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Multi-Objective Optimization Of Graphite Flotation Via Grinding–Classification–Reagent Interactions: A Modeling-Based Approach

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Abstract: Graphite flotation is strongly governed by complex interactions between grinding conditions, particle size classification, and reagent chemistry, particularly in mica-rich ores where selectivity remains a major challenge. In this study, a multi-objective optimization framework is proposed to improve both fixed carbon grade and recovery through an integrated modeling-based approach. A series of progressive flotation experiments were conducted, incorporating variations in grinding time, classification strategy, and reagent regimes. Performance indicators, including fixed carbon content, recovery, and a composite optimization score, were systematically analyzed to capture trade-offs between product quality and yield. Statistical correlations and response surface models were developed to quantify the individual and interactive effects of operating variables. The results reveal the existence of an optimal operational domain characterized by a balanced compromise between grade and recovery. Classification was identified as a key lever for enhancing selectivity, while excessive grinding led to diminishing returns due to fine gangue entrainment. The proposed models demonstrate good predictive capability and robustness around the optimum conditions, providing a reliable decision-support tool for process optimization.

Keywords: Graphite flotation; multi-objective optimization; Grinding and classification; Reagent interactions; Response surface modeling; Fixed carbon grade–recovery trade-off; Process optimization.

1. Introduction

Graphite is a strategic mineral widely used in lithium-ion batteries, refractories, lubricants, and advanced composites. Due to its natural hydrophobicity, flotation remains the primary beneficiation method for graphite ores (Chandrasekhar & Ramaswamy, 2002; Wills & Finch, 2016). However, in mica-rich deposits, flotation selectivity is significantly reduced due to the platy morphology and partial hydrophobic behavior of mica minerals, which promotes mechanical entrainment and reduces concentrate purity.

The optimization of graphite flotation therefore involves a complex trade-off between fixed carbon grade and recovery. Conventional single-objective optimization approaches often fail to capture this antagonistic relationship. Multi-objective frameworks, supported by statistical modeling and response surface methodologies, provide a rational strategy to identify balanced operating domains in complex mineral processing systems.

Despite recent advances in flotation modeling, limited studies have systematically integrated grinding, classification, and reagent interactions within a unified multi-objective optimization framework. The present study addresses this gap by developing a modeling-based approach applied to a mica-rich graphite ore from Madagascar.Materials and Methods

2. Materials

The graphite ore sample used in this study was collected from the Anjamanga deposit, Madagascar. The ore is characterized by a significant proportion of micaceous gangue minerals, which adversely affect flotation selectivity. Prior to experimentation, the sample was crushed, homogenized, and prepared under controlled laboratory conditions to ensure representativeness of the feed material.

The representative ore sample was crushed and homogenized prior to laboratory testing. The feed material exhibited a significant proportion of micaceous gangue minerals, which are known to negatively impact flotation selectivity. Grinding was performed under controlled laboratory conditions using a standard laboratory mill.

Flotation tests were conducted in a laboratory flotation cell under constant hydrodynamic conditions. Kerosene was used as collector, while appropriate frothers and depressants were added to enhance selectivity. The pH was maintained within a controlled range to ensure reproducibility.

A total of 15–17 experimental conditions were evaluated following a progressive optimization strategy. Grinding time, particle size classification at 100 mesh, and reagent interactions were systematically varied. Performance indicators included fixed carbon grade (%), recovery (%), and a composite score defined as (FC × Recovery)/100.

2.1. Experimental procedure

Flotation experiments were conducted using a laboratory-scale flotation cell under controlled operating conditions. Grinding was performed for variable durations in order to generate different particle size distributions. Particle size classification was applied to separate fine and coarse fractions prior to flotation testing. Kerosene was used as the primary collector, in combination with suitable frothers and depressants to enhance flotation selectivity. All experiments were performed under identical hydrodynamic conditions to ensure reproducibility and comparability of results.

2.2. Experimental design and modeling strategy

A total of 17 laboratory flotation experiments were conducted following a progressive optimization strategy. Grinding time, classification strategy, and reagent regime were systematically varied to evaluate their individual and interactive effects on flotation performance. Rather than relying on a single-factor experimental design, the study aimed to capture realistic process interactions representative of industrial graphite beneficiation circuits. The experimental dataset was subsequently used to develop response surface models describing the relationships between operating variables and performance indicators.

2.3. Definition of performance indicators

Flotation performance was evaluated using fixed carbon grade (FC, %), recovery (%), and a composite performance score defined as:

$$\text{Score} = \frac{FC \times Recovery}{100}$$

This composite score was adopted as a proxy for multi-objective optimization, allowing simultaneous consideration of concentrate quality and yield in a system characterized by an inherent grade–recovery trade-off.

2.4. Model development and validation

Polynomial response surface models were developed to capture non-linear relationships between operating parameters and flotation performance indicators. Model adequacy was assessed using the coefficient of determination (R^2) and residual analysis. The selected models exhibited satisfactory fitting accuracy and predictive capability within the experimental domain.

3. Results and Discussion

3.1. Progressive improvement of flotation performance

The successive flotation trials demonstrate a clear and consistent improvement in overall process performance (Figure 1). The gradual increase in fixed carbon grade, recovery, and composite performance score reflects the incremental optimization of operating conditions, including grinding time, particle size classification, and reagent strategy. This progressive behavior indicates a rational experimental pathway rather than random variability. However, the rate of improvement decreases at advanced stages, suggesting convergence toward an optimal operational domain. Such diminishing marginal gains are characteristic of mineral processing systems approaching their performance limits.

