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Application of Biomass-Derived Binders in Sand Casting for Sustainable Foundry Practices

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Abstract: *There is a huge requirement for environmentally compatible alternatives due to the increased environmental problem associated with synthetic resin binders in sand casting, for example, their poor recyclability and toxic gas emission. This research investigates the use of binders produced using biomass for green foundry practice. Once incorporated into silica sand molds, renewable ingredients like starch, molasses, lignin, and dextrin were systematically compared to conventional resin-bonded sand. Casting trials with non-ferrous alloys were performed following assessment of critical mold properties like green strength, dry strength, permeability, and collapsibility. Surface polish, accuracy of dimensions, and defect development were studied in the castings so formed, and the environmental cost was quantified through gas evolution tests. Based on initial findings, optimised biomass binder formulations are able to provide the same casting quality as traditional binders but, in addition, provide adequate mould strength, improved collapsibility, and a substantial reduction in toxic emissions. Based on the research, biomass-based binders present modern-day foundries with an economical and green solution that encourages the transition to green manufacturing and circular economy standards.*

Keywords: Sand Casting, Biomass Binder, Sustainable Foundry, Eco-Friendly Binders, Green Manufacturing

I. INTRODUCTION

Due to its cost-effectiveness and ability to handle complex geometries, sand casting continues to be among the most conventional and versatile metal-forming techniques, accounting for between 60 and 70 percent of world casting output [1]. Binders are critical to the sand casting process since they impart strength, permeability, and thermal stability to molding sand. Due to their high strength and dimensional accuracy, conventional binders such as sodium silicate, furan resins, and phenolic resins have been extensively used in foundries [2]. These binders also have some disadvantages, including poisonous gas emissions, huge energy expenditures on mold reclamation, and ecological hazard [3].Volatile organic compounds (VOCs), SOx, NOx, and polycyclic aromatic hydrocarbons (PAHs) are emitted when chemical binders decompose during molten metal pouring. These chemicals have a detrimental influence on employee security and cause pollution of the environment [4].

A trend toward more sustainable foundry methods, centered around the utilization of low-emission, bio-based, and renewable binder systems, is increasing in response to these concerns [5]. Biomass-derived binders such as starch, molasses, dextrin, guar gum, and lignin have been identified as promising alternatives. Since they are produced from agro-industrial and agricultural waste, these materials are abundant, cost-effective, and carbon neutral [6].Natural binders have been said to provide adequate mold strength with the additional benefit of significantly improving collapsibility and reducing dangerous gas emissions [7]. For small and medium-sized foundries who want to adopt green technologies, this renders them particularly suitable. Despite these advantages, problems of non-uniform mechanical performance, low hot strength, and sensitivity to moisture are hindering the widespread application of biomass binders [8].

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Mold properties have been enhanced due to recent advances in binder modification, for example, the inclusion of chemical cross-linkers or blending natural binders with bentonite [9]. In addition, in contrast to conventional binders, biomass binders can significantly reduce the environmental footprint of sand casting, as well illustrated by application of life cycle assessment (LCA) approaches [10].Hence, there is an urgent requirement for rigorous experimental assessment of binders originating from biomass to evaluate their viability as an alternative to synthetic resins. This research seeks to examine the performance of varied biomass binders with respect to green strength, dry strength, permeability, collapsibility, casting quality, and gas emissions, and determine optimized binder compositions that can be utilized in sustainable foundry practices. The results of this research are anticipated to facilitate the shift towards environmentally friendly casting processes, in coherence with global initiatives within Industry 5.0 and circular economy philosophies.

II. LITERATURE REVIEW

As binders influence mold strength, collapsibility, gas evolution, and finally casting quality, their performance has always been of paramount importance to the sand casting process. Due to their higher mechanical strength and dimensional stability, conventional organic binders such as urea-formaldehyde, furan resins, and phenolic resins have been used in foundries for centuries. Nevertheless, various studies have identified their primary disadvantage, which is the large amounts of release of hazardous air pollutants (HAPs), polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds during shakeout and pouring [1], [2]. Binder degradation contributes to as much as 70% of a foundry's volatile organic compounds (VOC) emissions, which are harmful to the environment as well as to its workers [3]. Consequently, there is increasing pressure on contemporary foundries to use sustainable and green binder. Consequently, there is increasing pressure on contemporary foundries to implement sustainable and eco-friendly binder systems. To this end, inorganic binders such as geopolymer systems and water-glass (sodium silicate) have been of interest. These binders are characterized by good collapsibility, high hot strength, and low gas emissions [4]. Detracts from their broader industrial use include reclamation issues, low storage stability, and sensitivity to moisture [5]. Hybrid binder systems, such as organo-bentonite mixes, have been proposed to enhance strength and collapsibility while reducing hazardous emissions [6].

