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Optimization of Hybrid Bentonite for Mechanical Properties of Green Sand Mould

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Abstract

Aim – As green sand moulding is the cheapest, fastest, and most commonly used method for metal casting process this research aims to optimize the hybrid bentonite for the mechanical properties of green sand mould which leads to a better-quality of casting and reduction in rework.
Materials – For the experiments green sand was prepared by mixing reclaimed sand, garcolap powder, hybrid bentonite and water. Hybrid bentonite is a mixture of bentonite (pure sodium bentonite containing more than 75% montmorillonite) and clay (bentonite clay having 40-55% montmorillonite).
Experiments/Methodology/Approach – Experimental results were optimized using Minitab software version 21 to find out values of bentonite, garcolap powder and water to be kept constant for experiments to optimize hybrid bentonite. In this research work mechanical properties of green sand like compactibility, permeability, mould hardness (MH), green compressive strength (GCS) and moisture content were measured for the experiments performed on specimen prepared from green sand in accordance with the IS: 1918-1966.
Findings – Experiments performed to optimize hybrid bentonite suggests best combine values of process parameters for hybrid bentonite with 85/15 ratio.
Research limitations/Implications – Hybrid bentonite composition optimized in this research can be applied to prepare hybrid bentonite for other casting industries only if the chemical composition of bentonite is approximately same as used in current work. If chemical composition of bentonite gets changed then researcher has to apply same methodology to find new composition of hybrid bentonite for their green sand moulding process.

Keywords: Hybrid bentonite, Green sand moulding, Mechanical properties, Optimization, Chemical composition

1. Introduction

Green sand moulding is one of the most widely used moulding methods in the metal casting industry due to its simplicity, low cost, and adaptability to a wide range of casting applications [1, 5, 9, 11, 19]. The diagram (Figure 1) shows the sequence of steps involved in the sand-casting manufacturing process used to produce metal components. It illustrates how raw materials and preparation steps lead to the final casted product. Core and pattern making begins with preparing the pattern, which is a replica of the final product, and the core, which is used to create internal cavities or hollow sections in the casting. Green sand preparation involves mixing of sand, clay, and water. This material is used to form the mould that will shape the molten metal. In mould making prepared green sand is packed around the pattern to create the mould cavity. Once the pattern is removed, the mould contains the exact shape of the desired part. Metal melting involves heating of metal in a furnace until it becomes molten. Then in pouring molten metal is poured into the prepared mould cavity through a gating system. Pouring is followed by cooling and solidification in which the molten metal cools and solidifies inside the mould, taking the shape of the cavity. Once solidified, the sand mould is broken and removed to extract the cast metal component. Then the casting is cleaned to remove excess sand and metal, and then inspected for defects and quality. Finally casted product is obtained and ready for further processing or use.

The process uses a mixture of silica sand, clay binder, and water to form moulds capable of withstanding molten metal during pouring [2, 3, 6, 15, 18]. Despite its name, "green" sand does not refer to colour but to the fact that the mould is used in a moist, uncured state. This method remains especially popular in ferrous and non-ferrous foundries because the moulding materials are readily available, recyclable, and suitable for both small- and large-scale production [4, 6, 7, 10, 20].

The quality and performance of a green sand mould depend largely on the properties of its constituent materials and their proportions [18, 21, 23]. Silica sand provides the basic framework of the mould, while the clay binder - most commonly bentonite - imparts strength by bonding the sand grains together in the presence of moisture [3, 8, 10, 13]. Water activates the clay, allowing the mould to achieve sufficient plasticity and cohesion. An appropriate balance among these components is essential, as excessive or insufficient binder and moisture can negatively affect mould strength, permeability, and surface finish [11, 12, 15, 16, 20, 22].

