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Enhancing Indian Bentonites for Foundry Green Sand Applications with the Addition of Minerals from India

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ABSTRACT

India has the second-largest metalcasting production in the world, with green sand molding as one of its predominant processes. Naturally occurring Indian bentonite has been used successfully for many years. Enhancing these bentonites to produce high-quality metal castings and reduce bond consumption by adding naturally occurring minerals has proven successful.

Keywords: green sand molding, bentonite, India

INTRODUCTION

Green sand molding operations, a globally prevalent process in the foundry industry, rely extensively on foundry-grade bentonite as the primary bonding mechanism. These naturally occurring minerals are mined and processed worldwide. The AFS publication, “Green Sand Additives,”[1] provides a comprehensive guide to the types of bentonites used. The three primary bentonites used are naturally occurring sodium, calcium, and modified bentonites, selected based on availability and geological sourcing in a specific country. The global importance of the green sand molding process underscores the need to understand the unique mineral compositions of bentonites from different regions.

Bentonite clays, in general, are primarily composed of the mineral montmorillonite. When referring to a naturally occurring sodium or calcium bentonite, the authors refer to the primary cation found in the geological ore mined in a specific deposit. Due to their natural occurrence, these materials contain varying quantities of cations, including sodium, calcium, magnesium, potassium, etc. This variability is why the "Modified Bentonites" section is referenced in the green sand additives publication.[1]

Based on availability, foundries worldwide can use blends of the available foundry-grade bentonites to meet specific foundry processes, considering factors such as metal type, molding machine operations, mixing/muller process, and many others.

TYPICAL BENTONITE COMPOSITIONS

The typical analysis of various bentonites has been in multiple publications for many years. In 2015, a detailed comparison of bentonites was published at the Indian Foundry Conference.[2] Based on this information, various bentonites are compared with X-ray fluorescence (XRF) analysis to understand the unique characteristics of foundry-grade bentonites. Table 1 compares foundry-grade bentonites from different mining districts around the world.

INFLUENCE OF MINERALOGICAL IRON IN INDIAN BENTONITE

One material that stands out in foundry-grade Indian bentonite is the iron oxide content. In the 2015, Indian Foundry Conference (IFC) paper, it was pointed out that Bentonite I (Indian) have a high iron content compared to Bentonite G (Greek) due to the available Fe-ions during the geological formation.

Iron is, on the one hand, part of associating minerals, e.g., hematite (Fe_2O_3), maghemite (γ-Fe_3O_3), and iron hydroxide such as goethite (FeOOH) (Figure 1). On the other hand, the iron can be found inside the predominate smectite clay of Bentonite I (Indian) as a part of the crystal structure, mainly the octahedron. This results in a different thermal behavior than Bentonite G (Greek) with a lower iron content.[2] This composition within the Indian bentonite will influence the metalcasting process during pouring, cooling, and shakeout.

Table 1. Bentonite and Ball Clay Compositions Analysis with XRF

Bentonite	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	LOI (%)
Indian	50.3	18.2	1.25	14.49	2.67	1.7	3.14	0.1	8.15
Modified Greek	55.2	17.5	0.74	5.17	3.83	4.8	2.92	0.8	9.15
Naturally Occurring Sodium, Wyoming	56.68	20.14	0.17	5.74	3.55	2.48	2.65	0.52	8.08
Naturally Occurring Calcium, Mississippi	61.82	17.25	0.82	4.93	3.31	3.36	0.28	0.75	7.49
Ball Clay	55.3	29.8	2.54	0.72	0.06	0	0	0.3	11.3

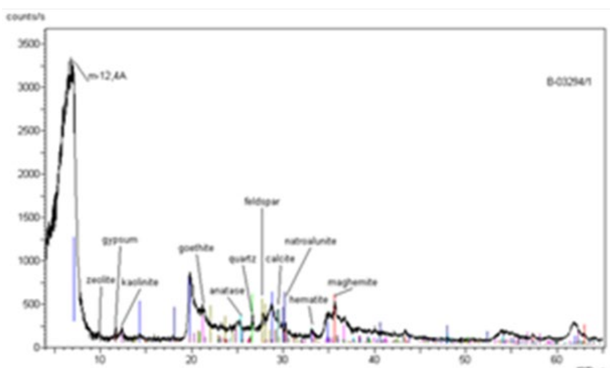

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Figure 1. The XRD mineralogical composition of Indian bentonite.

In the 2015 paper on Indian and European bentonites,[2] it was pointed out that when Thermogravimetry Differential Thermal Analysis (TG/DTA) is carried out, the effect of this elevated iron content is clear. At approximately 280C (536F) (DTG- peak 258.4C /497F), an endothermic reaction resulting from the decomposition of the hydroxides is visible as a mass loss on the TG-curve (Figure 2). The next endothermic reaction releases OH-groups inside the smectite structure, the so-called de-hydroxylation. The temperature range results from the iron inside the octahedron and the localization of these OH groups. The de-hydroxylation in Bentonite I (Indian bentonite), the loss of OH-groups, occurs at lower temperatures, and this irreversible process eliminates clay binding properties. The maximum de-hydroxylation speed (dG/dt) is at approximately 483C (901.4F). Due to the lower iron content inside Bentonite G (Greek bentonite), the de-hydroxylation happens at higher temperatures; the dG/dt maximum is around 720C/1328F (Figure 3). Figure 4 clearly shows the fast de-hydroxylation of Bentonite I (Indian) compared to Bentonite G (Greek).

By blending Bentonite I with Bentonite G in various proportions, improved thermal stability and performance can be created to that of 100% Bentonite G (Greek).

