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Predictive Modelling of Time-Dependent Green Sand Moulding Parameters Using the Taguchi Method

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Abstract

Green sand mould quality plays a pivotal role in casting reliability and dimensional accuracy, yet mould properties degrade over time due to environmental exposure and production delays. This study examines the time-dependent behaviour of critical mould characteristics – green compressive strength (GCS), mould hardness, and permeability – under varying process conditions. Using a Taguchi L27 orthogonal array, the effects of moisture content, ramming time, and holding time were systematically evaluated across 27 experimental setups, with sequential moulding under realistic foundry conditions. Regression models were developed to predict property degradation based on mould age, which is defined as the cumulative moulding and holding time. Results highlight that optimal property retention occurs at moderate ramming times, higher moisture content, and shorter holding periods. Case 2 (4% moisture, 5-second ramming, 10-minute holding) demonstrated the most favourable balance of strength, hardness, and gas permeability. The predictive models exhibited high accuracy ($R^2 > 0.94$), supporting their data-driven mould quality control application. These findings offer practical insights to improve maintainability, reduce casting defects, and enhance process reliability in sand casting operations. The research contributes to the broader goals of sustainable manufacturing and production system optimisation through statistically guided process management.

Keywords

Green sand moulding, process parameters, mould parameter degradation, mould age.

Introduction

The foundry sector constitutes a critical segment of the global manufacturing landscape, underpinning the production of vital components across automotive, aerospace, construction, energy, and agriculture industries. With global casting volumes exceeding 100 million tonnes annually, the economic and technological significance of this sector is indisputable. In emerging industrial economies such as India, small and medium-scale foundries represent a substantial proportion of the casting industry, contributing to both domestic supply chains and international exports (Doroshenko & Yanchenko, 2024; Kakade et al., 2023; Taub, 2023). Modern manufacturing systems, particularly those within the foundry sector, are undergoing significant transformation driven by the principles of Industry 4.0. This paradigm shift emphasises the integration of cyber-physical systems, automation, and intelligent data analytics to enhance operational efficiency and adaptability. In such environments, the interaction between technical systems, human operators, and the production context must be carefully managed to optimise performance. Smart manufacturing systems, enabled by machine-to-machine communication and real-time decision-making, adjust operational parameters dynamically in response to changing production requirements, resource constraints, and quality standards. These capabilities lay the foundation for intelligent foundries delivering consistent, high-quality castings under varying process conditions.

Within this context, green sand moulding presents both a challenge and an opportunity. Traditionally reliant on static quality control methods, the process does not fully account for time-dependent changes in critical mould properties such as strength, hardness,

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and permeability, particularly during the interval between moulding and pouring. As demonstrated in this study, foundries can transition towards proactive, data-driven mould quality management by applying predictive modelling and statistical optimisation techniques. This approach aligns with the objectives of Industry 4.0 by enabling responsive process control, reducing variability, and supporting sustainable manufacturing practices. Integrating such methods contributes to the development of adaptive production environments that enhance casting reliability and operational effectiveness in real-world industrial settings (Calabrese et al., 2019; Chakraborty et al., 2023; Paolanti et al., 2018; Romeo et al., 2018)

Green sand moulding remains dominant among moulding technologies due to its operational flexibility, cost efficiency, and capability to accommodate intricate geometries. Despite these advantages, the process is inherently sensitive to fluctuations in key moulding sand parameters – green compressive strength (GCS), surface hardness, moisture content, and permeability. These properties are highly dynamic and subject to degradation during the interval between mould preparation and molten metal pouring, a critical timeframe referred to as *mould age*. Variations in mould properties during this period can adversely affect dimensional accuracy, surface finish, and overall casting integrity (Borisade et al., 2023; Darshak A Desai, 2015; Sika & Ignaszak, 2020).

Current quality control practices in many foundries are predominantly static, relying on discrete measurements that do not adequately capture the temporal evolution of mould characteristics under real operational conditions. This disconnect between process dynamics and quality assurance represents a significant limitation in the drive toward reliable and consistent casting performance.

