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Evaluation of Foundry Properties of Locally Available Molding Sand with Bentonite Clay Additions for Cost-Effective Aluminum Alloy Casting

F. Hussain, M. Kamran, A. Inam, M. Ishtiaq *, M.H. Hassan, F. Riaz, T. Khan, M. Ammar, M. Salman
Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore, Pakistan.
* Corresponding author: E-mail: ishtiaq.imme@pu.edu.pk

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Abstract

This study addresses an existing gap by examining the foundry properties of Ravi River sands, a subject that has not been explored in earlier studies. Several mechanical and physical tests were used to assess the foundry qualities of sands from different areas. These local sands were used to make molds for Al alloy castings, and the parts' surface roughness (Ra) was assessed. The findings showed that the grain size of the sand varied by location, with the highest grain fineness number (GFN) being 106 and the lowest being 71. All samples exhibited a pH > 7, confirming their suitability for strong binder adhesion. The sand from Syed Wala Bridge had the highest grain fineness number (~106), whereas the sand from Sheraza Pattan Bridge had the lowest (~71). All sand samples showed a constant increase in mold strength when the binder (bentonite clay) percentage was raised from 5% to 25%. The study demonstrates the potential of Ravi River sands to eliminate reliance on imported materials and reduce costs.

Keywords: Molding sand, Bentonite clay, Grain size, Surface roughness, Strength

1. Introduction

The availability of locally obtained sand is important to a nation's economy, particularly in the foundry sector as it directly affects production costs [1]. The casting process is more cost-effective and efficient when locally accessible sand is used since it lowers shipping and procurement expenses. Because it affects the cast product's strength, surface finish, and general performance, the quality of the sand ultimately decides the product's quality. Superior castings are guaranteed by high-quality sand, which also increases production efficiency by lowering faults, decreasing rework, and prolonging mold life. Inadequate sand used for mold making can lead to casting issues such as rough surfaces, gas entrapment, weak mold structures, and ultimately higher rejection rates [2]. By optimizing local sand with the right composition, including the ideal amount of binder like bentonite clay [3], foundries can produce molds with superior strength, permeability, and durability. This approach fosters cost-effective and sustainable manufacturing while improving the casting process. A typical high-quality sand mold consists of 80-95% silica sand, 2-5% water, 5-10% bentonite clay, and 0.5-2% carbonaceous materials. This precise mixture is essential for achieving desired mold properties, such as strength, permeability, and surface finish, which directly affect the quality of the castings [4].

The literature survey indicates that researchers worldwide have extensively explored the suitability of locally available sands and bentonite clay deposits for foundry applications [5]. The impact of different binders and moisture contents on the shear strength and compactibility of sand molds was examined by J. Sadarang et al. [6]. Himanshu and B. Ravi [7] investigated how changes in the amount of binder and grain fineness number (GFN) affect the compressive and shear characteristics of sand molds. The impact of bentonite and cassava starch on the molding properties of silica sand was investigated by Atanda et al. [8]. The effect of matrix type on the molding properties of sand was studied by B. Samociuk et al. and they reported that barley malt can be used as a binder [9,10]. C. Ocheri et al. studied the effect of Acacia gum on the foundry properties of sand for core making [11]. Kausarian et al. [12] investigated the silica content of sands collected from Ketam and Muda Islands along the Kampar River. The green sand casting process parameters were optimized using Taguchi's method [13] and the normal boundary intersection method [14] to achieve the best quality characteristics for spheroidal graphite cast iron castings. The suitability of beach and river sands for casting applications was assessed by Bala et al. [15]. Similarly, sand samples from various rivers have been tested to evaluate their foundry properties [16-18].

Although numerous researchers have attempted to evaluate the foundry properties of sands from various regions, to the best of our knowledge, no published studies exist on the foundry suitability of sand from the Ravi River in Pakistan. This study explores the potential of local sands from the Ravi River in Pakistan for foundry applications, a topic not previously addressed in the literature. By evaluating the casting properties of sand samples collected from various locations along the river, the research aims to identify optimal sand sources for regional industries. The findings will support the development of more cost-effective and efficient production methods, providing actionable insights for adopting sustainable casting practices.