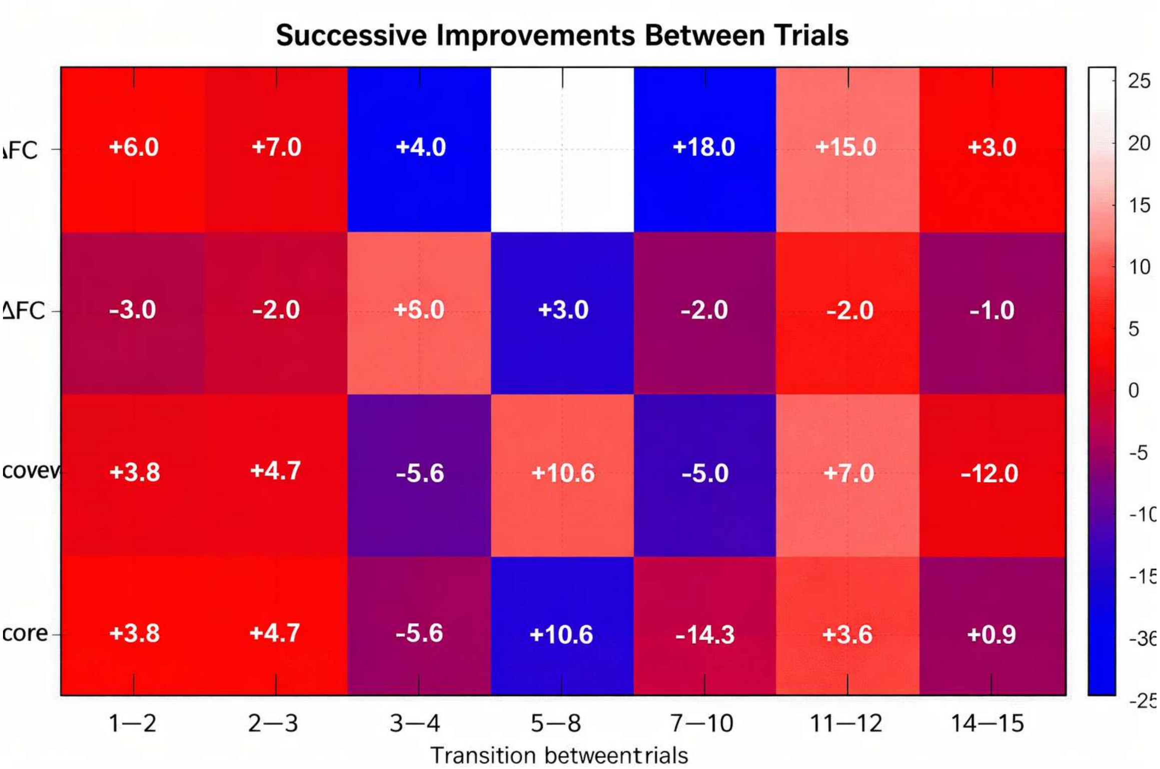


Figure 1. Improvement of flotation performance through successive experimental trials

Figure 1 illustrates the progressive improvement in graphite flotation performance obtained through successive experimental trials. The gradual increase in fixed carbon grade, recovery, and overall performance score reflects the incremental optimization of grinding conditions, classification strategy, and reagent regimes. The observed trend highlights a diminishing marginal gain at advanced stages, indicating convergence toward an optimal operating domain.

3.2. . Trade-off between fixed carbon grade and recovery

The relationship between fixed carbon grade and recovery (Figure 2) highlights a partial antagonistic behavior, which is typical of graphite flotation systems, particularly in mica-rich ores. High recovery values are often associated with increased gangue entrainment, resulting in lower concentrate quality. Conversely, higher fixed carbon grades are achieved under more selective conditions, frequently at the expense of recovery. This behavior confirms that single-objective optimization is insufficient and supports the adoption of a multi-objective framework. The use of a composite performance score allows a more balanced evaluation of beneficiation efficiency.