This study addresses this limitation through an experimental investigation into the time-dependent behaviour of green sand mould properties, considering the influence of key process parameters: moisture content, ramming time, and holding time. Employing a Taguchi L27 orthogonal array, the research systematically evaluates parameter interactions and their impact on property degradation. Predictive regression models are developed to quantify these changes, offering a robust analytical framework for proactive mould quality management. The outcomes of this research support data-driven decision-making and provide a foundation for integrating predictive maintenance and quality control into modern, computer-integrated foundry operations aligned with the principles of Industry 4.0 (Elam et al., 2006; Kumar et al., 2011a).

Literature review

Green sand casting is the most versatile process used in manufacturing due to its excellent design flexibility, complex shapes, and ability to reclaim silica sand (Kul et al., 2021; Mrzygłód et al., 2023). Modern foundries seek alternative moulding materials to replace the high-cost silica sand partially (Sandeep et al., 2019). Moisture content is critical in determining the strength and permeability of green sand used in casting moulds. Optimal moisture levels are essential for achieving high green compression strength and adequate permeability, while deviations from this range can significantly reduce mould quality. Green compression strength increases with moisture content up to an optimal point, after which further moisture addition leads to a decline in strength. For example, 5% moisture yielded the highest green compression strength in Yola natural sand, while 3–3.5% moisture was optimal for tailing sands with 4% clay content (Abdullah et al., 2012a, b; Ihom et al., 2012) The interaction between moisture and clay content is crucial; both must be balanced to maximise strength and minimise casting defects (Gui-Li et al., 2012; Meshkabadi, 2013). Excessive moisture reduces strength due to the weakening of sand grain bonds, while insufficient moisture leads to poor compaction and weak moulds (Ihom et al., 2012). Permeability (the ability of gases to escape the mould) depends on moisture content. Optimal permeability is achieved within a specific moisture range (typically 3–3.5% for certain sands), thus it ensures that the gases can escape without compromising mould integrity (Abdullah et al., 2012a, b; Gui-Li et al., 2012; Ihom et al., 2014; Kul et al., 2021). Too much moisture fills the voids between sand grains, reducing permeability and increasing the risk of casting defects like gas porosity (Ajay & Sharma, 2023; Gal & Nowak, 2021; Gui-Li et al., 2012; Udeorah et al., 2023) The combined effect of moisture and clay content is significant; both must be optimised for best permeability. To best balance strength and permeability, moisture content must be carefully controlled in green sand moulds. Both properties are important within a specific moisture range, and deviations can lead to casting defects or poor mould performance. The optimal moisture level of a green sand mould depends on the sand and clay composition. It typically falls between 3% and 6%. Ramming time is a key factor in sand compaction processes, directly influencing the density and porosity of sand, which in turn affects gas permeability and the risk of gas porosity defects. Longer ramming times generally increase sand compaction, reduce porosity, and lower gas permeability, thereby minimising gas porosity issues. Mechanical compaction is the primary process for reducing porosity in sand and sandstone. As compaction increases (such as with longer ramming time), porosity decreases significantly, especially during the initial stages of compaction. This reduction in porosity is a primary factor in improving the density and strength of the sand structure (Brzesowsky et al., 2014; Houseknecht, 1987; Xia et al., 2020). Experiments and models show that the greater the initial porosity, the more pronounced the reduction in porosity with compaction. Compaction-induced porosity reduction is most significant during the early stages. It tapers off as the sand becomes denser (Brzesowsky et al., 2014; Watanabe et al., 2022; Xia et al., 2020) The relationship between compaction and gas permeability is strong: as compaction increases, both porosity and gas permeability decrease, improving the sand's ability to resist gas migration (Dou et al., 2025; Tanikawa et al., 2019; Xia et al., 2020). Despite extensive research on the influence of individual process parameters in green sand moulding, a critical limitation persists in existing literature: most studies treat these parameters as static and uniformly distributed across all moulds. However, moulds are rarely poured immediately after preparation in practical foundry operations. Factors such as batch sequencing, handling delays, and workflow variability lead to significant time gaps between moulding and pouring, during which the properties of green sand moulds – particularly moisture content, strength, hardness, and permeability – undergo measurable changes. No study has investigated the time-dependent variability of green sand process parameters at the level of individual moulds. Existing experimental and optimisation frameworks (such as Taguchi, DoE, or ANN-based models) often overlook mould age as a dynamic variable, resulting in incomplete or non-generalizable insights for industrial implementation. This study fills that gap by focusing explicitly on the temporal degradation of mould properties, linking it to measurable process parameters and real-world handling conditions (Edoziuno et al., 2021; Jakubski & Dobosz, 2010a, 2010b; Ksk, 2019; Kumaravadivel et al., 2012; Parappagoudar et al., 2013; Tiwari et al., 2016).