2. Materials and Methods

2.1. Sand Sampling

Five key points along the Ravi River's shoreline—the Motorway Bridge, Head Balloki Reservoir, Syed Wala Bridge, Mari Pattan Bridge, and Sheraza Pattan Bridge—were used to gather sand samples. Because the Ravi River is a significant supplier of sand for Pakistan's foundry industries, which are located in the area, these locations were chosen for their industrial and geographic significance. The approximate distances between these locations are shown on the map in Figure 1. The collected sand was mixed with 5% to 25% binder (bentonite clay in this study) to prepare sand molds in the shape of cylindrical specimens (5.08 cm diameter × 5.08 cm height) for testing. For the sake of convenience, the samples will be referred to throughout the article as MPB sand (Mari Pattan Bridge), SPB sand (Sheraza Pattan Bridge), SWB sand (Syed Wala Bridge), HBR sand (Head Balloki Reservoir), and MB sand (Motorway Bridge).

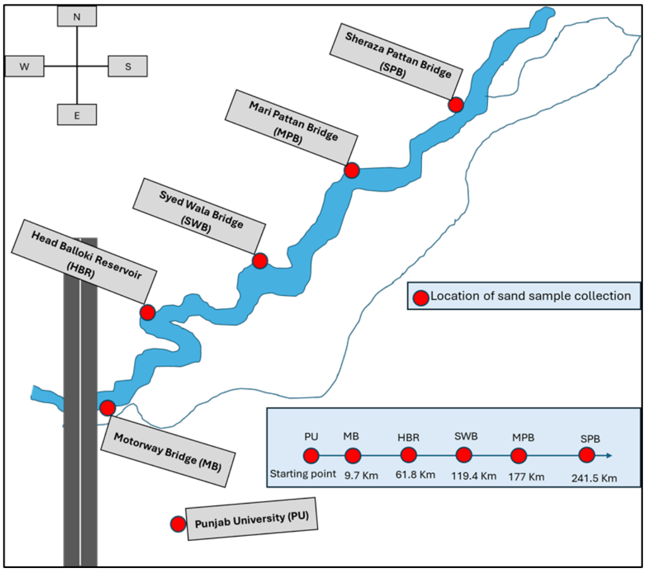

Fig. 1. Schematic map showing the approximate distances of locations from where sand samples were collected

2.2. Chemical Analysis

All sand samples were analyzed chemically utilizing quantitative inorganic analysis. Hydrofluoric acid (HF) and nitric acid (HNO_3) are used to dissolve the minerals after the samples have been dried and ground into a fine powder. Precipitation, filtering, igniting, and weighing are the methods used to extract silica (SiO_2). Gravimetric techniques are used to quantify other metal oxides, including magnesium oxide (MgO), calcium oxide (CaO), iron oxide (FeO_3), and aluminum oxide (Al_2O_3). The crystalline phases are ascertained by X-ray diffraction (XRD) examination, which offers information about the composition and characteristics of the sand samples. The chemical composition results are presented in Table 1.

Table 1.
The chemical composition (wt.%) of different sand samples selected for this study

Constituents	Location of the sand samples				
	MB	HBR	SWB	MPB	SPB
SiO_2	79.62	80.3	81.19	82.22	83.16
Fe_2O_3	3.14	2.82	2.98	2.49	3.47
Al_2O_3	5.70	7.07	6.89	6.91	6.05
CaO	0.40	0.38	0.51	0.37	0.43
MgO	0.11	0.15	0.17	0.18	0.18
Na_2O	0.19	0.18	0.17	0.26	0.12
K_2O	0.05	0.11	0.07	0.11	0.06

2.3. Grain Size Analysis

Sieve analysis was used to determine the grain size distribution of the selected sand samples using a laboratory sieve shaker (Octagon 2000 Digital). The GFN, reflecting the sand's grain size distribution was calculated using Equation 1 [19].

$$\text{GFN} = \frac{\text{Product}}{\text{\% weight retained}} \quad (1)$$

The flowability and strength of molding sand are two characteristics that are strongly influenced by the grain shape. A Scanning Electron Microscope (SEM, EFI Inspect S50) was utilized to view the morphologies of the sand grains employed in this study. Several sand samples were tested for pH using an electronic digital pH meter (Microprocessor-based pH tabletop meter, Model: AD8000).