Mechanical properties such as green compressive strength, shear strength, and mould hardness play a critical role in ensuring that the mould can resist erosion, deformation, and collapse during handling and metal pouring [1, 14, 17, 19, 23]. At the same time, adequate permeability is required to allow gases generated during pouring to escape, preventing defects such as blowholes and pinholes in the final casting [5, 9, 12, 21]. Achieving this balance remains a key challenge in green sand moulding, particularly under varying production conditions.

Because of these challenges, continuous research is being conducted to improve green sand mould performance through material modification and process optimization [3, 7, 11]. Understanding the green sand moulding process and the factors that influence mould behaviour is essential for developing improved moulding materials and achieving higher casting quality.

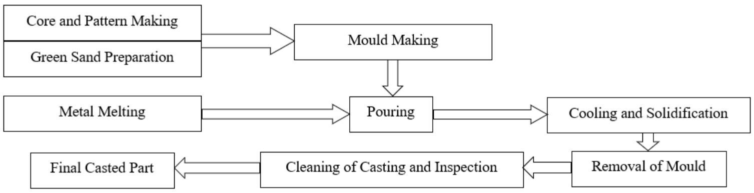

Fig. 1. Casting Process Steps [1]

1.1. Bentonite

Bentonite plays a vital role in the green sand moulding process, acting as the primary binder that holds sand grains together and gives the mould its required strength and stability. It is a naturally occurring clay, mainly composed of montmorillonite, and is widely used in foundry applications because of its high bonding capacity, swelling behavior, and ability to retain moisture [1, 5, 11, 12, 18, 20, 22, 23]. When mixed with sand and water, bentonite forms a cohesive structure that enables the mould to maintain its shape during handling and withstand the thermal and mechanical stresses encountered during metal pouring [15, 17, 18, 19, 21].

In foundry practice, sodium and calcium bentonites are the two most commonly used types, each offering distinct advantages and limitations. Sodium bentonite provides higher green strength and better swelling characteristics, while calcium bentonite offers improved thermal stability and lower moisture sensitivity [2, 3, 10, 13, 21, 22]. However, the use of a single type of bentonite often makes it difficult to achieve an optimal balance between strength, permeability, and mould durability. Inadequate binder performance can lead to common casting defects such as mould erosion, poor surface finish, and gas-related defects [4, 6, 14, 18, 19, 23].

To overcome these challenges, the concept of hybrid bentonite formed by combining different types of bentonite or modifying bentonite with suitable additives has gained increasing attention. Hybrid bentonite systems have the potential to enhance inter-particle bonding and improve mechanical properties while maintaining sufficient permeability in green sand moulds [7, 9, 16, 18, 20]. The effectiveness of such systems largely depends on the proportion and interaction of the bentonite components, making optimization a critical step.

The present research focuses on optimizing hybrid bentonite to improve the mechanical properties of green sand moulds. The specific objectives of this study are as follows:

- To investigate the effect of different hybrid bentonite compositions on the mechanical properties of green sand moulds.
- To analyze the influence of hybrid bentonite on mould strength and overall mould performance.
- To determine the optimal hybrid bentonite composition that provides improved bonding characteristics in green sand systems.
- To enhance the quality and reliability of the casting process by developing an improved binder system for green sand moulds.

These objectives aim to contribute to improved mould strength, better casting quality, and greater process reliability in foundry operations.

2. Experimental Methodology

Table 1 shows experiments designed using design expert software version 13 and results obtained from the experiments performed which was published in the previous research paper of the author [1]. Using these results overlaid contours were plotted to obtain values of process parameters and then response optimization has been done using Minitab software version 21 to find out optimum values of input parameters bentonite, garcolap powder and water to be kept constant during experiments performed for optimization of hybrid bentonite.

To prepare hybrid bentonite designations adopted were Bentonite- pure sodium bentonite / Clay- pure bentonite clay; 100/0, 95/5, 90/10, 85/15, 80/20, 75/25, 70/30, 65/35, 60/40, 55/45, 50/50, 0/100 – blends of hybrid bentonite containing 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 100% of bentonite clay respectively. Using these blends of hybrid bentonite test specimens prepared and experiments performed as mentioned in Table 2.2.