Materials & Methods

The current research addresses this gap by analysing the degradation of green sand mould properties over time, as influenced by critical process variables: moisture content, ramming time, and holding time.

Objective of study

This study investigates the time-dependent behaviour of green sand mould parameters under controlled yet realistic foundry conditions. Specifically, the study aims to evaluate the effects of three critical process variables – moisture content, ramming time, and holding time – on key mould characteristics including green compressive strength (GCS), mould hardness, and permeability. The study aimed at understanding the degradation patterns of these parameters over time and identifying trends that contribute to mould deterioration or stability. This enables data-driven process optimisation and proactive defect prevention in green sand casting environments.

Time intervals

Measurements were taken at fixed intervals after mould preparation to capture the dynamic variation of green sand mould parameters over time. For each batch of 10 moulds, the moulding time was 2 minutes. Moisture content, permeability, mould hardness and green compressive strength were measured in each mould sequentially (0, 3, 6, ..., 30 minutes). This time-resolved sampling allowed observation of property degradation trends (moisture loss, strength reduction, hardness increase, and permeability rise), which are often overlooked in conventional studies that assume mould properties remain constant.

Mould making time and mould holding time

- **Mould Making Time** was consistently maintained at 2 minutes per mould, reflecting the average production cycle in a typical foundry setup. This duration includes pattern positioning, ramming, and box removal.
- **Mould Holding Time** was varied systematically (10, 20, 30 minutes) as a key experimental variable. It directly contributed to mould age, influencing the extent of moisture evaporation, temperature equilibration, and surface hardening – all of which affect the final mould integrity.

Design of experiments (DoE) for mould combinations

Using a statistically structured Taguchi L_{27} orthogonal array, this study evaluates 27 parameter combinations under practical foundry conditions (Guharaja et al., 2006; Kumar et al., 2011b; Kumaravadivel et al., 2012; Singaram, 2010; Upadhye & Keswani, 2012). Each experimental setting involved the preparation of 10 moulds. The mould age is calculated as the sum of a fixed 2-minute moulding time and varying holding durations. As each mould in the batch was prepared sequentially with an average moulding time of 2 minutes, the age of each mould increased incrementally relative to its position in the sequence. When the second mould was completed at 18 minutes, the first mould had already been sitting idle for 2 minutes, making its age 4 minutes by the time the second was finished. Similarly, when the third mould was completed at 16 minutes, the first mould had aged four more minutes (total of 6 minutes), and the second had aged 2 minutes. Thus, the mould age increased linearly by 2-minute intervals across the 10 moulds, reflecting their progressive exposure time before pouring. This sequential ageing setup enabled the study to examine the time-dependent degradation of mould properties under consistent process conditions. Following this logic, each successive mould was completed 2 minutes earlier than before, resulting in the following mould ages just before pouring (assuming pouring starts at the end of the moulding process, i.e., at 30 minutes).

The aim is to capture and model the systematic deterioration of mould characteristics, enabling predictive process control and providing practical insights for improving casting consistency and operational efficiency. Table 1 presents the three key process parameters selected for this study and the three levels assigned to each based on standard foundry practices and operational feasibility.