2.4. Determination of Bentonite Clay Content

Bentonite clay is a vital component in molding as it acts as a binder that holds sand grains together to form a solid mold. Maintaining the correct clay content in the green sand is crucial; too little clay results in a weak, brittle mold, while excessive clay makes the mold too rigid and prone to cracking. Precise control of clay content is essential for producing high-quality sand-cast parts.

To determine the clay content, 250 grams of each sand sample were weighed and placed in a wash bottle. A mixture of 475 ml distilled water and 25 ml sodium hydroxide was added, and the bottle was agitated for 10 minutes. After filling the bottle to the marked level with water, it was stirred and allowed to settle. The liquid was siphoned off, and the remaining wet sand was dried in an oven at 105 ºC. This process was repeated three times for each sample, and the average clay content was calculated and expressed as a percentage.

2.5. Loss on Ignition Analysis

The amount of volatile compounds in molding sand is determined by the Loss on Ignition (LI) test. In this test, 10 grams of sand is placed in a crucible and heated at 100 °C for 2 hours in an electric oven and then allowed to cool inside the oven. This process burns off or vaporizes volatile materials such as moisture and organic compounds, resulting in a loss of weight. The weight loss is then calculated to determine the percentage of volatile materials in the sand. This measurement is crucial because high levels of volatile materials can impact the quality and stability of the sand mold during casting. The formula for calculating LI% is represented by Equation 3 [19].

$$\text{LI}(\%) = \frac{(\text{Initial sand weight} - \text{Final sand weight})}{\text{Initial sand weight}} \times 100 \quad (3)$$

2.6. Permeability Testing

Permeability in a sand mold measures how quickly air flows through a compacted green sand sample under controlled pressure. This property is assessed using a Ridsdale-Dietert permeability meter, which evaluates airflow through a prepared green sand specimen. The resulting value called the permeability number, is determined using the relationship given by Equation 2 [11], and it quantifies the mold's ability to let air and gases escape during the casting process.

Permeability Number (PN)= VH/PAT (2)

Where,
V= Volume of air passing through the sample (cm^3), H= Height of the Green sand sample (cm)
A= cross-sectional area of the sand sample (cm^2), P= Air pressure (cm of water), T= Time (sec.)

2.7. Mold Strength Testing

Standard sand molds, 5.08 cm in height and diameter, were prepared using a sand rammer. Tests conducted on these specimens included Green Compression Strength (GCS), Green Shear Strength (GSS), Dry Compression Strength (DCS), and Dry Shear Strength (DSS) using a Ridsdale-Dietert hand-operated universal sand strength machine. Green strength tests assessed the sand mold's ability to withstand its own weight and casting pressure, while dry strength tests evaluated resistance to hot metal erosion. For dry strength, specimens were heated at 105 °C for 2 hours in an electric oven (Matest Brand) to remove moisture and then allowed to cool before testing. These tests ensured the sand's performance and durability in casting.

2.8. Shatter Index Testing

The impact resistance of the sand mold was evaluated by dropping it from a height of 1.83 meters onto a steel anvil, allowing it to fall freely using a Ridsdale-Dietert Shatter Index tester. The toughness or plasticity of the sand mold was then determined by measuring the degree of disintegration that resulted. Equation 4 [11] represents the formula used to obtain the Shatter index (SI).

$$\text{SI} = \frac{(\text{Weight of sand remained on 13.2 mm mesh sieve})}{\text{Total weight of sand specimen}} \times 100 \quad (4)$$

2.9. Surface Roughness Measurement of cast Al-Si alloy samples

Castings from five different sand molds were evaluated for surface roughness using an Elcometer E124-3M surface roughness tester. The surface roughness of the samples was determined by the Ra values measured at various points on the cast surface. Ra values were obtained from three different positions on each casting, and the average value was calculated.