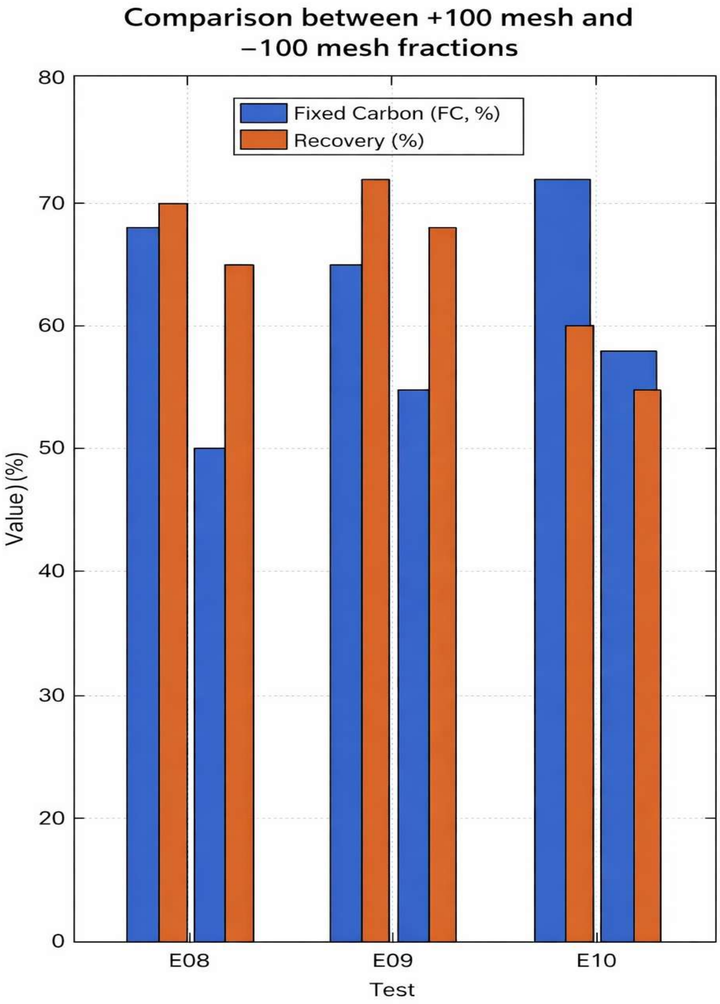


Figure 2. Relationship between fixed carbon grade and recovery

Figure 2 shows the relationship between fixed carbon grade and recovery for the different flotation tests. A partial antagonistic behavior is observed, highlighting the classical trade-off between product quality and yield. High recoveries are associated with increased gangue entrainment, while higher fixed carbon grades are achieved at the expense of recovery, justifying the use of a multi-objective optimization approach.

3.3. Influence of operating parameters and multivariate interactions

Correlation analysis between operating parameters and flotation performance indicators (Figure 3) reveals that grinding time, classification strategy, and reagent dosage exert dominant influences on both fixed carbon grade and recovery. The presence of significant correlations among variables confirms the multivariate nature of the flotation process. These interactions cannot be adequately described by univariate analyses, emphasizing the relevance of modeling approaches capable of capturing coupled effects between physical and chemical parameters.

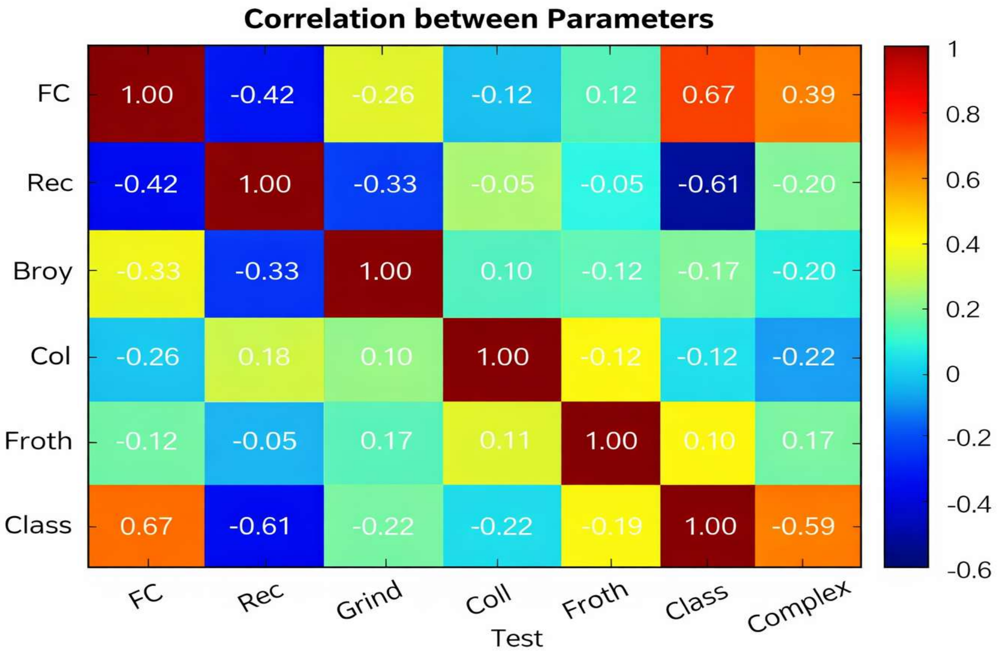


Figure 3. Correlation analysis between operating parameters and flotation performance indicators

Figure 3 presents the correlation matrix between key operating parameters and flotation performance indicators. Significant correlations reveal the dominant influence of grinding time, classification, and reagent dosage on fixed carbon grade and recovery. The results confirm the multivariate nature of the flotation process and the need for modeling approaches capable of capturing variable interactions.

3.4. Identification of an optimal compromise region

The trade-off diagram between fixed carbon grade and recovery (Figure 4) reveals the existence of an optimal compromise region. Extreme operating conditions favoring either grade or recovery alone result in sub-optimal global performance. Instead, the most efficient operating conditions correspond to intermediate values, where acceptable recovery is achieved without excessive dilution of the concentrate. This observation reinforces the concept that industrially relevant optimization targets balanced performance rather than absolute maxima of individual indicators.