Table 1
Experimental Parameters and Their Assigned Levels in Taguchi L_{27} Design

Parameter	**Level 1**	**Level 2**	**Level 3**
Moisture Content	3.5	4.0	4.5
Ramming Time (Sec.)	3	5	7
Holding Time (Minutes)	10	20	30

These levels were systematically combined using a Taguchi L_{27} orthogonal array to evaluate individual and interactive effects on mould property degradation. Table 2, below, outlines the 27 experimental runs derived from the Taguchi L_{27} orthogonal array. Each row represents a unique combination of moisture content, ramming time, and holding time.

These combinations were used to study the effect of individual and interactive parameters on the degradation of green sand mould properties under realistic foundry conditions. For each of the 27 experimental combinations defined in the Taguchi L_{27} orthogonal array, 10 green sand moulds were prepared sequentially, resulting in 270 moulds. These moulds were produced under controlled conditions using standard foundry practices. Following preparation, each mould was exposed to ambient foundry conditions, and key process parameters – moisture content, green compressive strength (GCS), mould hardness, and permeability – were measured individually. This allowed for the creation of a unique process parameter set for each mould,

Table 2
Full Factorial Design Matrix for L27 Orthogonal Array Experiments

Combination No.	**Moisture Content (%)**	**Ramming Time (Sec)**	**Holding Time (Min)**
1	3.5	3	10
2	3.5	3	20
3	3.5	3	30
4	3.5	5	10
5	3.5	5	20
6	3.5	5	30
7	3.5	7	10
8	3.5	7	20
9	3.5	7	30
10	4	3	10
11	4	3	20
12	4	3	30
13	4	5	10
14	4	5	20
15	4	5	30
16	4	7	10
17	4	7	20
18	4	7	30
19	4.5	3	10
20	4.5	3	20
21	4.5	3	30
22	4.5	5	10
23	4.5	5	20
24	4.5	5	30
25	4.5	7	10
26	4.5	7	20
27	4.5	7	30

capturing its condition at a specific mould age. The collected data was then used to analyse within-batch variability and assess how the properties degraded over time due to handling and environmental exposure. These mould-level observations identified consistent trends and degradation patterns, which were later modelled to establish predictive relationships between the input variables and the evolving mould characteristics. Figure 1 shows the process variation in the moulds (Pandit & Deshpande, 2021; Pandit et al., 2025; Pandit & Deshpande, 2023).

Moisture content plays a critical role in sand mould production, as it activates the clay binder, providing the cohesion and strength needed to maintain mould shape. It directly influences properties like green compression strength, mould hardness, and permeability. Green compression strength ensures the mould can withstand mechanical forces and molten metal pressure, while mould hardness resists abrasion and deformation, affecting the quality of the final casting. Permeability allows gases to escape; defects like blowholes and porosity can occur without it. However, excessive moisture can also cause gas-related defects, making its optimal control essential. Given their interdependence, these parameters were selected for the study to help minimise casting defects and rejections through careful monitoring.

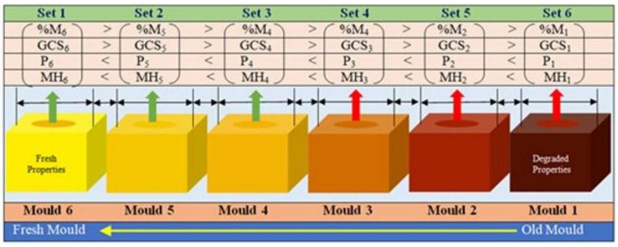

Fig. 1. Process parameters variation in different moulds (Pandit et al., 2025)

Tables 3 to 5 present representative results from 27 experimental combinations designed using the Taguchi L27 orthogonal array. These three tables correspond to initial moisture levels of 3.5%, 4.0%, and 4.5%, respectively. Ten sequentially prepared moulds were analysed for each condition to observe the time-dependent variation in key properties – moisture content, green compressive strength (GCS), mould hardness, and permeability. The trends captured here are consistent with the broader dataset, demonstrating how mould properties evolve with increasing mould age due to moisture loss and environmental exposure. Tables 3, 4 and 5 present mould property data for 10 sequentially prepared moulds with an initial moisture content of 3.5%, 4.0% and 4.5 %, respectively (Pandit & Dabade,