3. Results and Discussions

3.1. Phase identification by XRD

Table 1 displays the chemical composition (wt.%) of the selected sand samples as determined by the Quantitative Inorganic Analysis technique. Quartz (SiO_2) is the main crystalline mineral, and SiO_2 and Al_2O_3 are the major phases found in all samples. Figure 2 displays the samples' XRD analysis results. There are significant variations in the diffraction intensity at 2θ angles. The dominant crystalline peak in the XRD patterns of all sand samples corresponds to SiO_2, indicating its presence as the primary crystalline mineral. This is beneficial for molding sand mixtures, as quartz provides permeability, refractoriness, and chemical resistivity. A higher silica content in the sand enhances its moldability for casting applications. Additionally, minor impurity minerals, such as $CaCO_3$ are detected in small quantities, as evidenced by their faint peaks in the XRD patterns. These findings suggest that the sand samples are primarily composed of quartz, with minimal impurities.

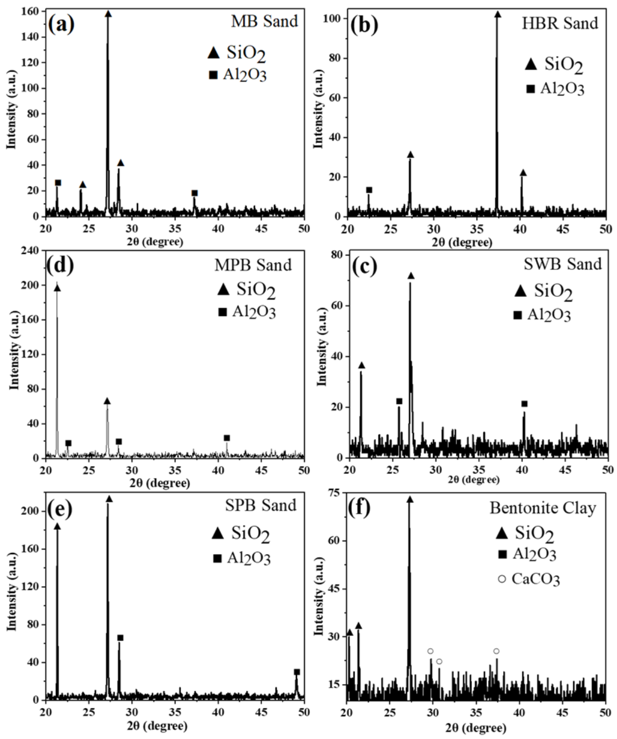

Fig. 2. XRD peaks showing the chemical composition of different sand samples (a) MB sand (b) HBR sand (c) SWB sand, (d) MPB sand (e) SPB sand (f) Bentonite clay. The XRD spectra depict the distinctive diffraction peaks corresponding to different mineral phases present in each sample

3.2. Grain Size Characterization

Figures 3 and 4 display the weight percentages of sand retained on each of the eleven sieves together with the matching GFN for various sand samples. The aperture size decreases as the sieve number rises. The sieves used in this study range from number 6 (3360 microns) to PAN (53 microns). A significant portion of sand (15–20%) is retained on sieve number 50, with noticeable quantities also found in sieves 100, 140, and 200.

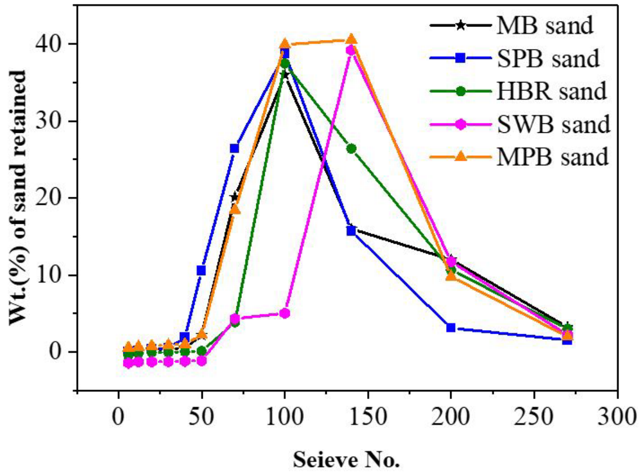

Fig. 3. Line graphs showing the weight retained on each sieve which is used to calculate the grain size. The higher fraction is retained on 75-150 sieves for all sand samples

