but does not guarantee good moisture or strength control. To minimize green sand variability, a manager needs to understand the fundamental relationships between clay, moisture, compactability and strength as well as the particulars where his/her sand system operates within this context. This paper provides two examples of production sand systems that have improved their compactability control and reduced the moisture and/or strength variability by using new strategies in the bond pre-mix addition. These strategies involve understanding where the sand system operates, understanding the measurement techniques, and how they both react to changes.

Foundry Y replaced conductivity-based moisture with optical moisture measurement in its available bond calculation used to adjust its bond pre-mix additions. This change improved compactability control by ~15%, reduced moisture variation by ~40%, and reduced strength variation by ~25%. Foundry Z reduced the bond pre-mix adjustment rate, narrowed the allowable bond pre-mix range, and switched from using available bond to an optical moisture target in adjusting bond pre-mix addition. All these changes improved compactability control by ~35% and reduced moisture variation by ~55%

The sand control principles can be applied generally in both manual and automatic adjustment of bond additions as follows:

1. Ensure proper mulling: equipment is maintained, and mulling time is sufficient.
2. Ensure proper compactability control: sampling equipment is operating properly, water measurement accurate and precise.
3. Review the history of how the sand properties react to different amounts of bond addition to adjust and narrow the range of permissible bond additions accordingly.
4. Upgrade and update moisture measurements both automatic and laboratory. Upgrade could mean a more precise thermal mass loss measurement in the laboratory or a different automatic measurement technique. Update by more frequent calibration of moisture measurement instruments.
5. Identify the properties such as moisture and compactability necessary for good casting and manipulate the additions to minimize the variabilities in these properties.
6. The speed of bond addition adjustments needs to account for how fast sand circulates through the system.

Understand that many green sand properties are moisture dependent, so it is most useful to compare different samples that have either matching compactability or moisture. While MB clay results remain useful for control, understand its limits of sample frequency, test precision, and variable sensitivity to other green sand properties.

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