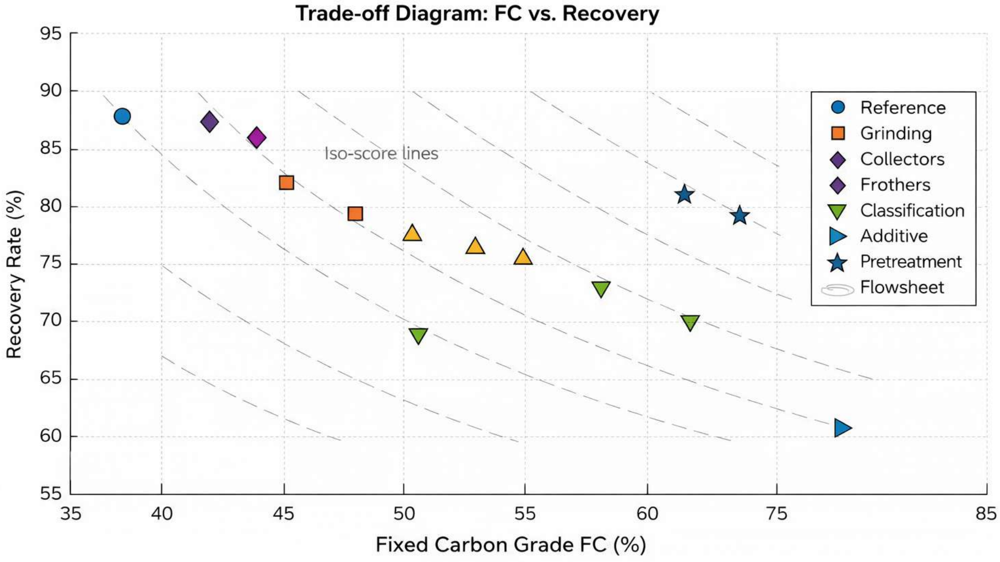


Figure 4. Trade-off diagram between fixed carbon grade and recovery

Figure 4 illustrates the trade-off between fixed carbon grade and recovery, highlighting the existence of an optimal compromise region. Extreme operating conditions favoring either grade or recovery alone result in sub-optimal global performance. The optimal zone corresponds to balanced operating conditions maximizing the overall beneficiation efficiency.

3.5. Effect of grinding conditions on flotation performance

Grinding time plays a critical role in graphite flotation performance (Figures 5 and 6). Insufficient grinding leads to incomplete liberation of graphite particles, resulting in low fixed carbon grades. Conversely, excessive grinding promotes the generation of fine particles, increasing gangue entrainment and reducing selectivity. An intermediate grinding regime provides optimal liberation while preserving graphite flake integrity, thereby enhancing both grade and recovery. These results are consistent with the known sensitivity of graphite flotation to particle size distribution.