The calculated GFN values for the sand samples from MB sand, HBR sand, SWB sand, MPB sand, and SPB sand are 100, 103, 106, 86, and 71, respectively. This indicates that the SWB sand is the finest, while SPB sand is the coarsest. Finer grain sands, as indicated by a higher GFN, have several practical implications for mold preparation. Sands with higher GFN require more thorough mixing with binders like bentonite clay and water to achieve the desired mold strength and permeability, leading to longer mixing times. Sands with higher GFN have increased surface area which necessitates more bentonite clay, raising both material and mixing and labor costs. Additionally, excessively high GFN can reduce permeability, increasing the risk of gas-related defects.

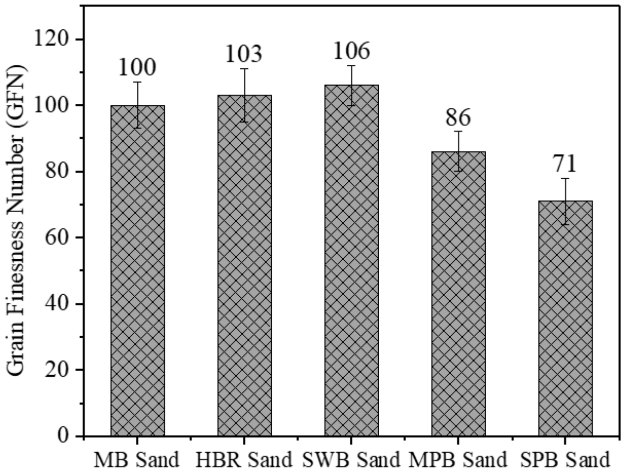

Fig. 4. Bar graphs illustrating the GFN of various sand samples. The GFN values for each sand sample are represented as bars, providing a comparison of the fineness of sands sourced from different locations

On the other hand, lower GFN values improve permeability but may lead to a coarser surface finish and weaker mold strength. Therefore, an optimal GFN is essential for producing high-quality casting molds. Burns [20] states that the GFN needed to cast non-ferrous metals should fall between 36 and 110. According to the findings, every sand sample that was chosen is appropriate for casting Al alloys. However, when choosing the best sand sample from the available possibilities, other important criteria must also be taken into account in addition to GFN.

3.3. Grain Shape

Figure 5 shows the SEM images of sand samples from all locations, captured at approximately the same magnification. The MB sand consists of sub-angular and elongated particles, while HBR sand contains angular, rounded, and elongated particles. The SWB, MPB, and SPB sands have a mix of rounded, sub-angular, and elongated grains, which improve binder cohesion and mold strength. Sub-angular to rounded grains promote even distribution of the sand-binder mixture during compaction and create more pores for gas escape during casting. These shapes allow the sand to interlock effectively, forming a dense mold with adequate porosity to prevent rupture.

