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The Utilization of Statistical Design Methodology in Predicting Abrasion Resistance of Concrete Mixtures Used in Harsh Environments: Durable Concrete and Sustainable Solutions

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ABSTRACT

This study uses Statistical Mixture Combined Design (SMCD) and the Kowalski-Cornell-Vining (KCV) model to optimize High-Performance Modified-Weight Concrete (HPMWC). It focuses on the effects and interactions between mixture components and process factors. The abrasion resistance of HPMWC, essential to withstand various harsh conditions including chemical and ice abrasion, was assessed using two ASTM standard methods: Sandblasting and Rotating Cutters. In addition, a novel laser scanning technique was used to improve the accuracy of the abrasion resistance evaluation. Prediction models were developed to identify optimal mixture components based on the required concrete. The research highlights the critical role of the initial design choices in minimizing cement consumption and optimizing structural dimensions by reducing concrete volume, ultimately lowering project emissions, and contributing to the need to reduce the lifecycle and carbon footprint of concrete.

KEY WORDS: Concrete; Abrasion; KCV; SMCD; Carbon; Ice.

INTRODUCTION

Concrete mix design involves careful selection and proportioning of components to meet specific performance criteria. Recent complexity arises from new materials, life-cycle performance demands, and environmental concerns. Strategic design choices are essential to minimize the overall volume of concrete and cement consumption, which is critical for lowering the carbon footprint of construction projects. Durability remains paramount, especially for concrete exposed to harsh environments like marine structures and offshore platforms, where it must withstand aggressive conditions, including waterborne particles, ice, and mechanical wear, leading to deterioration over time. HPMWC has been preferred for such demanding applications due to its reduced dead weight and enhanced durability (Bremner and Holm, 1995). However, the design of HPMWC often involves higher costs due to the use of supplementary cementitious materials and increased dosages of chemical admixtures. The complexity of these mixtures, characterized by multiple constituents and their potential interactions, necessitates advanced optimization techniques to achieve an optimal balance between performance, cost, and sustainability. This dual focus on durability and environmental impact highlights the importance of strategic concrete mixture design.

Traditional methods like one-factor-at-a-time (OFAT) struggle to capture variable interactions, increasing the cost of multi-criteria applications (Simon et al., 1997). Statistical Design of Experiment (DOE) methods, specifically Statistical Mixture Design (SMD), address this limitation for mixture experiments, where responses depend on component proportions rather than absolute levels (Anderson at el., 2018). However, SMD cannot account for process variables (e.g., mixing procedures, curing conditions). SMCD overcomes this, allowing the study of both mixture components and process variables (Myers et al., 2016). As the number of factors increases, so does the number of experimental runs. The Kowalski-Cornell-Vining (KCV) model (Kowalski et al., 2000) minimizes the required number of experimental runs while still examining mixture components, process factors, and interactions.

Abrasion resistance is a critical aspect of concrete durability, particularly in demanding environments such as hydraulic structures and Arctic offshore platforms. Traditional evaluation methods, including ASTM C418 (ASTM, 2020), ASTM C944 (ASTM, 2019a), ASTM C779 (ASTM, 2019b), and ASTM C1138 (ASTM, 2019c) measure abrasion resistance through mass loss, depth of wear, or volume loss but often lack detailed topographical information. Advanced 3D laser scanning has been used to provide precise surface topography data, enabling a deeper understanding of wear mechanisms (Shamsutdinova et al., 2019). While effective in laboratory settings, most laser scanners are unsuitable for field applications due to their sensitivity to vibrations. This study employs portable laser technology for field-compatible testing.

In summary, the design of HPMWC requires a balance between durability, sustainability, and cost. This work combines SMCD and the KCV model to optimize HPMWC mixtures, supported by portable laser scanning for precise abrasion analysis. The approach advances concrete design for harsh environments while reducing carbon footprint.

RESEARCH OBJECTIVES

The objective of this study is to design and optimize HPMWC using the SMCD method and KCV model, with a focus on understanding abrasion mechanisms. Key goals include:

1- Evaluate abrasion resistance using standardized tests (ASTM C944 and ASTM C418).

2- Apply advanced laser scanning technology (portable 3D laser scanner) to measure surface degradation and analyze wear mechanisms in HPMWC through 3D scans.

3- Develop predictive models to identify optimal material compositions for HPMWC, enhancing durability and reducing the life-cycle carbon footprint of concrete.