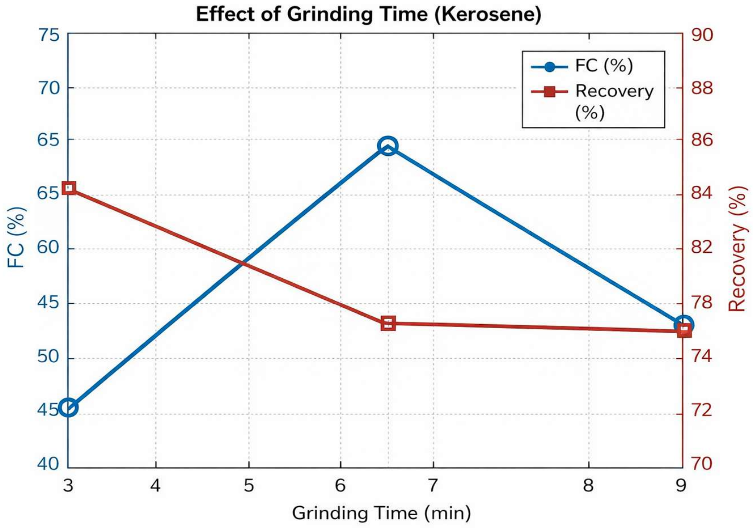


Figure 5. Effect of grinding time on flotation performance

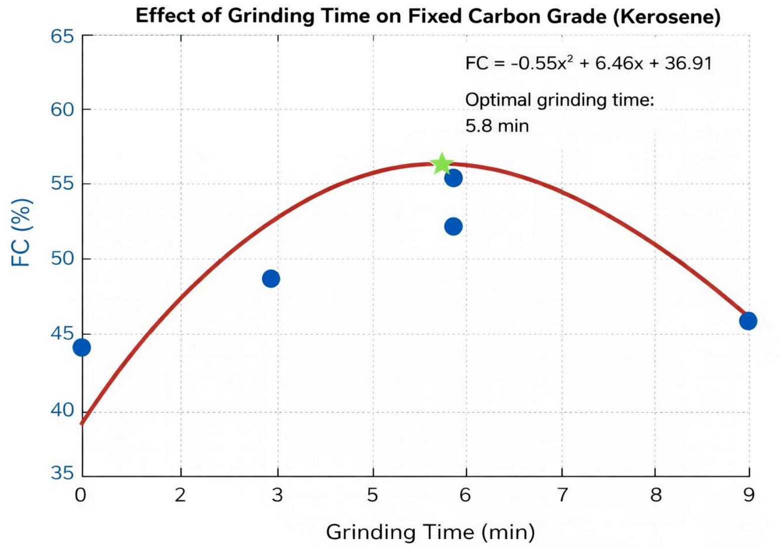


Figure 6. Influence of grinding conditions on fixed carbon grade

Figures 5 and 6 collectively illustrate the influence of grinding time on graphite flotation performance and fixed carbon grade. Insufficient grinding leads to incomplete liberation of graphite particles, resulting in low fixed carbon grades and suboptimal flotation efficiency. Conversely, excessive grinding promotes the generation of fine particles, which increases gangue entrainment and negatively impacts both selectivity and concentrate quality. An intermediate grinding time provides the most favorable balance between liberation and preservation of graphite flake integrity, leading to improved flotation performance. The evolution of fixed carbon grade with grinding time further highlights a non-linear behavior, indicating the existence of an optimal grinding condition. Controlled grinding enhances graphite liberation while minimizing flake degradation, which is essential for achieving high-quality concentrates and maintaining robust flotation performance.

3.6. Role of particle size classification

Particle size classification significantly improves flotation selectivity, as illustrated in Figures 7 and 8. By separating fine, gangue-rich fractions from coarser graphite particles, classification enhances fixed carbon grade without substantial loss in recovery. This effect is particularly pronounced in mica-bearing ores, where fine mica particles are easily entrained during flotation. Classification thus acts as a key lever for improving concentrate quality and should be considered an essential component of optimized graphite beneficiation flowsheets.

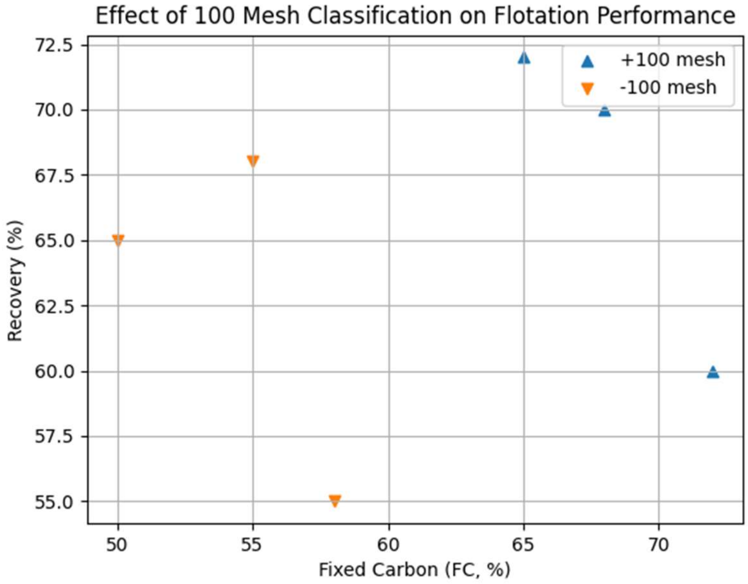


Figure 7. Effect of 100 mesh classification on fixed carbon grade and recovery

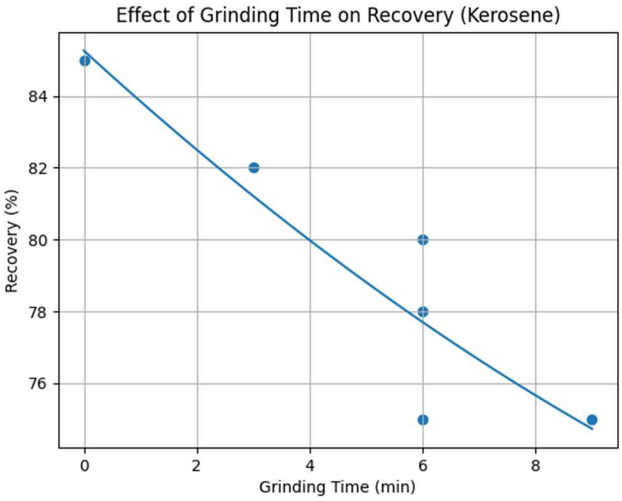


Figure 8. Effect of grinding time on recovery in the presence of kerosene.

3.7. Interaction between grinding and reagent regime

The combined effect of grinding conditions and kerosene dosage on flotation performance is shown in Figure 9. The results indicate a strong interaction between particle size distribution and collector efficiency. Under controlled grinding conditions, kerosene effectively enhances hydrophobicity and recovery. However, in overly fine systems, its selectivity decreases due to non-specific adsorption and increased entrainment. This interaction highlights the need for coordinated optimization of physical preparation and reagent chemistry.

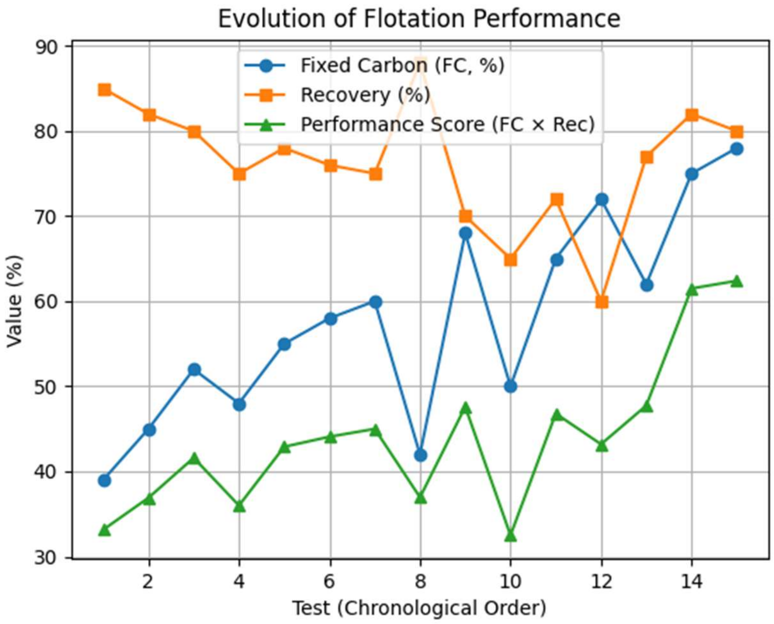


Figure 9. Evolution of flotation performance across successive tests.