Table 1.
Experiments and Results [1]

Exp. No.	Input Parameters			Process Parameters				
	Bentonite (gm)	Garcolap Powder (gm)	Water (mL)	Compactibility (%)	Permeability (unitless)	Mould Hardness (No.)	GCS (kg/cm^2)	Moisture (%)
1	10	0.3	10	47	100	77	950	4.2
2	12	3	12	54	84	89	1025	5.4
3	8	3	8	42	123	67	780	3.1
4	6.6	2	10	40	130	59	750	3.3
5	10	2	10	47	100	72	925	4.5
6	10	2	10	48	102	72	924	4.5
7	10	2	13.4	45	97	79	980	5
8	8	1	8	46	119	69	810	3.5
9	10	2	10	47	99	72	923	4.5
10	10	2	10	47	100	72	925	4.5
11	13.4	2	10	55	88	90	1150	5.2
12	8	1	12	44	121	64	790	3.7
13	8	3	12	43	115	65	835	4
14	12	1	12	52	89	87	1070	5.3
15	10	3.7	10	48	94	85	1040	4.9
16	10	2	6.6	49	105	76	895	3.8
17	12	1	8	53	87	89	1095	4.5
18	10	2	10	47	100	72	927	4.5
19	12	3	8	54	85	86	1065	4.9
20	10	2	10	47	100	72	924	4.5

Table 2.
Experiments Designed for Optimization of Hybrid Bentonite

	Exp. No.	1	2	3	4	5	6	7	8	9	10	11	12
	Blend (%)	100/0	95/5	90/10	85/15	80/20	75/25	70/30	65/35	60/40	55/45	50/50	0/100
Input Parameters	Pure Sodium Bentonite (gm)	10.5	10	9.5	9	8.4	7.9	7.4	6.8	6.3	5.8	5.3	0
	Pure Bentonite Clay (gm)	0	0.5	1	1.5	2.1	2.6	3.1	3.7	4.2	4.7	5.2	10.5
	Reclaimed Sand (gm)	200	200	200	200	200	200	200	200	200	200	200	200
	Garcolap Powder (gm)	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Water (mL)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	Mixing Time (min)	5	5	5	5	5	5	5	5	5	5	5	5

3. Test Material and Methodology

Ingredients used to make green sand are shown in the Figures 2 to 4. Fixed values of input parameters used are reclaimed sand 200gm, hybrid bentonite 10.5gm, garcolap powder 1.7gm, and water 12.5mL (table-2.2) obtained from response optimization done using Minitab software. To prepare green sand mix 200gm reclaimed sand was mixed with garcolap powder, bentonite and water using hands for five minutes. From this blend test specimens were prepared as per IS 1918-1966 [25] and to perform the experiments calibrated instruments were used.

Table 3.1 shows chemical composition of pure sodium bentonite and pure bentonite clay found by WD-XRF analysis. All the testing specimens were prepared, and tests were performed on calibrated equipment in accordance with the IS: 12446-2007 [24] and IS:1918-1966 [25]. Detailed procedure for experiments performed has been described below

Fig. 2. Reclaimed Sand

Fig. 3. Bentonite

Fig. 4. Garcolap Powder

Table 3.
Chemical Composition of Pure Sodium Bentonite and Pure Bentonite Clay

Test Parameter	SiO_2	Fe_2O_3	Na_2O	MgO	Al_2O_3	K_2O	CaO	TiO_2	MnO	P_2O_5	SO_3
Pure Sodium Bentonite Concentration (%)	63.542	2.715	4.514	5.411	17.216	0.327	4.713	1.221	0.341	-	-
Pure Bentonite Clay Concentration (%)	51.714	16.48	8.265	3.638	15.047	0.114	2.15	1.176	0.127	0.584	0.705

3.1. Test Specimen Preparation:

For testing, a standard cylindrical specimen (Figure 5) was prepared using 150 gm of green sand with the specified weight, in accordance with IS 1918–1966. The test specimen had a height of 50.8 ± 0.03 mm and a diameter of 50.8 mm. The measured quantity of green sand was carefully placed into the specimen container and levelled uniformly. The calibrated ramming head was then gently lowered into the container until it just rests on the sand surface. Next, the rammer weight was slowly raised by hand to the full height and allowed to fall freely. This ramming operation was repeated two more times, giving a total of three rams, to obtain the standard test specimen [25].