Table 3
Case I – Time-Dependent Variation of Mould Properties for Moisture Content 3.5% with Ramming Time 3 sec and Holding Time 10 min

Mould No.	Time at the end of the moulding process	Age just before pouring	% Moisture	GCS	Mould Hardness	Permeability
1	20	30	2	1126	94	158
2	18	28	2.1	1142	94	157
3	16	26	2.2	1158	94	154
4	14	24	2.2	1173	93	152
5	12	22	2.4	1189	93	150
6	10	20	2.5	1205	93	148
7	8	18	2.5	1221	92	146
8	6	16	2.6	1236	92	144
9	4	14	2.8	1252	92	142
10	2	12	2.9	1268	91	140

Table 4
Case II – Time-Dependent Variation of Mould Properties for Moisture Content 4 % with Ramming Time 5 sec and Holding Time 10 min

Mould No.	Time at the end of the moulding process	Age just before pouring	% Moisture	GCS	Mould Hardness	Permeability
1	20	30	2.3	1161	96	153
2	18	28	2.4	1182	95	151
3	16	26	2.5	1203	94	149
4	14	24	2.7	1224	92	146
5	12	22	2.8	1245	92	143
6	10	20	3.1	1266	92	141
7	8	18	3.2	1287	92	139
8	6	16	3.4	1308	91	136
9	4	14	3.7	1329	91	134
10	2	12	3.9	1350	90	133

Table 5
Case III – Time-Dependent Variation of Mould Properties for Moisture Content 4.5% with Ramming Time 7 sec and Holding Time 10 min

Mould No.	Time at the end of the moulding process	Age just before pouring	% Moisture	GCS	Mould Hardness	Permeability
1	20	30	2.5	1192	94	151
2	18	28	2.6	1217	93	147
3	16	26	2.8	1242	93	144
4	14	24	2.9	1266	92	141
5	12	22	3.1	1291	92	138
6	10	20	3.2	1316	91	135
7	8	18	3.4	1341	91	132
8	6	16	3.5	1366	91	129
9	4	14	3.7	1390	90	125
10	2	12	3.8	1415	90	122

2012; Pandit & Deshpande, 2021; Pandit & Deshpande, 2023). This study numbered the moulds following the First In, First Fill (FIFL) sequence. This approach ensured that each mould was studied in the exact order in which it was prepared, maintaining consistency in the casting process and minimising variability due to time-dependent factors.

Table 6 presents regression line slopes representing the change rate in key mould parameters – moisture content, green compressive strength (GCS), mould hardness, and permeability – across the three experimental cases. These slopes quantify how each property varies with mould age, offering a comparative assessment of the dynamic behaviour under different process conditions.

Table 6
Slopes of process parameter changes in various cases

Parameter	Case 1	Case 2	Case 3
% Moisture	–0.05	–0.1	–0.08
GCS	–7.88	–10.5	–12.39
Mould Hardness	0.17	0.3	0.22
Permeability	1.03	1.18	1.58

As seen in Table 6, Case 2 exhibits the most balanced performance, with moderate moisture loss, significant improvement in mould hardness, and controlled permeability increase. While Case 3 shows the highest GCS and permeability slopes, the rapid changes may risk mould stability. In contrast, Case 1 maintains the slowest property changes but with less strength development. Overall, the slope analysis supports Case 2 as the most favourable setting for maintaining mould quality over time.