3.8. Global performance evolution and selectivity enhancement

The evolution of overall flotation performance indicators (Figures 10 and 11) shows a simultaneous improvement in fixed carbon grade and recovery as optimization progresses. The increasing quality–recovery ratio reflects a transition from entrainment-dominated behavior toward selective graphite flotation. This trend confirms that the adopted optimization strategy successfully enhances process selectivity while maintaining acceptable yields.

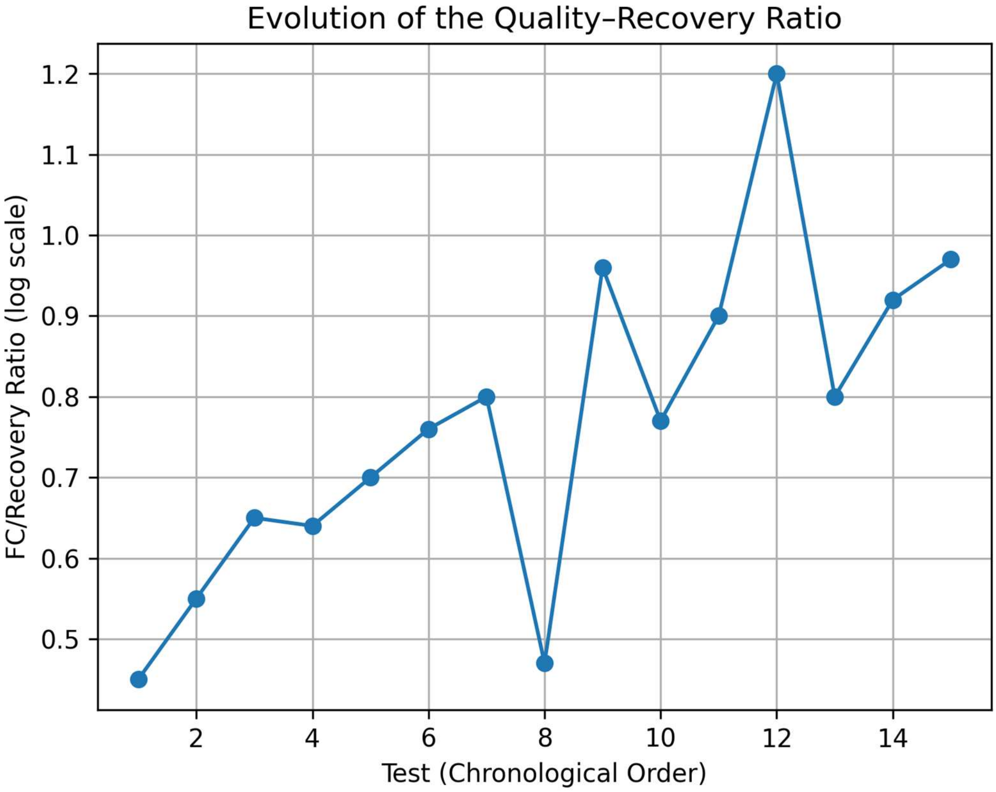


Figure 10. Evolution of the quality–recovery ratio across successive flotation tests