Fig. 5. Testing Specimen

3.2. Compactability Test Procedure:

Prepare the test specimen as explained earlier in section 3.1. Before removing the specimen from the container, the calibrated testing scale (Figure 6) was used to measure the distance between the top edge of the specimen container and the top surface of the prepared specimen. This measured distance directly represents the compactability of the sand in percentage [25].

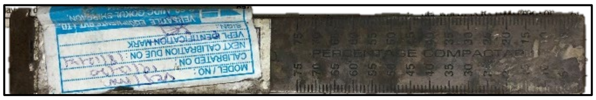

Fig. 6. Testing Scale

3.3. Permeability Test Procedure:

A calibrated permeability tester supplied by Versatile Equipment Pvt. Ltd. (Figure 7) was used to determine the permeability of the sand. The prepared test specimen [25] was placed carefully in the tester, and the selector was set to the O-P position. Allow the water level to stabilize, then noted the reading shown. Finally, compared this reading with the reference table provided on the tester to determine the permeability (unitless) value.

3.4. Mould Hardness Test Procedure:

Prepared the cylindrical test specimen [25] as explained earlier. While the specimen was still inside the specimen container, use the calibrated mould hardness tester (Figure 8) to take the hardness number reading carefully.

3.5. GCS Test Procedure:

To determine the green compressive strength, the prepared green sand test specimen [25] was placed in a calibrated Universal Strength Machine manufactured by Kelsons Testing Equipment (Figure 9). The specimen was mounted on the machine table, and the machine was then started. A gradually increasing load was applied to the specimen until it fails. At the moment the specimen breaks, the value displayed on the screen was noted as the green compressive strength (GCS) in kg/cm^2.

Fig. 7. Permeability Tester

Fig. 8. Mould Hardness Tester

3.6. Moisture Content Test Procedure:

For moisture content determination 7 gm of green sand was placed in the upper chamber of the calibrated moisture tester. Then 1 gm of calcium carbide (CaC_2) was added to the sand and mixed thoroughly for about 1.5 minutes [25]. After that the tester was closed properly. The moisture tester displayed a reading on the screen (Figure 10), which was taken as the percentage moisture content of the sand.

Fig. 9. Universal Strength Machine

Fig. 10. Moisture Teller

4. Result Analysis and Discussion

Figure 11 represents overlaid contour plot of compactability, moisture, permeability, GCS and mould hardness for input parameters. The plot clearly identifies an optimum operating window at moderate garcolap percentage and medium water content, where mould hardness and GCS are satisfactory while maintaining acceptable permeability and compactability. This region represents the best compromise among all properties for green sand mould preparation under the given bentonite content.

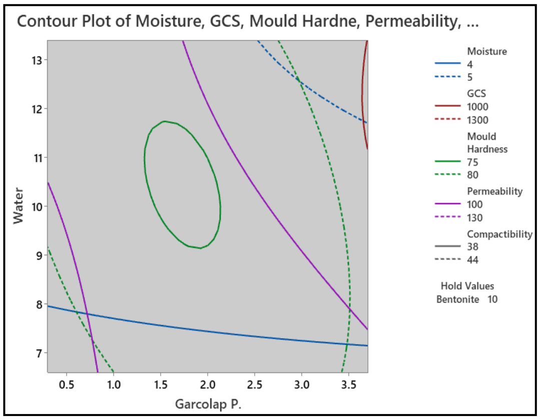

Fig. 11. Overlaid Contour Plot for Process Parameters

Then response optimization (Figure 12) performed suggests an overall composite desirability of 0.7430, indicating a reasonably good compromise among all responses. Optimized values of input parameters obtained from response optimization are bentonite 10.5gm, garcolap powder 1.7gm, and water 12.5mL. Table 4.1 represents results obtained from the tests performed as mentioned in Table 2.2. These results were utilised to plot graphs which represent effect of hybrid bentonite on various process parameters (Figures 13 to 18).