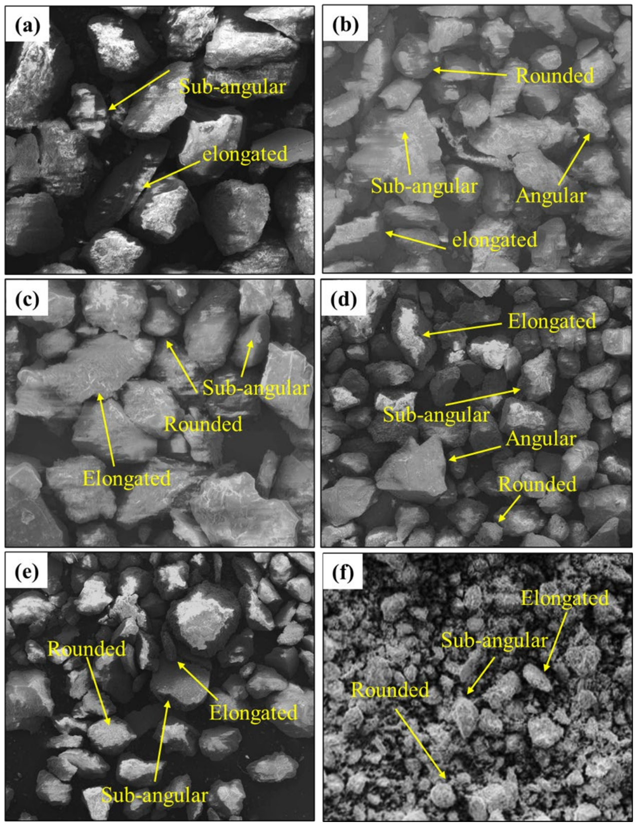

Fig. 5. SEM micrographs of sand samples providing a close-up view of the particle shapes, sizes, and surface characteristics of different sand samples (a) MB sand, (b) HBR sand, (c) SWB sand, (d) MPB sand, (e) SPB sand, and (f) Bentonite Clay

Angular grains, with their sharp edges, form stronger bonds, enhancing mold durability. However, they require more binder due to their larger surface area. Despite this, angular sands are preferred for demanding casting applications, as the added binder increases mold strength [21].

3.4. pH Value

The pH values of the MB, HBR, SWB, MPB, and SPB sands were determined to be 7.3, 7.5, 7.6, 7.9, and 8.02, respectively. According to research by Loto and Adebayo [22], higher alkalinity makes it easier for bentonite clay to be distributed optimally throughout the sand mixture, which improves the mechanical qualities of the final sand mold.

3.5. Bentonite Clay Content

Bentonite clay content in all these sand samples is given in Table 2. For Al-Si alloy casting, maintaining a bentonite clay content of 5 to 12% is essential for achieving optimal mold strength, surface finish, gas permeability, thermal stability, and ease of mold removal. These factors collectively contribute to the production of high-quality castings. Therefore, SPB sand having a bentonite clay content of less than 5% is not suitable for good castings unless further clay is added during mold making.

Table 2.
Bentonite clay content (%) of different sand samples

Sample	Sand Location				
	MB	HBR	SWB	MPB	SPB
Bentonite Clay (%)	5.12	5.36	6	4.9	4.4

3.6. Volatile Content

The volatile content was determined by loss on ignition test. This test also helps determine whether the sand mixture contains any organic compounds or chemicals that emit gasses when heated. MB, HBR, SWB, MPB, and SPB sands were found to have LI values of 0.7%, 0.4%, 0.71%, 0.37%, and 0.33%, respectively. Consistent with established guidelines, the ideal LI value should be below 3% [20]. This threshold ensures minimal impurities and optimal sand quality.

3.7. Permeability and Strength of Sand Molds

The permeability number (PN) and strength of molds with 5% bentonite clay (cross-sectional area of 25.81 cm^2), including GSS, GCS, DSS, and DCS, for all molds made from different sand samples, are presented in Table 3. The effect of increasing bentonite clay content on strength is illustrated graphically in Figure 6 (a-d). These measures allow for a thorough comparison of the various sand samples and offer insightful information about the sand's performance and appropriateness for different casting applications.