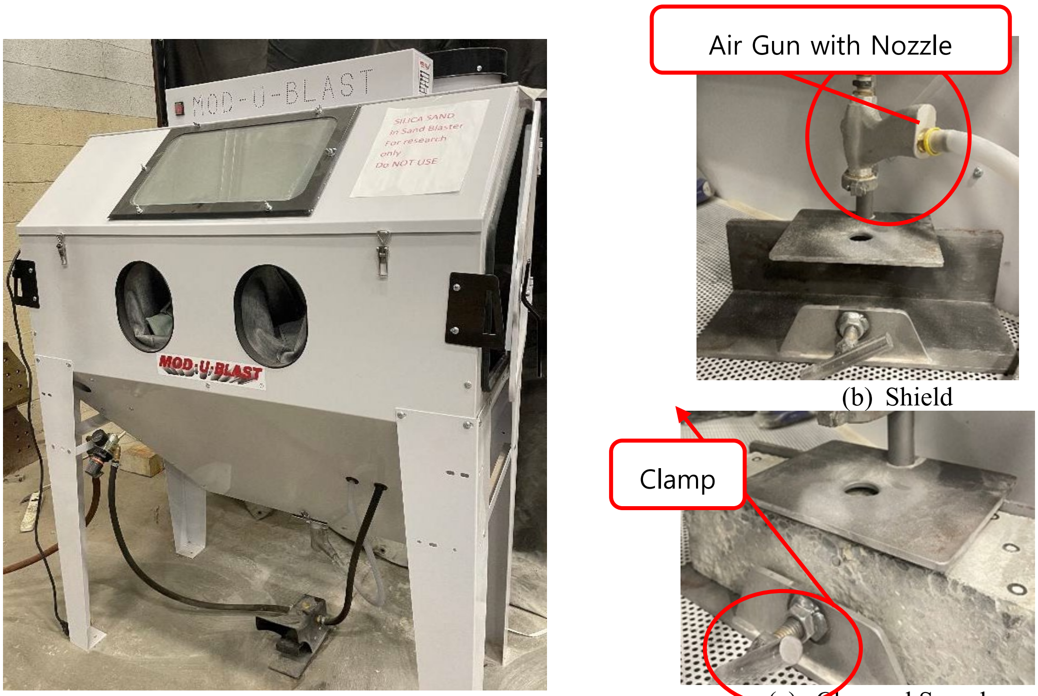
MIXTURE DESIGN

A total of 34 experimental runs were designed and conducted to model concrete properties using the SMCD methodology and KCV model. Six components—cement (C), metakaolin (M), fine aggregates (FA), normal weight coarse aggregates (NWA), lightweight coarse aggregates (LWA), and water (W)—were investigated, along with one process variable: the maximum size of normal weight coarse aggregate (MAS), which was studied at three discrete levels (10, 14, and 20 mm). Table 1 details the mixture components and their respective ranges. Mixture proportions maintained a constant absolute volume per experimental trial, adhering to SMCD constraints. To improve workability, EXP 950 was used as a water reducing agent (superplasticizer). The dosage was determined in consultation with the manufacture as well as the need for each mix to be reasonably workable (slump ranged between 60 and 200 mm across the 34 concrete mixtures). The superplasticizer dosage ranged between 25 and 325 ml. A fixed retarder dosage of (50 ml) was added across all mixtures. The properties and types of materials used, along with detailed information on the concrete mix design, fresh and hardened properties, can be found in the thesis by Khalil (2025).

Each mixture (0.075 m³ volume) was mixed, poured, molded, and later demolded under controlled conditions at Memorial University of Newfoundland's Concrete Lab. Stalite Expanded Slate LWA was soaked (48 hours) and air-dried (24 hours) to achieve a saturated surface dry (SSD) condition. After mixing, the concrete was cast into molds and compacted in accordance with ASTM C192/C192M (ASTM, 2019d). After 24 hours, specimens were demolded and cured in lime-saturated water at 23°C until testing at the age of 56 days. The subsequent phase evaluated mixture properties, focusing on abrasion resistance.

Table 1. Mixture Components and Ranges (m^3).

Mixture Components	Lower Limit	Upper Limit	Mixture Components	Lower Limit	Upper Limit
Cement	0.128	0.132	Lightweight Aggregates	0.144	0.348
Metakaolin	0.009	0.038	Normal Weight Aggregates	0.070	0.190
Fine Aggregates	0.290	0.340	Water	0.154	0.160



(a) Sandblasting Cabinet (c) Clamped Sample

Figure 1: Sandblasting Test Apparatus.