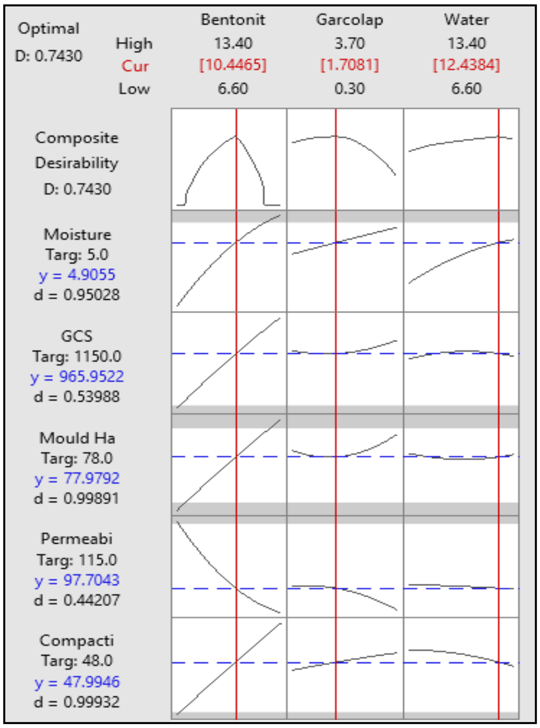

Fig. 12. Response Optimisation

Table 4.
Result of Experiments Performed

	Exp. No.	1	2	3	4	5	6	7	8	9	10	11	12
	Blend (%)	100/0	95/5	90/10	85/15	80/20	75/25	70/30	65/35	60/40	55/45	50/50	0/100
Process Parameters	Compactability (%)	48	46	45	47	45	44	43	40	39	37	36	35
	Permeability (unitless)	99	106	115	136	130	122	125	104	95	90	86	80
	Mould Hardness (No.)	76	74	77	80	79	77	76	75	74	73	73	72
	GCS (kg/cm2)	1485	1445	1427	1435	1401	1362	1290	1186	1097	1012	967	1065
	Moisture (%)	5.4	5.2	5.1	5.3	5	4.6	4.2	3.5	3.6	3.8	4.1	4.4

Figure 13 shows effect of various hybrid bentonite composition on compactability of green sand. The highest compactability about 48% is obtained with 100% pure sodium bentonite, indicating that pure bentonite shows the best compactability. As bentonite clay is gradually increased the compactability slightly fluctuates but shows an overall decreasing trend. A small rise is observed at the 85/15 composition, suggesting a locally favourable mix. Beyond 70/30, the compactability decreases more noticeably, showing that higher clay content adversely affects compactability. The lowest compactability about 35% is seen with 100% clay.

Bar chart (Figure 14) depicts the variation of permeability for different pure sodium bentonite and bentonite clay composition. For 100% pure sodium bentonite, the permeability value is around 99, indicating moderate permeability. As small amounts of clay are added (95/5 and 90/10), permeability increases gradually. The permeability reaches a maximum value 136 at the 85/15 bentonite and clay composition, showing the most favourable structure for fluid or gas flow. Beyond this point, with further increase in clay content (80/20 to 100% clay), permeability generally decreases, indicating that higher clay content tends to block pore spaces. The lowest permeability 80 is observed for the 100% clay composition which shows its compact and less permeable structure.