Table 3.
Permeability number and mold strength with 5% bentonite clay for different sand molds

Sand Sample	PN	GSS (KN/m^2)	GCS (KN/m^2)	DSS (KN/m^2)	DCS (KN/m^2)
MB sand	96	5	20	70	253
HBR sand	95	13	22	80	258
SWB sand	108	15	26	98	275
MPB sand	86	14	24	91	267
SPB sand	116	16	28	108	284
MB sand	96	5	20	70	253
HBR sand	95	13	22	80	258

Across all samples, a distinct pattern shows that the mold strengths steadily rise as the bentonite clay proportion does. This is explained by bentonite clay's binding qualities, which reinforce the mold by improving the cohesiveness and adhesion between the sand grains. Higher GCS, DCS, GSS, and DSS values result from the mold's improved resistance to compression and shear pressures due to the increased bentonite clay content. This association emphasizes how important bentonite clay is in foundry applications and how it significantly increases mold strength. It has been demonstrated that the SWB sand has a higher mold strength than the other four sand samples due to its finer grain size. The optimal GCS and DCS for casting Al alloys are 50–70 KN/m^2 and 200–550 KN/m^2, respectively. Al alloys are prone to casting flaws such as blowholes and pinhole porosity, thus the sand mold must have enough strength and permeability. This lessens the possibility of flaws by allowing the hot vapors produced during the pouring operation to exit the mold. The findings demonstrate that all sand types are suitable for Al alloy casting applications since they all attain GCS and DCS values within the suggested range at a 10 (wt.%) bentonite clay addition.

The findings show a positive relationship between the sand molds' GSS and DSS and their bentonite clay content, with both characteristics rising as the bentonite content does. However, it's important to note that excessive bentonite clay addition can compromise the reusability and lifespan of the molding sand, which is undesirable. Considering these factors, an optimal bentonite clay content of 10 (wt.%) is identified as the sweet spot, striking a balance between enhanced mold strength and maintaining acceptable reusability and lifespan of the molding sand mixture.

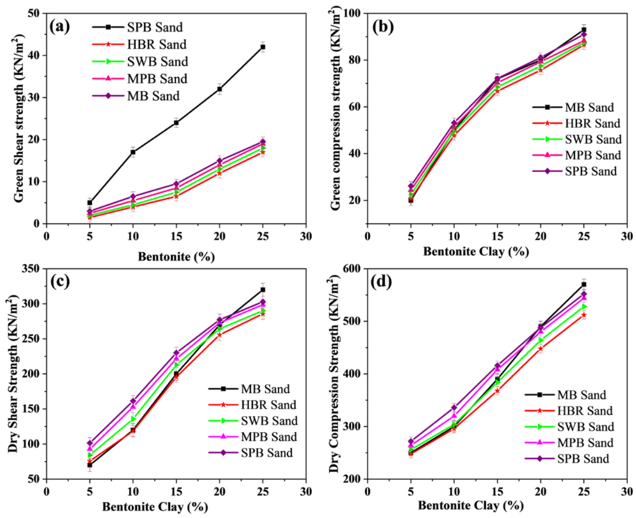

Fig. 6. Variation of strength properties with increasing bentonite clay content. (a) Green shear strength (b) green compression strength (c) dry compression strength (d) Dry Shear Strength

3.8. Shatter Index

It is known that a low shatter index of sand mold value can lead to friability during mold withdrawal, while excessively high values may be detrimental, as they can hinder the final removal of castings after solidification and require greater force to break the mold, or even damage the casting during removal. A shatter index in the range of 85% to 95% is generally considered ideal for sand molds to ensure sound casting [23]. An ideal collapsibility value falls within this range, making it possible to remove the casting from the mold with ease and without causing any harm. The shatter index of the different sand molds made from different sand samples is given in Table 4. All sand mold samples exhibited shatter index values within the range of 82% to 87%.

Table 4.
Shatter Index (%) of molds made from different sand samples

Sample	Sand Location				
	MB	HBR	SWB	MPB	SPB
Shatter Index (%)	85	86	83	82	87

3.9. Effect of Different Sands on the Surface Roughness of Al-Si Casting Samples

Al-Si alloys, known for their excellent casting properties and mechanical performance, were cast using molds made from different sand samples. The surface roughness of the LM-13 alloy castings, measured by Ra values, is summarized in Table 5. Surface roughness significantly impacts mechanical and corrosion properties—smoother surfaces improve fatigue life and resistance to wear, while rougher surfaces lead to stress concentrations, reducing strength. The mold made from SPB sand, with a GFN of 71, resulted in the roughest casting surface (3.6 µm), whereas the mold from SWB sand, with a GFN of 106, produced the smoothest surface (1.68 µm). The results suggest that finer sand grains (higher GFN) yield castings with smoother surfaces. For high-quality castings, SWB sand is recommended due to its 6% bentonite clay content and superior surface finish capabilities.