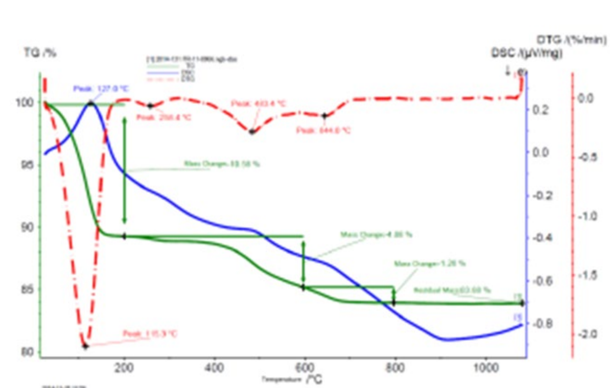

Figure 2. Thermal Analyses of Bentonite I (Indian).

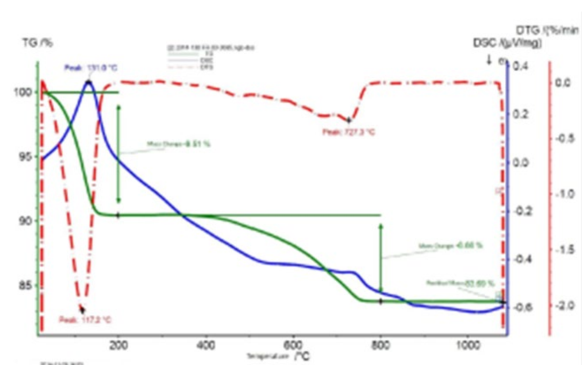

Figure 3. Thermal Analyses of Bentonite G (European bentonite).

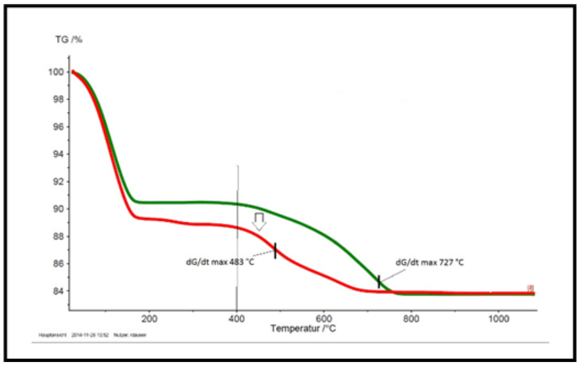

Figure 4. Mass loss of Bentonite I (red) and Bentonite G (green). Bentonite I has a much faster de-hydroxylation, resulting in an irreversible destruction of bentonite properties.

Color is often used to illustrate the mineralogical characteristics of bentonites to understand the unique differences between the various bentonite materials mined and processed. Bentonites occur in many uniquely different colors. Considering the various iron levels in bentonite, the higher iron levels can result in yellow to red characteristics (Figure 5) compared to other bentonites that can be gray to lighter colors (Figure 6).

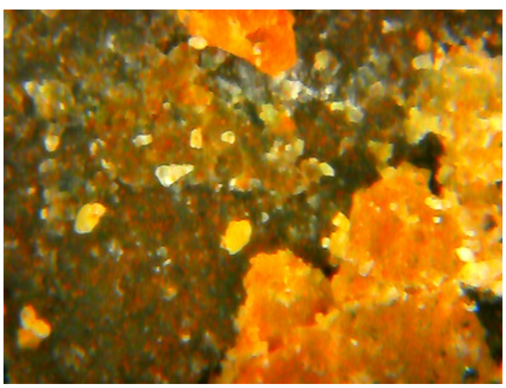

Figure 5. Unprocessed iron-rich bentonite ore at 35x magnification.

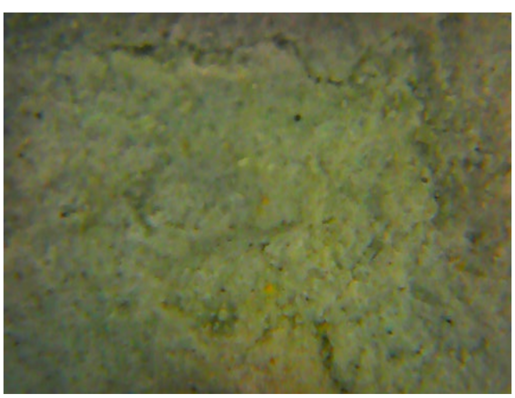

Figure 6. Unprocessed bentonite ore at 35x magnification.

MINERAL BLENDING TO ENHANCE FOUNDRY GREEN SAND OPERATIONS

The 2015 paper highlighted the benefits of blending two unique bentonite materials in varying ratios to enhance green sand molding operations in Indian Foundries (Indian and Greek).[2] The foundry industry in India has successfully blended various ratios of bentonite from different continents for many years. One of the predominant blends is Indian bentonite and Wyoming bentonite. The disadvantage to blending bentonites from other continents is not molding sand performance but economical. The cost of shipping, base material, etc. Therefore, this paper will utilize local materials from India to enhance molding sand performance in green sand foundries, resulting in the benefit of localized shipping and improved economics.

BLENDING BONDING CLAY INTO BENTONITE AS THE BINDING MECHANISM FOR GREEN SAND

Different clays have been blended successfully into green sand molding operations for many years. One of the earliest references to this concept is in the AFS book, "Foundry Sand Practice," by Clyde Sanders.[3] In Sanders' book, these blended clays are called "bonding clay." Based upon multiple foundry references, three primary clays, fireclay, China clay, and ball clay, have been used successfully in green sand foundry operations when blended at varying levels with bentonite clay.[3]

Wikipedia defines fireclay as a range of refractory clays used in the manufacture of ceramics, especially fire brick. The United States Environmental Protection Agency defines fireclay very generally as a "mineral aggregate composed of hydrous silicates of aluminum ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) with or without free silica. Fireclay is resistant to high temperatures, having fusion points higher than 1,600C (2,910F); therefore, it is suitable for lining furnaces, as fire brick, and for the manufacture of utensils used in the metalworking industries, such as crucibles, saggars, retorts, and glassware. Its stability during firing in the kiln means that it can be used to make complex items of pottery such as pipes and sanitary ware.