The graph shown in the Figure 15 illustrates the variation of mould hardness for different pure sodium bentonite and bentonite clay composition ratios. At 100% pure bentonite, the mould hardness is 76, indicating moderate hardness. A slight decrease in hardness is observed at the 95/5 composition. The mould hardness increases with further addition of clay and reaches a maximum value of 80 at the 85/15 bentonite and clay ratio. Beyond 85/15, the mould hardness gradually decreases as the clay content increases. At higher clay proportions (60/40 to 50/50), the hardness values fall in the range of 73-74. The lowest mould hardness about 72 is observed for 100% clay.

The bar chart shown in the Figure 16 represents the variation of green compressive strength (GCS) expressed in kg/cm² for different pure sodium bentonite and bentonite clay blend ratios. The highest GCS value 1480 kg/cm² is obtained for 100% pure bentonite, indicating very high strength. As clay content is gradually increased (95/5 to 90/10), the GCS slightly decreases but remains relatively high. A small improvement is noticed at the 85/15 composition, showing better bonding and load-bearing capacity. Beyond 85/15, the GCS shows a continuous decreasing trend with increasing clay content. The lowest GCS value 970 kg/cm² is observed at the 50/50 composition. At 100% bentonite clay, the GCS increases slightly again but remains lower than bentonite rich compositions.

The graph (Figure 17) illustrates the variation of moisture percentage for different pure sodium bentonite and bentonite clay combination ratios. The highest moisture content about 5.4% is gained by 100% pure bentonite, indicating that bentonite rich sand requires more moisture for proper bonding. As clay is gradually added (95/5 and 90/10), the moisture content slightly decreases. A small increase in moisture is noticed at the 85/15 composition, suggesting an optimum water requirement for bonding at this ratio. Beyond 85/15, the moisture content shows a continuous decreasing trend, reaching a minimum value of 3.5% at the 65/35 composition. After this minimum point, moisture content starts increasing again with higher clay proportions. For 100% bentonite clay, the moisture content rises to 4.4%.

The Figure 18 presents combined effect of pure sodium bentonite and bentonite clay composition known as hybrid bentonite on five important green sand mould properties**;** compactability, permeability, mould hardness, moisture content, and green compressive strength. Highest compactability observed at 100% pure bentonite which gradually decreases with increase in clay content indicates that bentonite rich blends are easier to compact, while higher clay content reduces workability. Permeability increases initially and reaches a maximum around the 85/15 mix. Beyond this ratio, permeability decreases due to pore blockage by excess clay. A sharp rise is again observed for 100% clay, indicating a different pore structure. Mould hardne**ss** increases with clay addition and reaches its maximum value at 85/15 combination ratio. Further increase in clay content reduces hardness due to poor bonding and excess fines. Moisture percentage is higher for bentonite rich mixtures. Minimum moisture content is observed around 65/35 ratio. Moisture increases again at higher clay content, especially for 100% clay. Green compressive strength (GCS) is highest for 100% bentonite and remains relatively high up to 85/15 ratio blend. Gradually decreases with increase in clay content, reaching minimum at 50/50 ratio. Slight recovery is seen at 100% clay. This same kind of results for hybrid bentonite has been observed by other authors also [2, 6, 12, 15].