Table 5.
Surface Roughness of cast products

Sample	Sand Location				
	MB	HBR	SWB	MPB	SPB
SR (Ra) (µm)	1.96	1.80	1.68	2.5	3.6

To further analyze surface characteristics, SEM images of LM-13 alloy castings produced using molds from different sand samples are shown in Figure 7. SEM analysis shows the primary α-Al phase and eutectic silicon phase in the microstructure [24]. Needle-like precipitates were found at grain boundaries, while spherical precipitates were distributed in the Al matrix. Overall, the surface of all castings appears smooth, with no visible cracks or unwanted impurities.

Since the primary focus of this paper is on evaluating the foundry properties of locally sourced molding sand with bentonite clay additions for cost-effective Al alloy casting, an in-depth discussion of the cast alloy's microstructure falls outside the scope of this study.

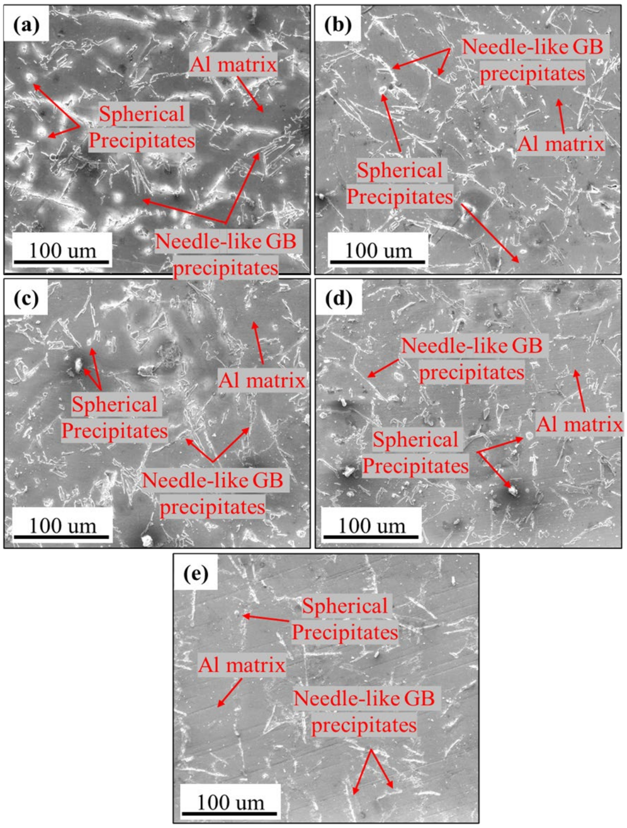

Fig. 7. SEM images of a casted LM-13 Al-alloy sample in molds made from different sand types, showing the morphology of precipitates in the Al matrix: (a) MB sand, (b) HBR sand, (c) SWB sand, (d) MPB sand, and (e) SPB sand. The images highlight the variation in precipitate distribution and morphology within the aluminum matrix

4. Conclusions

The following results are derived from the aforementioned investigation:

- Of all the sand samples, the sand from Syed Wala Bridge had the highest grain fineness number (~106), while the sand from Sheraza Pattan Bridge had the lowest (~71).
- All of the sand samples had pH values higher than 7, indicating that they were alkaline.
- The strength of the sand mold increased with an increase in bentonite clay from 5% to 25% for all sand samples.
- All of the sand samples had Loss on Ignition values < 3%, which is a desirable range for creating castings of superior quality.
- The sand from Syed Wala Bridge is recommended as the best option for foundry applications, as the castings produced using this sand sample exhibited the lowest surface roughness, approximately 1.68 µm
- Future studies could explore the long-term durability and performance of these sands in repetitive casting cycles.

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