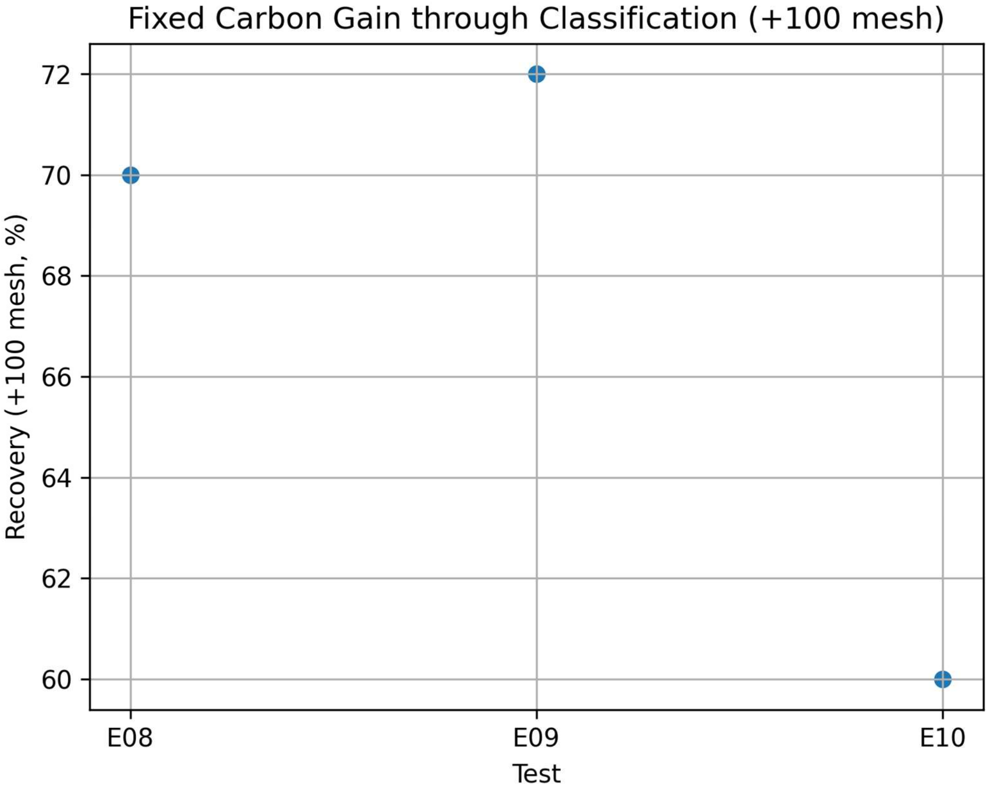


Figure 11. Fixed carbon improvement achieved through particle size classification (+100 mesh fraction).

3.9. Modeling-based optimization and response surface analysis

The variation of the composite performance score with grinding conditions (Figure 12) exhibits a clear maximum, confirming the existence of an optimal operating regime. The influence of polynomial model order on fitting accuracy (Figure 13) demonstrates that higher-order models are required to capture the non-linear interactions inherent to the flotation process. The response surface generated from the developed model (Figure 14) identifies a well-defined optimal region, characterized by moderate sensitivity around the optimum. This robustness indicates that the proposed modeling approach provides reliable predictive capability and practical decision-support for process optimization.

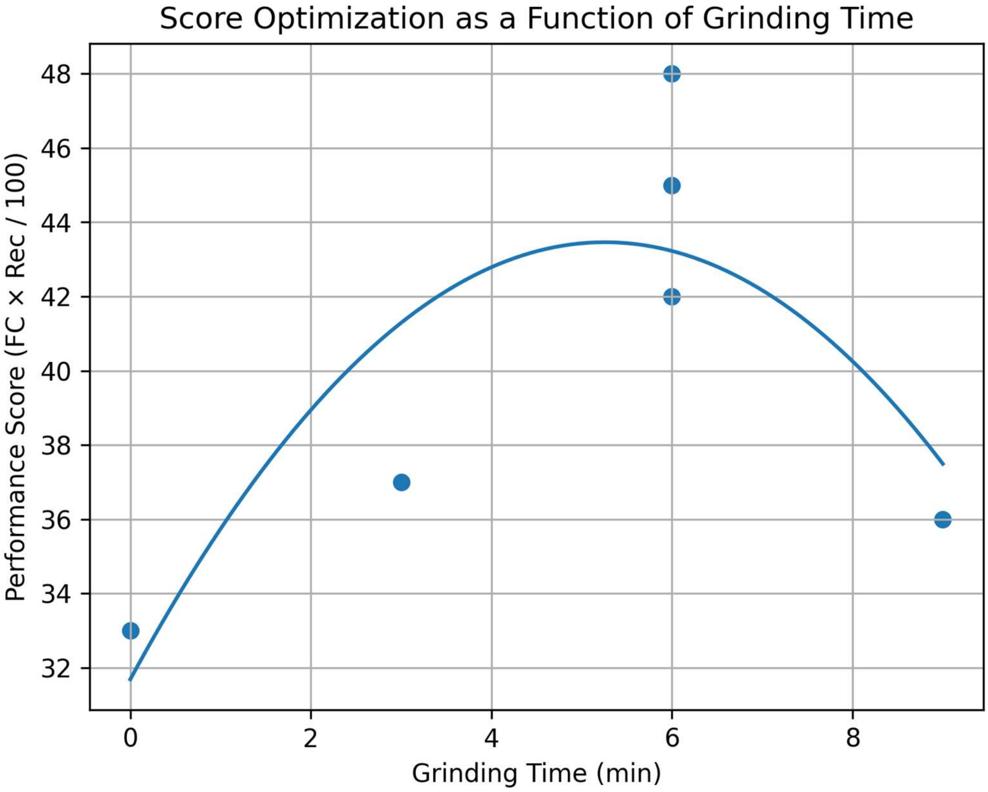


Figure 12. Score optimization as a function of grinding time.