Figures 2 to 4 illustrate the regression plots showing the time-dependent variation of mould parameters under three different combinations of moisture content, ramming time, and holding time. Each figure reflects

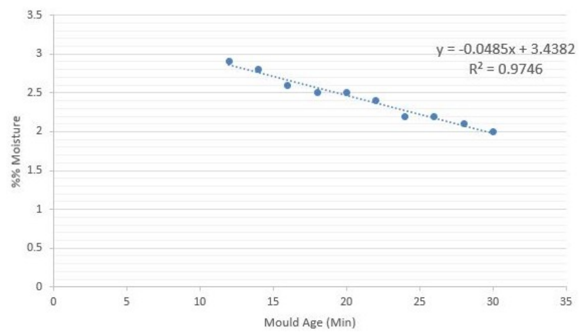

Fig. 2. Regression plot for variation in moisture content 3.5% with Ramming Time 3 sec and Holding Time 10 min.

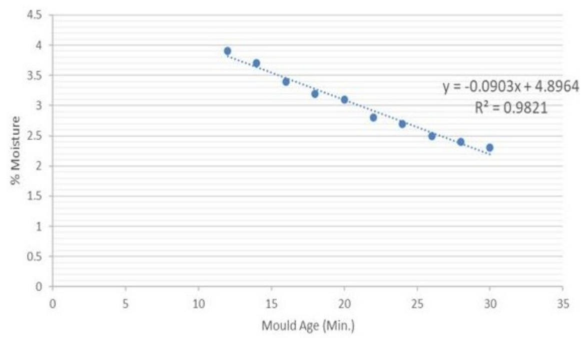

Fig. 3. Regression plot for variation in moisture content 4% with Ramming Time 5 sec and Holding Time 10 min.

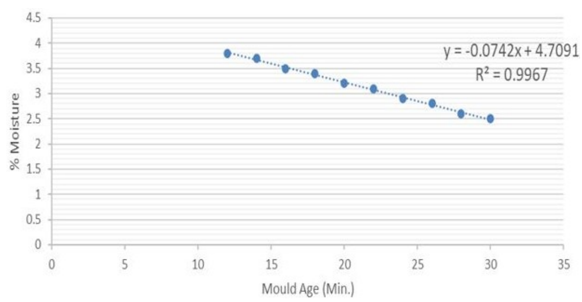

Fig. 4. Regression plot for variation in moisture content 4.5% with Ramming Time 7 sec and Holding Time 10 min.

how key properties – moisture content, green compressive strength (GCS), mould hardness, and permeability – change with increasing mould age, providing a visual representation of the dynamic behaviour in each case.

From the regression plots, it is evident that all cases exhibit predictable trends with strong linearity. Case 1 (Figure 2) shows the most gradual changes across all parameters, indicating stable but slower development of mould properties. Case 2 (Figure 3) demonstrates well-balanced progression, with higher strength and controlled permeability, supporting its selection as the optimal condition. Case 3 (Figure 4), while achieving the highest strength and permeability values, also shows steeper slopes, suggesting more aggressive and potentially less stable property shifts. The graphical analysis reinforces the numerical results, validating the time-sensitive influence of process parameters on mould behaviour.

Based on the data presented in Tables 3 to 6, Case 2 demonstrates the most balanced and favourable behaviour among the three mould preparation conditions. It achieves a moderate moisture loss rate (slope = -0.10), faster than Case 1 but more controlled than Case 3. This controlled drying helps retain adequate moisture for sand bonding while preventing excessive evaporation that could lead to surface defects or structural instability. Additionally, Case 2 shows consistent and strong Green Compression Strength (GCS), increasing from 1161 to 1350, with a slope of -10.5. This indicates the mould retains good cohesive strength over time without degrading as rapidly as in Case 3.

Furthermore, Case 2 offers the best mould hardness and permeability performance. The highest mould hardness slope (0.30) reflects improved surface resistance and mechanical strength, essential for maintaining mould integrity during metal pouring. Its permeability slope (1.18) also indicates efficient gas evacuation, reducing the risk of casting defects, while avoiding the excessive porosity observed in Case 3. In contrast, Case 1 provides weaker mechanical properties and slower permeability growth, while Case 3, though high in GCS and permeability, may compromise mould stability due to rapid property changes. Overall, Case 2 achieves an optimal balance of strength, hardness, and gas permeability, making it the most suitable choice for quality and consistency in green sand casting.