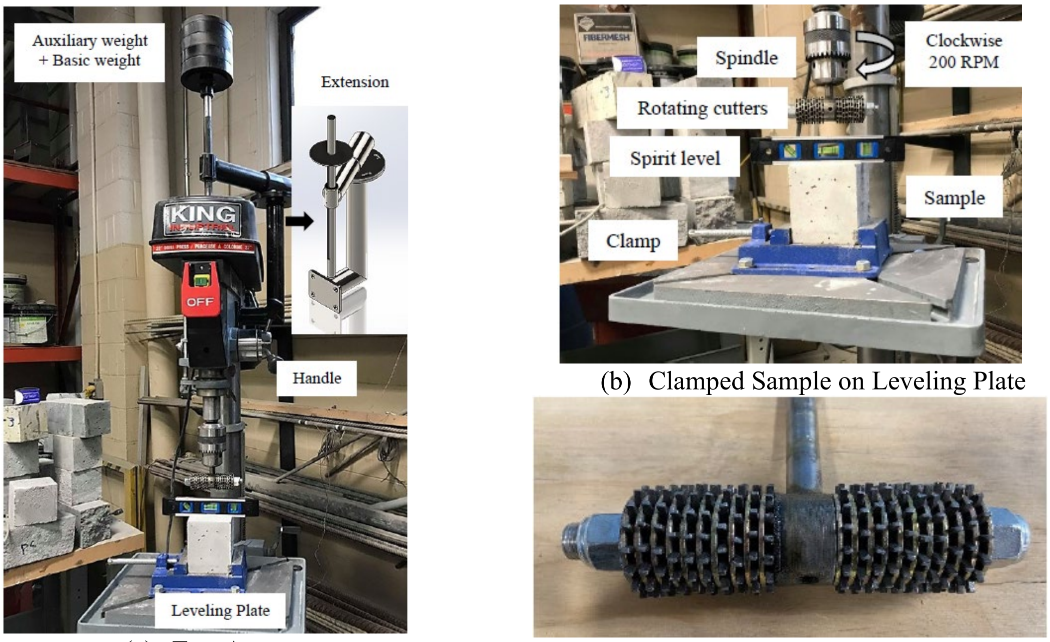
ABRASION RESISTANCE EVALUATION

ASTM C418: Sandblasting Method

ASTM C418 evaluates concrete abrasion resistance by sandblasting surfaces with silica sand to simulate water-borne abrasives (ASTM, 2020). Material loss volume, measured via modeling clay, is expressed as an abrasion coefficient (cm³/cm²). However, the method has limitations, including potential clay-filling errors and lack of surface topography data. Alternative approaches, such as mass loss or depth measurements, have been employed (Sadek and Hasan, 2021; Seyedfarizani et al., 2022).

A commercial sandblasting cabinet (Figure 1a) with a 100-psi air gun delivered 600 ±25 g/min of ASTM C418-graded silica sand (20-30). The setup included a hardened steel nozzle (45° internal walls), a coated shield, and a clamp (Figures 1b, 1c) to confine abrasion to a 25 mm diameter area. Concrete prisms (100 × 100 × 400 mm) were clamped 75 ±2.5 mm from the nozzle and blasted for 1 minute. Each sample underwent four tests. Post-test, laser scanning analyzed 25 mm² cavities for depth, volume, and abrasion coefficient (Figure 2).

Figure 2: Abraded Sample Using Sandblasting Technique.



(a) Test Apparatus

(b) Clamped Sample on Leveling Plate

(c) Rotating Cutters

Figure 3: Rotating Cutters Test Apparatus (Abdel-Hafez et al, 2021).

ASTM C944: Rotating Cutters Method

ASTM C944/C944M (ASTM, 2019a) specifies a method to evaluate abrasion resistance of concrete or mortar surfaces using rotating cutters, simulating mechanical wear. The test involves rotating cutters at 200 r/min under controlled loads (98 ± 1 N or 197 ± 2 N). Abrasion resistance is measured via mass loss or average abrasion depth, with lower values indicating better performance. However, the standard lacks guidelines on measurement frequency or groove count, leading to variability and high coefficients of variation (Abdel-Hafez et al., 2021). Advanced methods like 3D laser scanning improve accuracy by capturing non-uniform wear patterns (Abdel-Hafez et al., 2021).