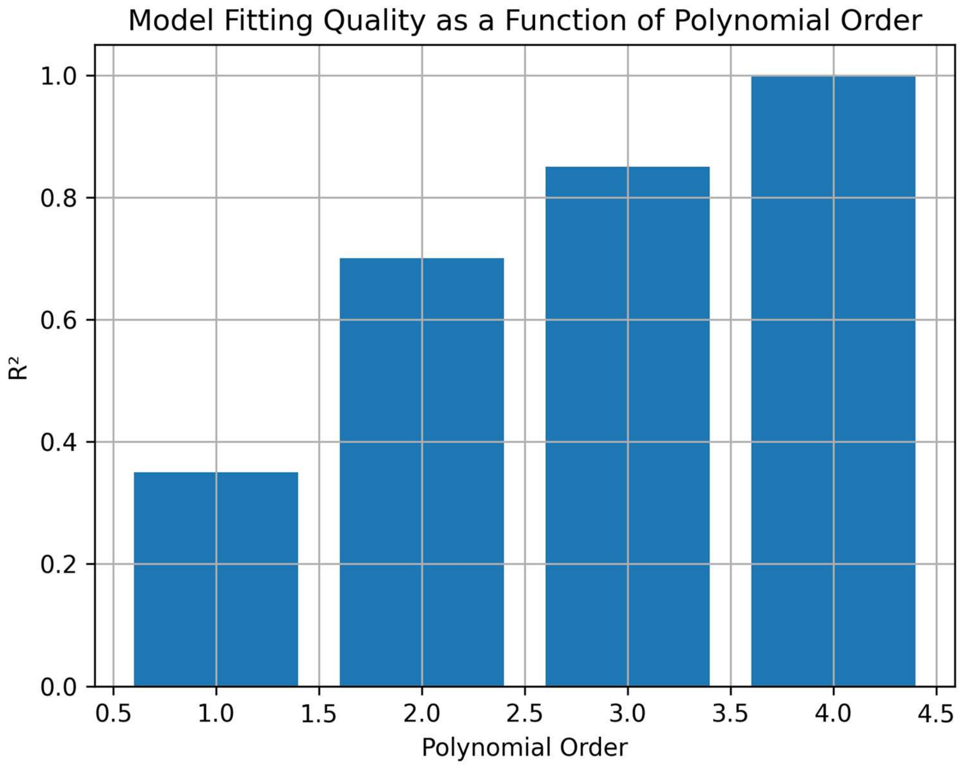
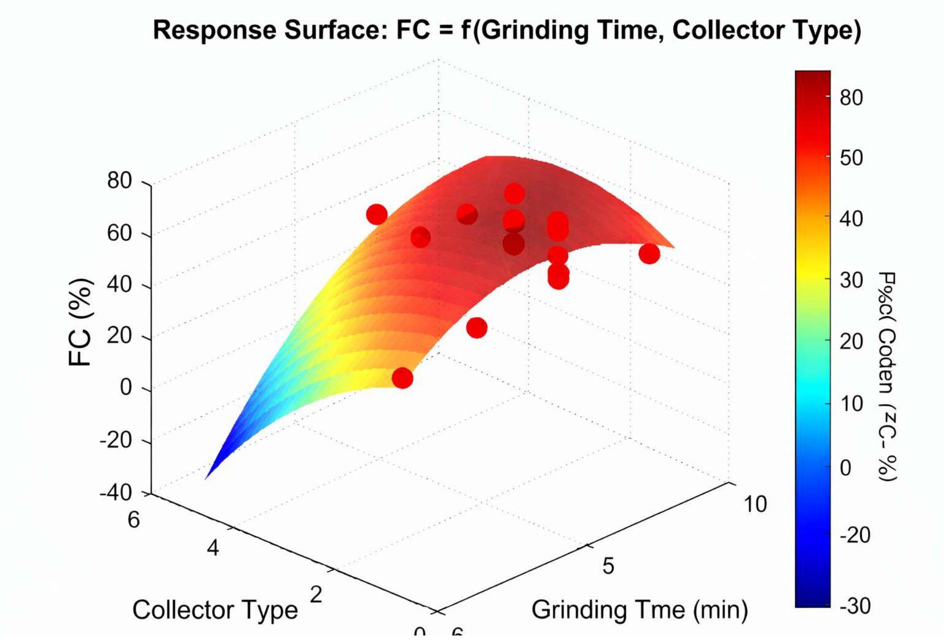


Figure 13. Model fitting quality as a function of polynomial order.

Figure 14 illustrates the response surface generated from the polynomial model, highlighting the interaction between grinding time and flotation performance. The surface reveals a well-defined optimal region corresponding to intermediate grinding conditions, where the composite performance score reaches its maximum. The curvature of the surface confirms the non-linear behavior of the system and demonstrates the sensitivity of flotation efficiency to variations in grinding intensity. The relatively smooth gradient around the optimum indicates a degree of operational robustness, suggesting that slight deviations from the optimal grinding time would not drastically reduce performance.



3.10. . Overall interpretation

Taken together, the results demonstrate that graphite flotation performance is governed by complex interactions between grinding, classification, and reagent regime. The multi-objective, modeling-based approach adopted in this study successfully rationalizes these interactions and enables the identification of balanced operating conditions that maximize overall beneficiation efficiency. Rather than targeting extreme values of individual performance indicators, the optimized flowsheet achieves a robust compromise between concentrate quality and recovery, which is essential for industrial application.

4. Conclusion

This study demonstrates that graphite flotation performance is governed by strongly coupled interactions between grinding conditions, particle size classification, and reagent regime. The proposed multi-objective modeling framework successfully identified a robust operating domain that balances concentrate quality and recovery.

The optimized conditions nearly doubled fixed carbon grade compared to initial tests while maintaining acceptable recovery levels. The integration of composite scoring and response surface analysis provides a scalable methodology applicable to other complex flotation systems involving antagonistic performance objectives.

From an industrial perspective, the identification of a stable optimum grinding regime represents a key lever for improving both technical and economic performance in graphite beneficiation circuits.

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