Wikipedia defines rocks that are rich in kaolinite, and halloysite, are known as kaolin or China clay. In many parts of the world, kaolin is colored pink-orange-red by iron oxide, giving it a distinct rust hue. Lower concentrations of iron oxide yield the white, yellow, or light orange colors of kaolin. Kaolin is an important raw material in many industries and applications.

Wikipedia defines ball clays as kaolinitic sedimentary clays that commonly consist of 20–80% kaolinite, 10–25% mica, and 6–65% quartz, along with small amounts of organic matter (such as lignite) and trace amounts of other minerals, such as pyrite and siderite. They are a common raw material for various types of ceramics, where their primary roles are to impart unfired strength and plasticity or to aid rheological stability during the shaping processes. Most ball clays impart colors ranging from buff to cream to off-white when fired in an oxidizing atmosphere.[4]

Table 1 contains a typical composition analysis with XRF on ball clay, and Figure 7 is a thermal analysis of ball clay.

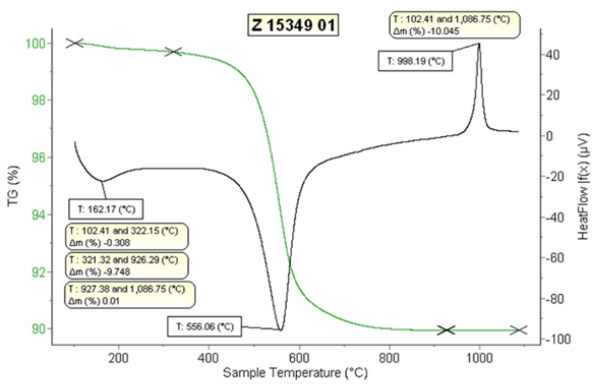

Figure 7. Thermal analysis of ball clay.

Additional information about ball clay from Sanders' book has been shared:

"*…they have high fusion points over 3092 F (1700 C) and most generally possess small amounts of organic materials. The small mineral crystal size of ball clays, compared to plastic fireclays and kaolin, impart their greater bonding power to them. The structure of the crystals is also slightly different from that of plastic fireclays.*

Sanders also pointed out that:

Kaolinite clays as a mineral group are generally characterized by possessing high refractoriness unless they are contaminated with lower fusion minerals. They have relatively lower green bonding properties than bentonite in foundry sand mixtures. Kaolinites are one of the following three main types: fireclay, ball clay, and China clay."[5]

The addition of these different bonding clay types has allowed the foundry industry to utilize different characteristics contributed by blended clay technology. Table 2 references the quantity of blended clays that have been successfully used in green sand molding operations.

Table 2. Comparison of Bonding Clays

Mineral	Maximum Volume Clay Blend with Bentonite	Methylene Blue Uptake
Fire Clay	10%	Minimum
China Clay	15%	Minimum
Ball Clay	30%	Minimum

A critical consideration for successfully integrating these clays is monitoring the volume of material introduced into the green sand molding system. The concept is referred to as "mass balance" since the bonding clays have a minimal methylene blue titration uptake, which is the primary method for monitoring the volume of clays utilized as the bonding mechanism in green sand molding operations. This technique is documented and easy to apply.[6]

Since this paper focuses on integrating Indian ball clay with Indian bentonite, a focus on a specific volume of ball clay is to be reviewed compared to the maximum volume of clay that can be blended with bentonite. In 2021, a US Patent was issued that explains in detail the application of ball clays with various bentonites for foundry applications worldwide. The table in the patent references the volume of ball clay at 30%.[7] In this paper's investigation, the laboratory and casting information will report levels between 5 and 10% for this evaluation of Indian bentonite and Indian ball clay.

APPLYING MINERALOGICALCHARACTERISTICS TO FOUNDRY GREEN SAND MOLDING

Two protocols were completed to evaluate green sand molding sand with various clay types as the bonding mechanism with seacoal in relation to foundry casting performance. The first protocol involves preparing a green sand mixture with seacoal in a simulated durability study. The second protocol involved producing castings at the University of Northern Iowa with information developed in the first protocol.

PROTOCOL 1: SIMULATED GREEN SAND MOLDING EVALUATION

Most foundry research facilities and universities focusing on foundry research have the equipment and trained personnel to complete this protocol. This protocol differs from traditional evaluation methods because the procedure evaluates a prepared green sand molding mixture. Historical durability testing is based upon bentonite only in a furnace for thermal characteristics, which is then mulled/mixed with silica sand (without seacoal or carbonaceous materials) to evaluate changes in green sand properties.[8]

Protocol 1 prepares complete molding sand that contains the bonding mechanism, organic additives (seacoal), silica sand, and water before thermal exposure. This is important because it comes closer to the metalcasting process in foundries.

Preparation and Thermal Exposure Methodology

1. Prepare 2000 grams of molding sand using a 63 AFS GFN 4-screen silica sand with a clay binder volume of 9% and 1.8% seacoal.
2. The prepared sand is mulled for 7 minutes at 45% compactability in a lab muller. (Figure 8)
3. Remove the prepared molding sand from the muller and evaluate this prepared mixture as the baseline database according to the current AFS "Mold and Core Test Handbook." These tests include moisture, compatibility, specimen weight, wet tensile strength, green compression strength, green shear strength, permeability, and dry compression strength.
4. For the subsequent evaluation, add the prepared baseline sand into a cast iron Dutch oven by packing and filling consistently. A #10 Dutch oven with legs (4 quart/3.8 Liter–10-inch diameter/25 centimeter) is used because it will fit correctly into the furnace chamber) with a cast iron lid. (Figures 9 and 10)
5. The Dutch oven with a lid containing the prepared molding sand is placed into the furnace for 2 hours at 550C/1022F. (Figures 11 and 12)
6. Remove the Dutch oven with the lid from the furnace and allow it to cool to room temperature.
7. Remove the lid and take a photo of the prepared sand mixture because a visual comparison is valuable for observing the clay and seacoal decomposition. (Figure 13)
8. Remove and homogenize the prepared molding sand and evaluate its methylene blue content to add the preblend to correct the burned-out minerals at the muller for the next testing cycle.
9. Return the prepared molding sand exposed to the high temperature to the muller. Add the required clay binder, seacoal, and water to develop a 45% compactability for a 7-minute mulling cycle.
10. Remove the prepared molding sand from the muller and evaluate it according to the test procedures in the current "AFS Mold and Core Test Handbook." These tests include Moisture, Compatibility, Specimen Weight, Wet Tensile Strength, Green Compression Strength, Green Shear Strength, Permeability, and Dry Compression Strength.
11. This is the completion of one cycle of the durability study.
12. Four cycles were completed to evaluate the investigated clay binder and seacoal performance for this investigation.
13. No new sand was added during the investigation because there was no significant loss of prepared sand.