A custom apparatus, adapted from a drill press, was fabricated to meet ASTM requirements. Key modifications included replacing the spring with a U-shaped extension for direct load application, ensuring stability, vibration elimination, and precise load control. Cutters (82.5 mm diameter) were constructed using 20 dressing wheels and 22 washers. A custom holder secured 100 × 100 × 100 mm concrete cubes for testing (Figure 3a–c). Tests applied a 197 N load at 200 r/min for two minutes per, cleaning the sample after each minute, following ASTM C944/C944M. Three samples per mixture. To reduce variability, dressing wheels and washers were replaced hourly. Post-test, debris was removed with compressed air, and samples were reweighed to determine mass loss. Grooves of varying size/depth resulted from testing (Figure 4) were assessed via weight loss and abrasion depth.

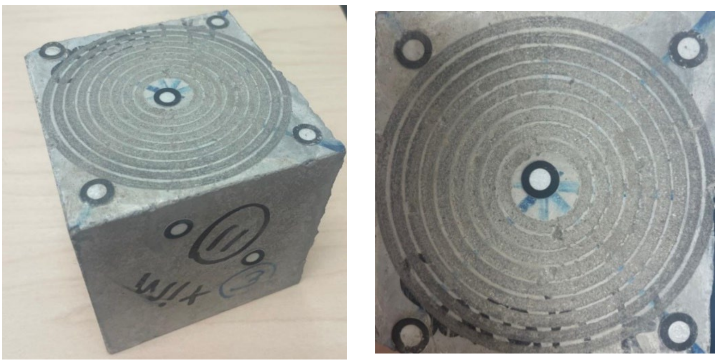


Figure 4: Tested Sample Using Rotating Cutters Method at 56 days.

3D Laser Scanning Technology

3D laser scanning improves abrasion resistance measurement by capturing detailed surface topography and wear patterns, offering both qualitative and quantitative data (Creaform, 2019). It has proven effective abrasion evaluation in harsh environments like Arctic platforms (Shamsutdinova et al., 2019). However, traditional scanners are lab-restricted and vibration-sensitive, limiting field use (Liu et al., 2023). This study employs a portable HandySCAN 3D scanner to enable lab and field applications (Figure 5).

Scans were performed pre- and post-testing. Data from the handheld scanner were processed in VXelements (Creaform, 2022), aligning surfaces using reference points and the “target best fit” feature. Point clouds were converted to CAD-compatible mesh files, and abraded volumes were calculated in AutoCAD (Autodesk, 2022) by subtracting aligned surfaces. The scanner’s precision (0.02 mm ± 0.04 mm/m) ensured highly accurate measurements.

Figure 5: 3D Portable HandySCAN by Creaform.

DISCUSSION OF RESULTS

Abrasion Resistance Visual Results of ASTM C418

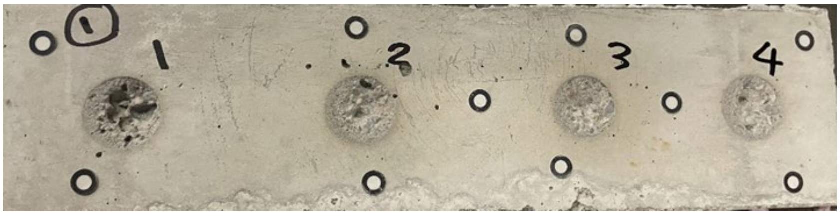
Visual inspection of concrete abrasion resistance helps assess damage types, wear patterns, and variability across mixes. Concrete composite nature, made of aggregates and paste, results in uneven abrasion due to differing material properties. In harsh environments, concrete surfaces wear unevenly, with weaker components eroding faster abrasion and leaving protruding aggregates. This combination creates a unique abrasion pattern and increases variability in test results. Understanding these mechanisms is crucial for evaluating abrasion resistance in applications where concrete weight reduction is critical and LWA aggregate is used.

ASTM C418 results revealed significant variability in abrasion within samples. This raises questions about the consistency of test methods, especially when using the oil-based clay method, which is prone to human error. Laser scanning provided precise measurements (Figure 6a–d). The irregularity in the abrasion patterns is evident. For instance, cavity 1 exhibited dislodged LWA, while cavity (3) showed wear limited to paste and fine aggregates, with no exposure of LWA. This variability highlights the differing abrasion mechanisms even in identical mixtures.