Results

The experimental data revealed distinct trends in mould property development across the three test cases. In **Case 1**, which was prepared with 3.5% moisture, a 3-second ramming time, and a 10-minute holding period, the rate of moisture loss was the slowest, with a slope of -0.05. Correspondingly, it exhibited the lowest increase in permeability at 1.03. However, the Green Compression Strength (GCS) and the development of mould hardness were relatively low, indicating that while the moulds retained moisture effectively and remained dimensionally stable, their mechanical integrity was limited.

Case 2, prepared with 4% moisture, 5-second ramming, and a 10-minute holding time, demonstrated more favourable results. It showed a moderately faster moisture loss rate with a slope of -0.10, a higher GCS slope of -10.5, and the most substantial increase in mould hardness at 0.30. The permeability slope was 1.18, suggesting efficient gas escape during the pouring process. These values indicate enhanced strength and surface properties while maintaining acceptable moisture and gas permeability balances.

In contrast, **Case 3** exhibited the highest GCS and permeability values, with the permeability slope reaching 1.58. However, this case also experienced the most rapid moisture loss, indicating instability over time. Although the mechanical strength was superior, the sharp changes in properties could compromise mould consistency and overall casting reliability.

Discussion

The comparative evaluation of the three experimental cases illustrates the impact of moisture content, ramming time, and holding time on the time-dependent behaviour of green sand mould properties: green compressive strength (GCS), mould hardness, and permeability. The findings reveal distinct performance trends associated with each parameter combination, offering practical insights for process optimisation in industrial moulding environments.

Case 1, configured with lower moisture content (3.5%), minimal ramming (3 seconds), and extended holding time (10 minutes), demonstrated the slowest rate of moisture loss and the lowest increase in permeability. However, this stability came at the cost of reduced GCS and limited hardness development. These results suggest that while such conditions help retain moisture and restrict gas flow, they compromise the mechanical integrity of the mould, increasing the risk of deformation or failure during casting.

Case 2 (4% moisture, 5-second ramming, 10-minute holding) emerged as the most balanced configuration. The moderate moisture content promoted efficient sand particle cohesion, while the intermediate ramming time ensured sufficient compaction. This combination resulted in steady GCS progression, significant hardness enhancement, and a moderate, controlled increase in permeability. These attributes are critical for producing structurally robust moulds capable of withstanding metallostatic pressure and facilitating effective gas evacuation, thereby reducing the risk of casting defects such as gas porosity and dimensional inconsistencies.

In contrast, **Case 3**, which involved higher moisture (4.5%) and extended ramming (7 seconds), recorded the highest GCS and permeability values. However, these benefits were accompanied by a rapid moisture decline and a steep gas permeability increase. While elevated permeability can facilitate gas escape, excessive values may lead to erosion or surface roughness in the final casting. Additionally, accelerated moisture loss may cause micro-cracking or premature degradation of the mould structure.

Overall, the results affirm that Case 2 presents the most favourable trade-off among strength, surface hardness, and gas permeability. This condition ensures mechanical reliability and functional suitability for producing high-quality, defect-free castings. These findings support the development of data-informed guidelines for mould preparation, enhancing maintainability and process stability in green sand casting operations.

Conclusions

This study highlights the critical role of dynamic process parameters – namely, moisture content, ramming time, and holding time – in determining the performance and stability of green sand moulds in casting operations. The time-dependent degradation of green compressive strength, mould hardness, and permeability significantly influences the quality and reliability of cast components. Case 2 (4% moisture, 5-second ramming, 10-minute holding) demonstrated the most favourable balance of mechanical integrity, gas permeability, and moisture retention among the investigated parameter combinations. These findings provide a data-driven foundation for optimising mould preparation processes, improving dimensional accuracy, reducing defect rates, and enhancing maintainability within production systems. The regression models developed in this study also offer a practical tool for predictive quality control. Future research should focus on integrating real-time monitoring technologies and expanding the analysis to different sand formulations and alloy types, thereby supporting broader implementation in modern, sustainable foundry practices aligned with Industry 4.0 objectives.

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