Figure 8. The prepared sand is mulled in a laboratory muller.

Figure 9. Empty #10 Dutch oven. Figure 10. Full oven.

Figure 11. The furnace. Figure 12. Furnace interior.

Figure 13. The Dutch oven with sand after heating.

Utilizing Protocol 1 to Evaluate Blends of Indian Bentonite and Indian Ball Clay

Two formulas and a baseline were evaluated using the simulated durability protocol. Table 3 shows the three formulas evaluated.

Table 3. Comparison of Bonding Clay Formulas

	Indian Bentonite %	Indian Ball Clay %	Seacoal
Baseline	80	0	20
Preblend 1	75	5	20
Preblend 2	70	10	20

Each mixture completed four cycles. Photographs were taken at the end of each heating cycle as a general observation. Figures 14 to 17 are visual representations of this investigation.

Figure 14. First Cycle.

Figure 15. Second Cycle.

Figure 16. Third Cycle.

Figure 17. Fourth Cycle.

The first evaluation in the testing protocol is the concept of consumption of clay binder and seacoal required to replace the materials consumed in the thermal exposure (Figure 18). This is determined by the methylene blue clay titration of the Indian bentonite and a mathematical correction for the Indian ball clay of either 5% or 10% (based upon the preblend formulation) that does not have a methylene blue clay uptake (utilizing the concept of Mass Balance). Since the clay blend was added as a preblend containing seacoal, the quantity of seacoal could not be added independently and is dependent upon the burn-out rate of the clays. Since this is the common practice in traditional foundries, the researchers have maintained this consistently.

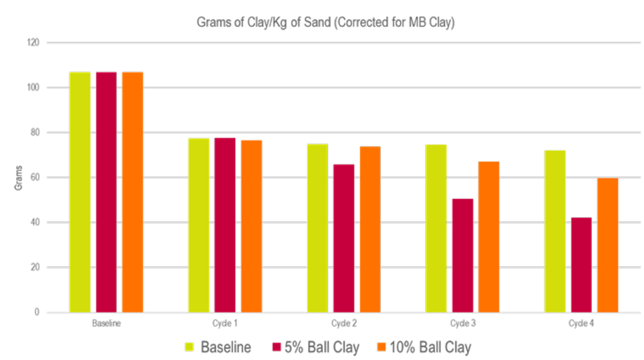

Figure 18. Durability of the prepared molding sand (Measured by consumption).

The subsequent evaluation is completed to determine moisture demand to develop a 45% compactability in the prepared green sand (Figure 19). The value of including seacoal in this protocol supports the understanding that the decomposition characteristics of seacoal influence moisture requirements in prepared molding sand. As observed in Figures 14 to 17, the seacoal has initiated decomposition and started to develop oolitics on the surface of the prepared green sand, which influences moisture demand for the required compactability. Moisture demand is also influenced by the clay or clay blend that has started to surface hydration, which properly develops a bonding mechanism.

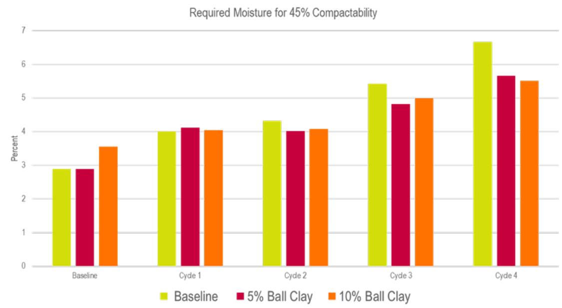

Figure 19. Moisture demand for the prepared molding sand.

Green compression strength measurements can be found in (Figure 20).

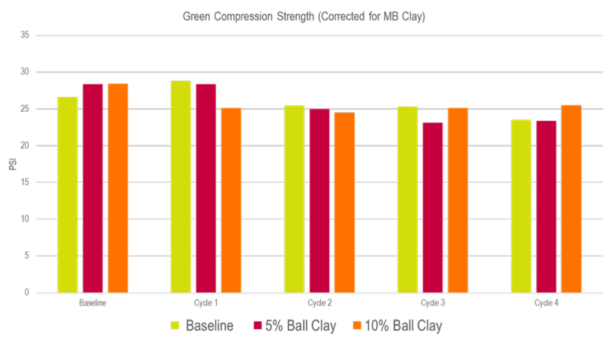

Figure 20. Green compression strength of the prepared molding sand.

Wet tensile strength has become an essential characteristic in green sand molding. The data from this investigation are shown in Figure 21.

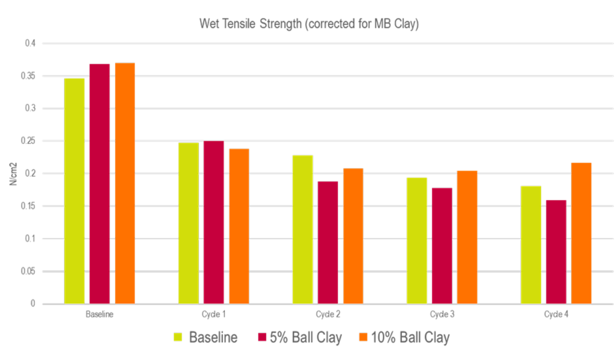

Figure 21. Wet tensile strength of prepared molding sand.