The experimental numerical results were obtained using the MASSPROP command in AutoCAD. For the Sandblasting results, the maximum abraded depth, the volume of abraded cavities, and the abrasion coefficient A_c were obtained. A_c is expressed in cm^3/cm^2 and calculated using the following equation (ASTM, 2020):

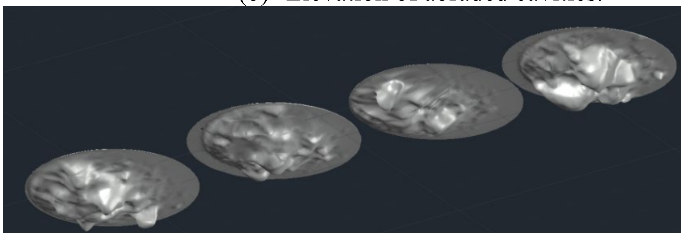
$$A_c = \frac{V_{ij}}{A} \qquad (1)$$

where: V_{ij} = Volume of the cavity i in a j mixture in cm^3 and A is the abraded area expressed in cm^2.

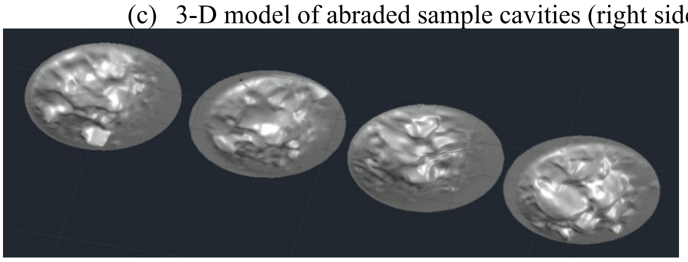


(a) Photograph of abraded sample.

(b) Elevation of abraded cavities.



(c) 3-D model of abraded sample cavities (right side).



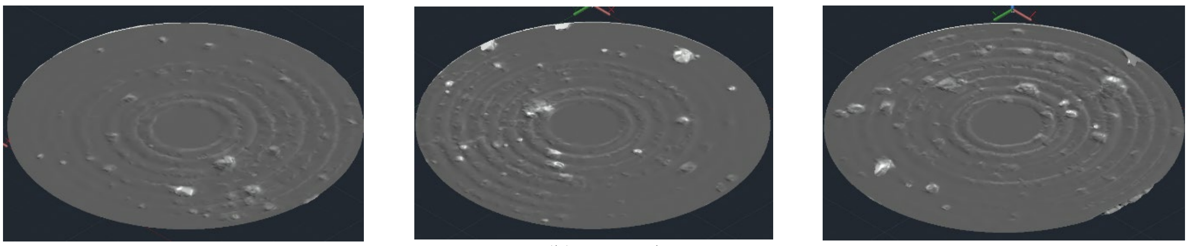
(d) 3-D model of abraded sample cavities (left side).

Figure 6: Sandblasting visual results for mix 1 (Laser Scanning).

Abrasion Resistance Visual Results of ASTM C944

Figure 7 shows 3D models of abraded grooves for Mixtures 5, revealing similar wear patterns within and between mixes. The rotating cutters only penetrated the mortar of the HPMWC, failing to reach the NWA or LWA due to the concrete's high durability (Figure 7). This limited the depth of abrasion and provided little insight into the abrasion mechanism of the aggregates. The results require attention to the method's accuracy in representing HPMWC's abrasion behavior and comparing resistance across mixes. Further modification to this method may be required for testing HPMWC.

For the Rotating cutters test, the average abraded depth was obtained from the 3D models and recorded in mm, along with the abrasion weight loss WL recorded in g.



(a) Sample 1 (b) Sample 2 (c) Sample 3

Figure 7: Rotating Cutters Processed Data (3D Models for Mix 5 Abraded Grooves).

Prediction Models and Optimization

This section outlines the model identification and validation process for assessing abrasion resistance. Initially, various models were developed to describe the response, with the KCV model used for experimental design. ANOVA and the least squares method were applied to establish multivariate relationships between performance characteristics and mixture components/process factors. Design Expert V13 software (Stat-Ease, 2022) was used to analyze the data, generating a matrix of possibilities to identify the best model. The analysis started with the KCV model, including all possible terms and interactions, and was refined using the Bayesian Information Criterion (BIC) backward selection tool to balance fit and complexity, avoiding overfitting

Model selection is framed as a hypothesis test, where the null hypothesis assumes no significant terms or relationships, and the alternative hypothesis suggests at least one term is significant at a significance level of $\alpha = 0.05$. The Reduced Quadratic × Linear model was selected for the Abrasion Coefficient (Ac) and the Rotating Cutters Average Abraded Depth (AD), while the KCV model was chosen for Rotating Cutters Weight Loss (WL). Equation 2 presents the prediction model for the Abrasion Coefficient response as an example.