Studies have come to center on biomass-derived binders, including lignin, guar gum, molasses, dextrin, and starch, to address sustainability concerns. These materials offer a cost-effective and eco-friendly alternative to petrochemical-based resins because they are renewable, biodegradable, and can be easily obtained from agricultural and agro-industrial waste products [7]. The three processes that give rise to the production of polymeric gels (starch and dextrin), sugar cross-linking (molasses), and thermal softening or char formation (lignin) are those that give rise to their binding mechanism [8]. When compared to synthetic resins, the natural binders provide better collapsibility, reduced toxic gases emitted, and sufficient green and dry strength for castings of non-ferrous, as proven by many studies [9]. In addition, their disintegration usually yields more straightforward combustion products, minimizing risks to the workplace [10].

Despite these advantages, biomass binders do have limitations.Via chemical modification (e.g., esterification, etherification, and grafting) and blending them with bentonite or inorganic materials, efforts have been made to improve their performance [12].These strategies have shown promising improvements in water resistance and heat strength with maintaining environmentally desirable attributes. Compared to petrochemical counterparts, biomass binders can significantly reduce the carbon footprint of casting operations, as determined by life cycle assessment (LCA) studies [13].

Their biodegradability and renewable nature are congruent with Industry 5.0 and the circular economy principles of resource efficiency and sustainable production. Mass industrial implementation remains riddled with challenges, however, particularly with regards to ensuring constant quality, compatibility with existing foundry equipment, and effective sand reclamation [14]. To sum it up, studies show that biomass binders possess a lot of potential as environmentally friendly alternatives to conventional binders in sand casting. They can reduce the environmental impact of foundries, enhance collapsibility, and minimize poisonous emissions. Their mechanical limitations, process sensitivity, and scalability issues, on the other hand, call for increased experimental research into their need. To

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establish their industrial applicability and sustainability benefits, further studies need to focus on optimizing binder formulations, performing comprehensive emission studies, and integrating entire life cycle assessment methodologies.

III. MATERIAL & METHOD

A. Material

The molding medium chosen for this research work was silica sand with an average grain fineness number of 55, which is a commonly used foundry practice material. The following binders derived from biomass were explored as substitutes for traditional phenolic resin:

- Starch (corn-based, powdered form)
- Molasses (sugarcane industry by-product, liquid with viscous consistency)
- Lignin (alkali lignin recovered from paper mill waste)
- Dextrin (partially hydrolyzed starch, powdered form)

Each binder was blended with silica sand at various weight percentages (2–8 wt.%) with controlled water addition (2–3 wt.% for starch/dextrin, 1–2 wt.% for lignin/molasses). As a reference, a series of specimens was prepared with 5 wt.% phenolic resin binder.

B. Specimen Preparation

According to AFS standards, test specimens were prepared to determine green compressive strength, dry strength, permeability, and collapsibility. Hand ramming was employed to ensure uniform compaction in specimen molding.

C. Mechanical Test of Mold

- The Universal Sand Testing Machine (UTM) was employed to determine the Green Compressive Strength.
- The samples were oven dried for two hours at 110 °C prior to their dry strength being determined.
- Permeability was determined using the AFS permeability meter.
- Collapsibility was determined by heating bonded specimens to cast temperature (900–1000 °C) and determining residual strength.

D. Trials for Casting

In order to determine the efficiency of the binder under real foundry conditions, a simple brass alloy (Cu–Zn) was employed as casting metal. The brass was melted in an oil-heated crucible furnace and then cast into sand molds prepared at 1000 ± 10 °C. Castings were cleaned and subjected to the following treatments after solidification:

- Measurement of surface finish (by means of a surface profilometer to obtain the Ra value)
- Vernier caliper and CMM for certain samples for verification of dimensional accuracy.
- Examination of defects (visual, radiography, microstructure in the region around defect areas)

E. Assessment of the Environment

A gas chromatography system was utilized to quantitate gas evolution on mold-metal contact. Resin-bonded and biomass-binder molds were tested for CO, CO_2, SO_2, and VOC levels.

IV. RESULT & DISCUSSION

A. Mechanical Properties of Molding Sand

As per the test results, green compressive strength of biomass-bonded sands was marginally less than that of resin-bonded sands but remained in an acceptable range for mold handling. Molasses (6 weight percent) exhibited the highest green strength (125 kPa) among all the binders, followed by lignin (110 kPa), starch (105 kPa), and dextrin (95 kPa). In comparison, green strength of phenolic resin-bonded sand was approximately 140 kPa.