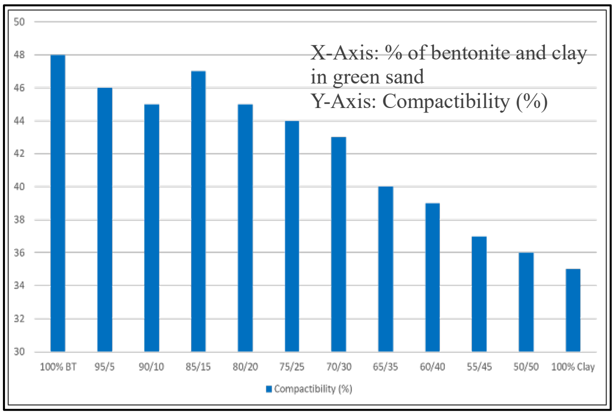

Fig. 13. Effect of Hybrid Bentonite on Compactability

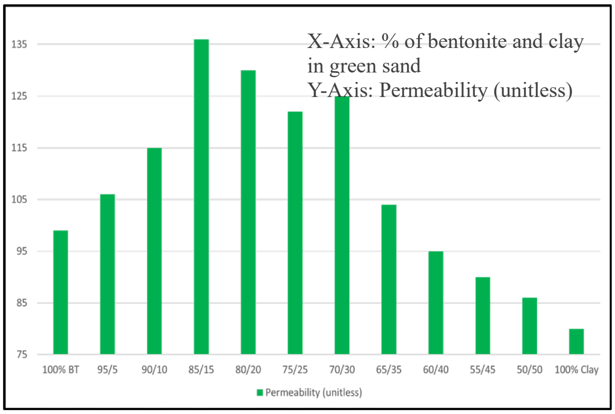

Fig. 14. Effect of Hybrid Bentonite on Permeability

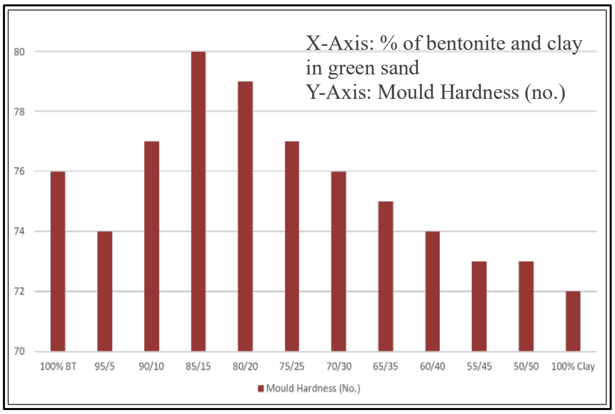

Fig. 15. Effect of Hybrid Bentonite on Mould Hardness

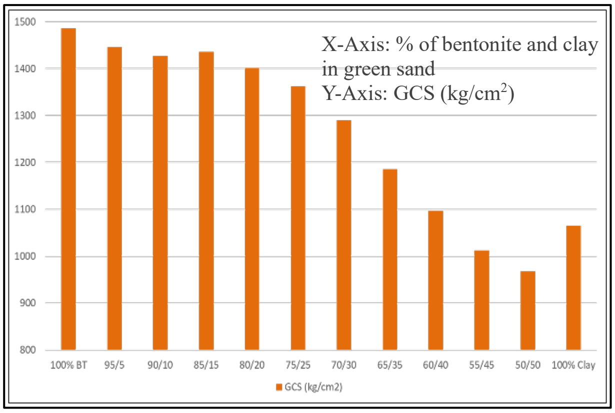

Fig. 16. Effect of Hybrid Bentonite on Green Compressive Strength

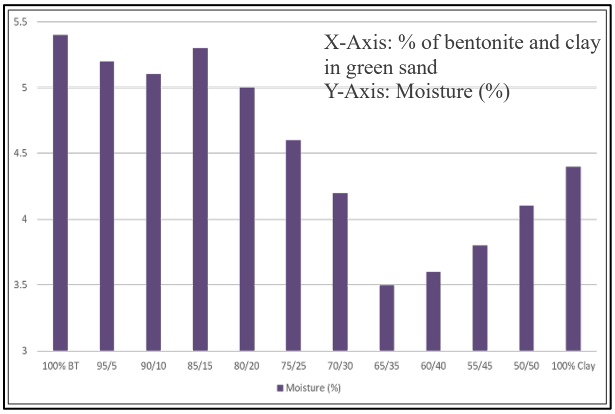

Fig. 17. Effect of Hybrid Bentonite on Moisture

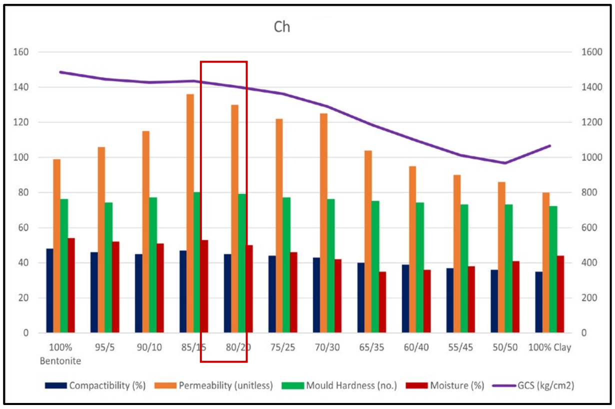

Fig. 18. Effect of Hybrid Bentonite on Combined Process Parameters

5. Conclusion

➢ Results clearly indicate that compactability (%) gradually decreases as the proportion of clay increases and bentonite decreases. It starts at about 48% for 100% bentonite and steadily drops to around 34% for 100% clay, indicating that bentonite rich compositions exhibit better compactability, while clay dominant mixtures show poorer performance. Therefore, for applications requiring higher compactability, hybrid bentonite with a higher percentage of bentonite is preferable.

- Findings from experiments represent that permeability is strongly influenced by the hybrid bentonite. Permeability initially increases as clay is added to bentonite, reaching a maximum value around the 85/15 mixture. After this point, permeability gradually decreases with further increase in clay content, reaching the lowest value at 100% clay. This suggests that a moderate clay addition improves pore structure and air passage, while excessive clay reduces permeability.
- Outcome of tests depict that mould hardness number slightly increases from 100% bentonite to around the 85/15 - 80/20 mixtures, where the highest hardness values are observed. Afterward, mould hardness gradually decreases as clay proportion increases, indicating reduced resistance of the mould surface with higher clay content. Excessive clay content reduces mould hardness, likely due to poor bonding structure, while balanced proportions of bentonite and clay provide better mould strength and stability.