The following evaluation was completed to develop the bonding mechanism's green shear strength (Figure 22). Green shear strength allows the measurement of green sand across the molding sand surface compared to a compressive load on green sand when measured in green and dry compression. This characteristic directly relates to specific casting defects in green sand foundries.

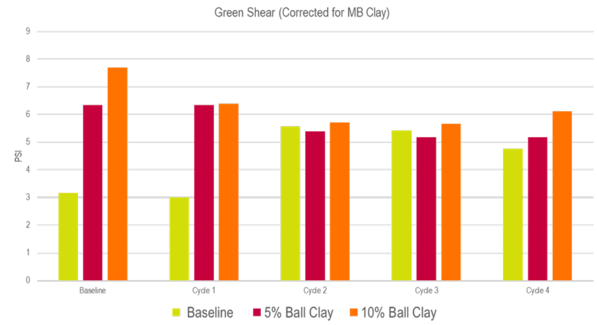

Figure 22. Green shear of prepared molding sand.

Dry compression strength was the final evaluation completed in this protocol (Figure 23).

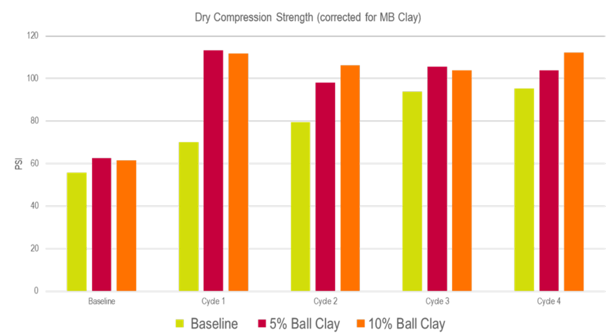

Figure 23. Dry compression strength of the prepared molding sand.

Utilizing Protocol 1 to Evaluate Blends of Indian Bentonite and Indian Ball Clay

1. Positive Indications of the Prepared Molding Sand
   a. Less bonding clay required to prepare molding sand (Improved Durability)
   b. Less moisture required for desired compactability
   c. Wet tensile strength increased at 10% ball clay additions.
   d. Green shear strength increased.
   e. Dry compression strength increased.
2. Neutral Indications of the Prepared Molding Sand
   a. Green compression strength was not significantly different.

The primary reason for completing the laboratory-simulated green sand molding evaluation is because it is a cost-effective method to evaluate green sand binders and organic additives in a practical laboratory environment. Upon completion of the study, the information can be used to develop a casting trial protocol at a foundry test casting center or university capable of molding, pouring, and evaluating green sand molding operations.

PROTOCOL 2: PRODUCTION AND EVALUATION OF TEST CASTINGS AT NORTHERN IOWA UNIVERSITY

Methodology

The green sand mixtures were produced using a Simpson F 1-1/2 Muller. The 350 lb. batches were produced for each sample (Figure 24). The molds were prepared with a Herman Molding Machine (Figure 25). Step-block test castings were poured using Class 30 gray iron to evaluate the performance of the three Indian bentonite blends over four cycles. The step-block castings weighed approximately 70 lbs. each (Figures 26–28), with the molds weighing 330 lbs. (Figures 29 & 30), providing a 4.7:1 sand:metal ratio. The target compactability was 45%, and the target total clay content of 9%.

Figure 24. The green sand mixtures were produced using this muller.

Figure 25. Molds were prepared using this molding machine.

Figure 26. The step-block casting pattern (cope).

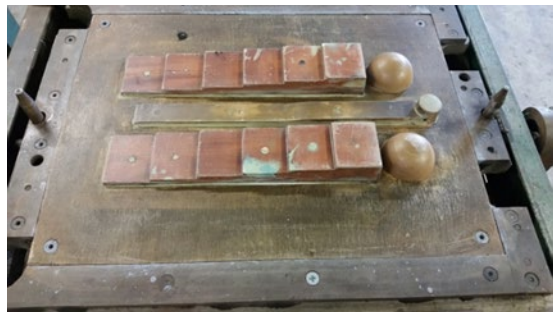

Figure 27. The step-block casting pattern (drag).

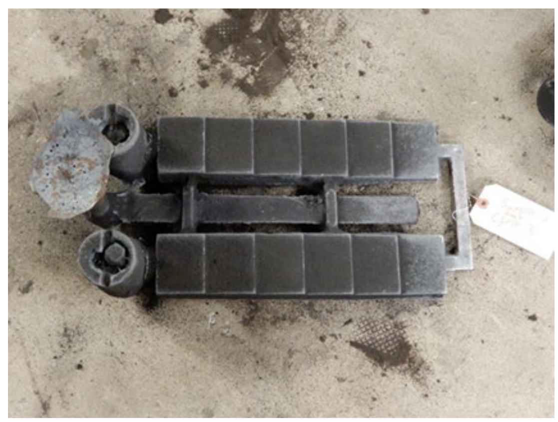

Figure 28. The actual step casting produced in this study.

Figure 29. The prepared molds before pouring.

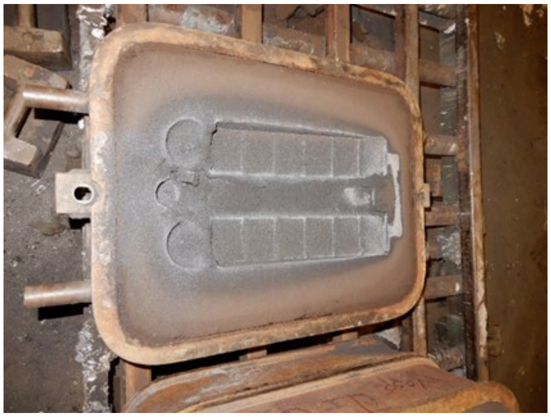

Figure 30. The drag mold after pouring.