The dry strength values were also similar in pattern, with starch and dextrin giving moderate strength and molasses and lignin providing relatively higher bonding due to heat polymerization of organic ingredients. Surprisingly, the dry

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strength of lignin-bonded sand (380 kPa) was quite close to that of resin-bonded sand (420 kPa). Permeability-wise, biomass-bonded sands compared favourably with resin-bonded sand. Starch and dextrin molds possessed 15–20% greater permeability values, allowing gasses to be released more freely during pouring. This indicates a reduced tendency for blowholes and other gas-related defects in the casting. With respect to resin-bonded molds, biomass-bonded molds were much more collapsible. Biomass molds lost nearly 60% of residual strength after exposure to molten brass at 1000 °C, whereas resin-bonded molds retained 40–50% of strength. Due to the fact that it minimizes casting stresses and facilitates shakeout, this property is highly desirable.

B. Casting Trial Results

With linear shrinkage values comparable to resin-bonded sand molds, the brass castings produced in biomass-bonded molds exhibited accurate dimensions. Starch-bonded and dextrin-bonded molds exhibited marginally higher surface roughness (Ra) values (~8–10 µm) compared to resin-bonded molds (~6 µm). However, lignin- and molasses-bonded molds exhibited a surface polish of approximately 7 µm, which was satisfactory and foundry compliant.

Analysis of defects indicated that enhanced permeability in starch- and dextrin-bonded castings led to lower gas porosity. Conversely, since sugar-type compounds failed to fully decompose, local carbon-rich surface layers were evident in some molasses-bonded castings at times. Lignin-molded castings demonstrated optimal strength, permeability, and surface finish balance, creating flaw-free castings with minimum defects.

C. Environmental Performance

In the comparison between biomass binders and resin binders, gas evolution studies revealed significant reductions in toxic gas emissions. While starch- and dextrin-bonded molds predominantly emitted CO_2 and water vapor, phenolic resin-bonded molds emitted high levels of VOC, SO_2, and phenol fumes. Even though lignin and molasses emitted slightly higher CO due to incomplete combustion, their emissions were 30–40% lower than those of resin-bonded molds [1].

This is a testament to the viability of biomass binders as acceptable alternatives environmentally, lending support to the international effort to reduce harmful emissions and carbon signatures in foundries.

Table 1 – Mechanical Properties of Biomass vs. Resin Binders

Binder Type	Green Strength (kPa)	Dry Strength (kPa)	Permeability (No.)	Collapsibility (%)	Remarks
Phenolic Resin (Control)	140	420	85	40	High strength, low permeability, difficult shakeout
Starch (6 wt.%)	105	310	100	65	Good permeability, higher collapsibility, slightly rough surface
Dextrin (6 wt.%)	95	295	102	68	Highest permeability, best collapsibility, moderate strength
Molasses (6 wt.%)	125	370	92	60	High strength, acceptable surface finish, risk of carbon pickup
Lignin (6 wt.%)	110	380	95	63	Balanced properties, good casting quality, best substitute

Table 2 – Casting Trial Observations

Binder Type	Surface Roughness (Ra, µm)	Dimensional Accuracy	Defect Tendency	Observations
Phenolic Resin	6.0	Excellent	Low gas porosity	Best surface finish, but high toxic emissions
Starch	9.0	Good	Very low porosity	Slightly rough surface but eco-friendly
Dextrin	10.0	Good	Very low porosity	Highest permeability, easy shakeout
Molasses	7.0	Good	Occasional carbon pickup	Strong molds, minor surface carbonization
Lignin	7.0	Very Good	Minimal defects	Best compromise of strength, finish & eco-performance

Table 3 – Environmental Performance (Relative to Resin)

Binder Type	Gas Emissions (VOC, SO_2, Phenols)	CO/CO_2 Emissions	Eco-Impact Compared to Resin
Phenolic Resin	Very High	Moderate CO, VOCs	Poor (toxic fumes, harmful residues)
Starch	Very Low	Mainly CO_2, H_2O vapor	Excellent (eco-friendly, renewable)
Dextrin	Very Low	Mainly CO_2, H_2O vapor	Excellent (low emission, safe)
Molasses	Low–Moderate	$CO + CO_2$	Good (30–40% lower toxic gases than resin)
Lignin	Low	$CO + CO_2$	Very Good (balanced emission control)

V. RESULTS AND DISCUSSION

Prospective results for eco-friendly sand casting result when binders developed from biomass are compared to the conventional phenolic resin. Uses requiring easy shakeout may take advantage of the excellent collapsibility and environmental friendliness of starch and dextrin, which showed moderate green and dry strength. Molasses maintained excellent environmental performance with a greater dry strength that was comparable to resin. Lignin was found to be a successful all-around binder because it balanced its strength, permeability, and surface polish. The benefit of biomass substitutes is exemplified by the poor environmental performance of phenolic resin, even though it has higher mechanical strength and surface polish. All things being equal, binders from biomass have the potential to replace synthetic binders in green foundry operations since they significantly reduce their detrimental impacts on the environment while maintaining satisfactory quality castings.

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