$$Ac = -2077.49W + 17.92C - 27.91M - 31.51FA - 94.63NWA - 74.48LWA + 2874.23W\times C + 3155.57W\times M + 2808.23W\times FA + 3006.28W\times NWA + 3003.30W\times LWA - 663.26C\times M - 206.88C\times FA - 140.00C\times LWA - 64.84M\times FA + 7.69M\times LWA - 0.72W\times MAS + 0.55C\times MSA + 0.16M\times MAS - 40.33FA\times NWA - 46.10FA\times LWA + 0.02\,FA\times MAS + 0.06NWA\times MAS + 0.09LWA\times MAS. \quad (2)$$

The model's adequacy was verified both quantitatively and graphically. ANOVA lack-of-fit tests showed P-values greater than 0.05 for all responses, indicating the model adequately describes the relationship between variables and abrasion resistance. Table 2 presents the fit statistics of the models. Predicted R^2 values range from 0.44 to 0.72, suggesting the model can explain a significant portion of the variability for new data. Adjusted R^2 values range from 0.59 to 0.89, indicating the model accounts for a substantial portion of the variability in the dependent variable after adjusting for the number of predictors. The difference between predicted and adjusted R^2 values is within an acceptable range, indicating reasonable model performance. ANOVA assumptions of Normality, constant variance, and independence were all checked using the residuals plots and are all found valid and met.

Table 2 Statistics of Goodness of Fit for the Developed Valid Models.

Response	Model	R^2	Adjusted R^2	Predicted R^2
A_c	Reduced Quadratic x Linear	0.97	0.89	0.68
AD	Reduced Quadratic x Linear	0.72	0.59	0.44
WL	KCV model	0.97	0.87	0.72

The developed prediction equations enable the optimization of concrete mixtures for desired performance characteristics using the Desirability Function Criteria approach. This method transforms individual responses into desirability values (0 to 1) and combines them into an overall desirability function, which is maximized to determine the optimal mixture composition (Derringer and Suich, 1980). Importance levels (1 to 5) can be assigned to each response based on project priorities, with the overall desirability (D) calculated using:

$$D= (d_1^{r1} \times d_2^{r2} \times \ldots \times d_n^{rn})^{1/\sum r_i} \quad (3)$$

For this study, the goal is to maximize compressive strength and minimize the abrasion coefficient, with acceptable ranges and target values defined. The optimized mixture (Table 3) achieves a desirability of D = 0.975, with predicted values of compressive strength (108.6 MPa) and abrasion coefficient (0.22).

Table 3. Predicted Mixtures for Maximum Strength and Minimum Abrasion Coefficient

Mix Number	W (m^3)	C (m^3)	M (m^3)	FA (m^3)	NWA (m^3)	LWA (m^3)	MAS (mm)
1	0.16	0.132	0.038	0.324	0.147	0.198	10
2	0.160	0.132	0.038	0.325	0.147	0.198	14
3	0.160	0.132	0.038	0.323	0.143	0.203	20

By adjusting the importance and target values of each response, engineers can tailor the optimization process to balance strength, durability, and abrasion resistance. Practical constraints, such as material availability and cost, can also be incorporated to ensure real-world applicability.

CONCLUSIONS

Abrasion Mechanism in HPMWC and Comparison of Results

The laser scanning technique provided valuable insights into the topography of abraded surfaces and their variability. This variability is inherent in concrete due to its heterogeneous nature. The accuracy of the laser scanning measurement method justifies its use in large structures, especially offshore, where the topography of abrasion is of great importance.

The Sandblasting method provided more comprehensive information about the abrasion mechanism compared to the Rotating Cutters method. The latter showed limitations in evaluating HPMWC, as it only abraded the mortar and failed to abrade the aggregates.

Advancements in Experimental Design and Sustainability

This study presents a first-of-its-kind application to employ SMCD methodology and the KCV model in designing and optimizing HPMWC mixtures for enhanced abrasion resistance. The method showed effectiveness, enabling simultaneous optimization of six components and variables in just 34 runs, significantly fewer than traditional methods.

The prediction models developed in this study provide engineers with a scalable framework to balance abrasion resistance, strength, and environmental impact across various applications. These models and optimization tools enable targeted optimization, enhancing structural sustainability by reducing cement and concrete usage and minimizing the lifecycle carbon footprint.

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