The resulting castings were analyzed using a Romer absolute arm laser scanner. Color maps were produced for each casting, which were used to calculate the deviation from expected casting dimensions (Figure 31).[9]

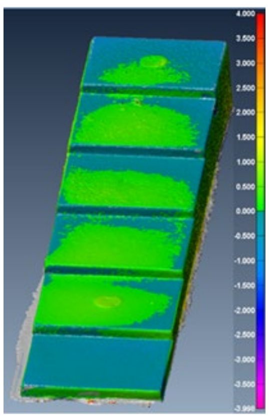

Figure 31. Casting imaging from the laser scanner.

Evaluating Blends of Indian Bentonite and Indian Ball Clay

In this casting evaluation phase, three clay bonding formulas with 20% seacoal were evaluated based on the knowledge gained in the simulated green sand molding evaluation. Table 4 shows the three formulas evaluated. (Note: the scientific planning team selected 8% ball clay in Preblend 2 for this Protocol instead of 10% ball clay from Protocol 1 because the data from Protocol 1 and additional Indian bentonite studies completed in parallel suggested a lower volume of ball clay (8%) is preferred.)

Table 4. Comparison of Bonding Clay Formulas for Casting Production

	Indian Bentonite %	Indian Ball Clay %	Seacoal
Baseline	80	0	20
Preblend 1	75	5	20
Preblend 2	72	8	20

Figures 32 to 37 show the resulting green sand properties.

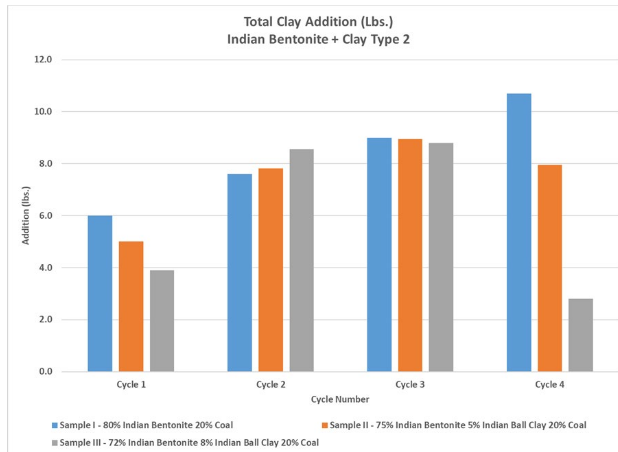

Figure 32. Durability of the prepared molding sand (measured by consumption).

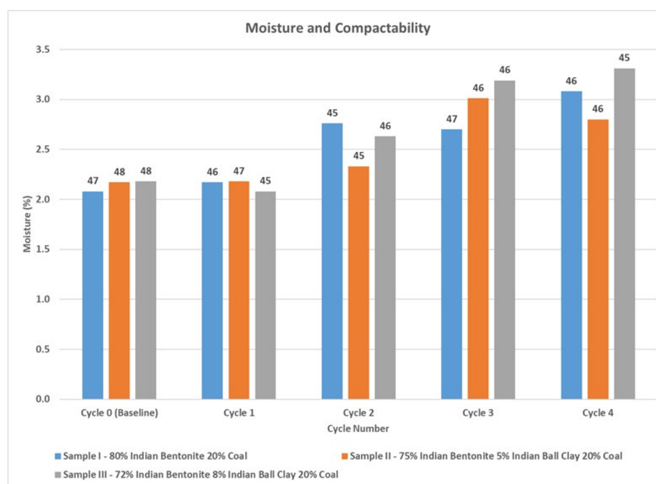

Figure 33. Moisture and compatibility measurements.

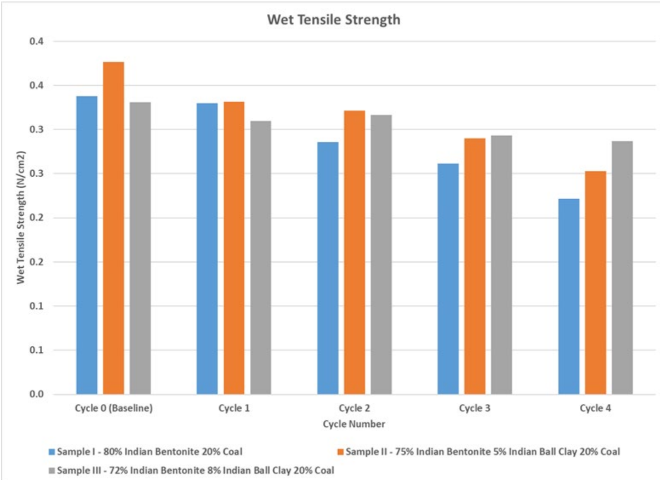

Figure 34. The wet tensile strength of the prepared molding sand.

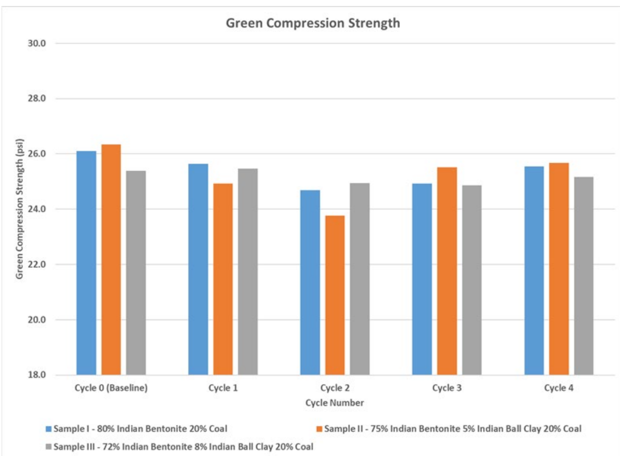

Figure 35. The green compression strength of the prepared molding sand.