- Inference from results represent that moisture content (%) generally decreases from 100% bentonite to about the 65/35 mixture, showing that bentonite-rich mixtures retain more moisture, while intermediate mixtures require less water. Beyond this point, moisture content slightly rises again toward 100% clay, indicating different water retention behaviour in clay-dominant mixtures. An optimum moisture range appears around the 80/20 to 85/15 composition, which supports good mould properties.
- Experimental observations indicate that green compressive strength (GCS) steadily declines as clay content increases. The highest strength is observed in 100% bentonite, while the lowest value appears around the 50/50 mixture, with a slight increase again at 100% clay. This indicates that bentonite contributes significantly to the bonding strength of the moulding sand. Bentonite rich sand mixtures provide higher green compressive strength. An optimum balance of strength is achieved near the 85/15 combination hybrid bentonite. Excessive clay content reduces the green compressive strength, which may weaken the mould and make it unsuitable for heavy metal pouring operations.
- End results clearly show that mixtures with higher bentonite content provide better compactability and green compressive strength, while moderate clay addition (around 85/15 or 80/20) improves permeability and mould hardness. However, excessive clay reduces most of the desirable moulding properties and pure bentonite or pure clay lacks balanced performance. Therefore, a balanced bentonite-clay ratio is necessary to achieve optimal moulding sand performance. The 85/15 hybrid bentonite composition provides an optimum balance of mould properties: good permeability, maximum mould hardness, adequate compactibility, controlled moisture, and high green compressive strength. Hence, the 85/15 hybrid bentonite mix is most suitable for producing sound and stable green sand moulds in foundry applications.

Acknowledgement

All the experimental work and tests have been carried out at “Fine Cast India Private Limited”, Anand, Gujarat. Currently the industry is using bentonite clay binders’ system. To determine the chemical composition of bentonite WD-XRF analysis done at Sophisticated Instrumentation Centre for Applied Research and Testing (SICART), Anand facility.

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Statements & Declarations

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