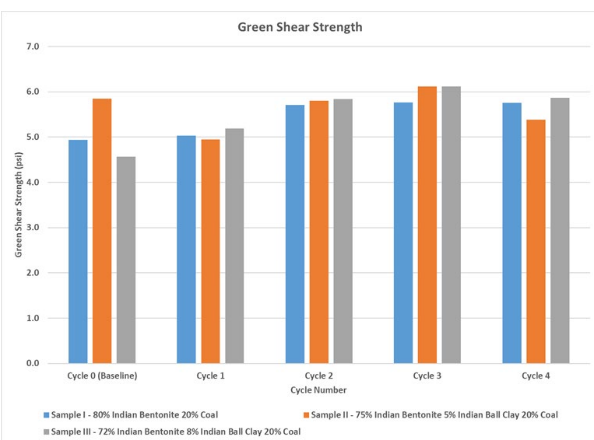

Figure 36. The green shear strength of the prepared molding sand.

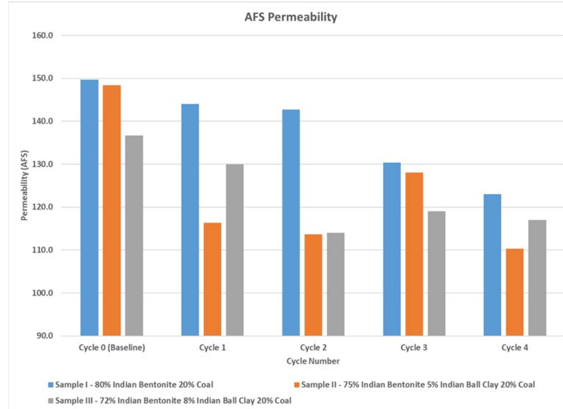

Figure 37. The permeability of the prepared molding sand.

Photographs of the prepared molding sand were taken at 35x magnification of the baseline and last (fourth) cycle (Figs. 38 & 39).

Figure 38. Baseline sand. Figure 39. Cycle 4 sand.

Observations from the 2nd Protocol Evaluation

1. Positive Indications of the Prepared Molding Sand
   a. Less bonding clay required to prepare molding sand (Improved Durability);
   b. Less moisture is required for desired compactability; and
   c. Wet Tensile Strength increased;
   d. Green Shear Strength improved slightly.
2. Neutral Indications of the Prepared Molding Sand
   a. Green Compression Strength was not significantly different.

A general comparison of the green sand properties of the two testing protocols can be found in Table 5.

Table 5. Comparison of the Green Sand Properties of the Two Testing Protocols

	Protocol 1: Simulated green sand molding evaluation.	Protocol 2: Casting Production at UNI
Bond Consumption	Improved	Improved
Moisture Demand	Improved	Slightly Improved
Green Compression Strength	Neutral	Neutral
Wet Tensile Strength	Improved	Improved
Green Shear Strength	Improved	Slightly Improved
Dry Compression Strength	Improved	Not Available at Testing Facility

A critical performance characteristic of any metal casting investigation is the ability to produce quality casting due to the changes in the bonding mechanism for green sand. This study will review two elements that impact casting surface integrity.

The first element of this investigation is the reason for this study, which is the influence of bonding clays added to Indian bentonite. Second is the influence of seacoal and any carbonaceous material on the metal casting surface. The influence of seacoal is well documented and can be observed in Figure 40.[10] For this reason, the seacoal quantity in the preblends was held constant for the entire casting test protocol. Since the clay blend was added as a preblend containing seacoal, the quantity of seacoal could not be added independently and is dependent upon the burn-out rate of the clays. Since this is the common practice in traditional foundries, the researchers have maintained this consistently.

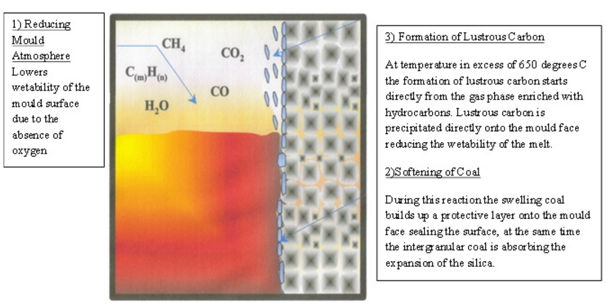

Figure 40. How the seacoal works.

Figures 41 and 42 show the resulting casting measurements. Table 6 compares the results from cycle 4 found in Figures 41 and 42. Cycle 4 was selected because the prepared molding sand had the highest degree of Oolitisation on the surface of the silica sand, as seen in Figures 38 and 39. Analytically, the lower percentage of points over 0.5 mm is preferred when measuring the casting surface.[9] Figures 43 to 48 show images of the actual castings.

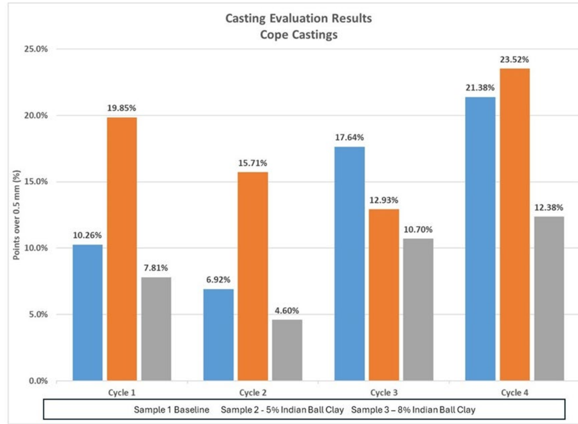

Figure 41. Casting measurements of the cope surface of the castings.

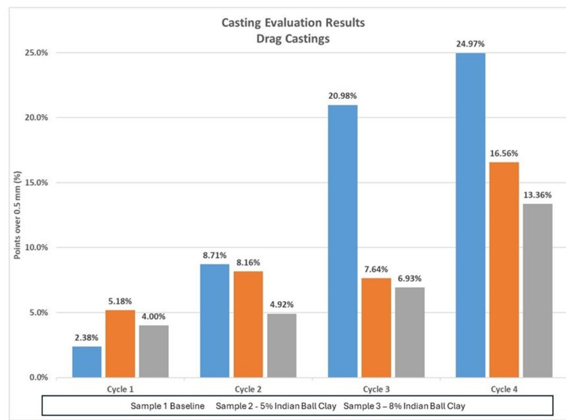

Figure 42. Casting measurements of the drag surface of the castings.

Table 6. Comparison of Cycle 4 Casting Measurements

		Baseline	5% Indian Ball Clay	8% Indian Ball Clay
Cope Surface	Cycle 4	21.38%	23.52%	12.38%
Drag Surface	Cycle 4	24.97%	16.56%	13.36%

The lower percentage of points over 0.5 mm found in the preblend containing 8% Indian ball clay compared to the baseline (no Indian ball clay) is, on average, a 45% improvement in both the cope and drag Surfaces. The authors agree with the original information shared from Sander's book that ball clays have high fusion characteristics over 3092 F (1700 C). The resulting high fusion characteristics benefit thermal durability.[5]

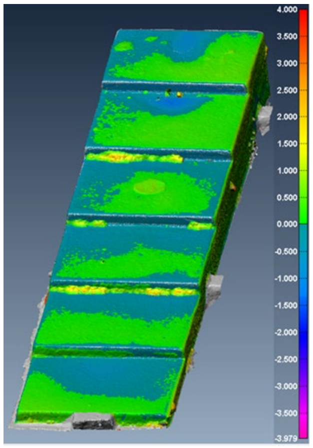

Figure 43. Baseline cope.

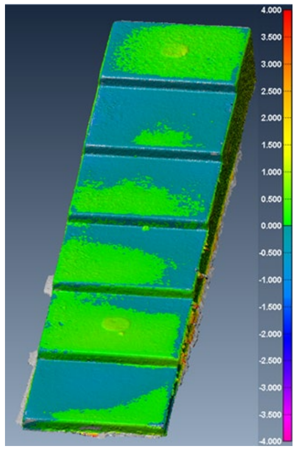

Figure 44. Baseline drag.

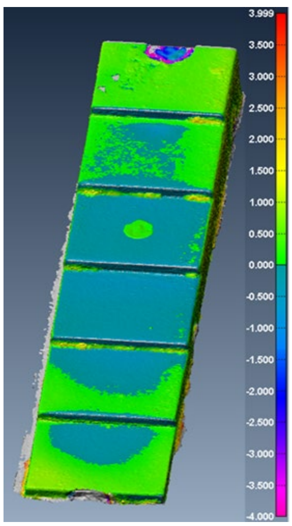

Figure 45. 5% BC cope.

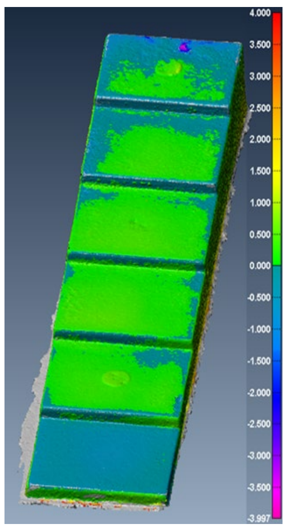

Figure 46. 5% BC drag.

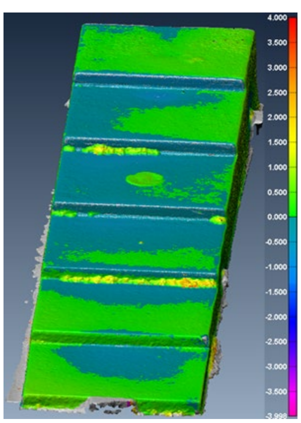

Figure 47. 8% BC cope.

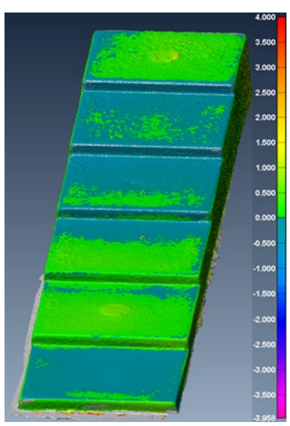

Figure 48. 8% BC drag.

CONCLUSION

Indian bentonite-bonded green sand has been successfully utilized in green sand molding worldwide for many years. The green sand molding process and the resulting casting surface can be enhanced by blending additional bonding materials that naturally occur in India.

- Adding 5 to 8% Indian ball clay improves the molding sand characteristics and casting surface finish compared to blends produced with only Indian bentonite. The addition of 8% Indian ball clay was preferred.
- Consumption of the premix containing Indian ball clay is improved compared to a preblend produced with only Indian bentonite.
- Wet tensile properties are increased when a preblend containing Indian ball clay is compared to a preblend produced with only Indian bentonite.
- Green compression strength and green shear strength are not significantly changed when a preblend containing Indian ball clay is compared to a preblend produced with only Indian bentonite.
    - However, considering less preblend was utilized in the final prepared sand mixtures, the fact that the green compression strength and green shear strength stayed the same pointed out an improvement in the prepared molding sand.

ADDITIONAL CONCLUSIONS

- Using these two protocols to understand green sand bonding mechanisms is effective (Table 5).
- There are multiple benefits to developing a laboratory protocol that simulates green sand molding techniques.
    - Cost effectiveness.
    - Time utilization.
    - The ability to test multiple scenarios before total casting production.
- These two protocols have been applied to additional bonding clay studies mined and processed worldwide. There is unlimited potential for additional studies.
    - 2018 investigation into European bonding clays and carbons.[11]
    - 2019 investigation into United States bonding clays and carbons.[12]

ACKNOWLEDGMENTS

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ADDITIONAL READING

Indian bentonite and the mineralogical iron naturally occurring within this bentonite influence emission reduction (BTEX) of green sand molding during pouring, cooling, and shakeout. A study of European and Indian bentonite blends was published in the *International Journal of Metal Castings* (IJMC), Volume 13, issue 3 (July 2019), titled "Evaluation of Green Sand Premixes for Emission Characteristics (Enhanced)."