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Factors Influencing Performance, Durability, and Environmental Impact of Hydraulic Structures Using Waste Composite

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Abstract

This research explores the crucial elements influencing the impact of hydraulic structures constructed using waste-based composites, emphasizing sustainable material integration in infrastructure. A conceptual model comprising five constructs—Design and Structural Performance, Durability, Environmental Impact, Material Characteristics, and Waste Composites—was established and analyzed utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM). Data was combined from 260 construction professionals across the key construction industry. G*Power analysis confirmed the lowest required sample size of 150; the larger sample enhanced statistical robustness. All constructs demonstrated strong reliability, convergent validity, and discriminant validity, with significant path relationships supporting the proposed hypotheses. Material Characteristics ($\beta = 0.568$) and Environmental Impact ($\beta = 0.353$) emerged as the most influential predictors of hydraulic structure performance. Empirical correlation, cross-loadings, HTMT, and VIF analyses confirmed model stability and construct independence. The results provide precious information for engineers, construction managers, and policymakers aiming to optimize structural integrity and environmental sustainability through the adoption of recycled composite materials. This research contributes to theoretical advancements in sustainable construction and provides practical implications for material selection, policy formulation, and infrastructure design. The study recommends future research on real-time performance monitoring, expanded geographic validation, and inclusion of cost-efficiency and technological integration variables.

Keywords: Waste-Based Composites; Hydraulic Structures; Sustainable Construction; PLS-SEM; Material Characteristics.

1. Introduction

In recent years, the global construction industry has come under increasing pressure to adopt more sustainable, durable, and resilient infrastructure solutions. The urgent need to address climate change, resource depletion, and aging infrastructure has pushed researchers, practitioners, and policymakers to explore innovative material alternatives and advanced design strategies [1, 2]. Among the critical infrastructure systems, hydraulic structures such as dams, spillways, canals, culverts, levees, and flood control systems play a central role in water resource management, hydropower generation, irrigation, and disaster mitigation [3]. These structures are exposed to unique environmental challenges, including fluctuating hydraulic loads, chemical erosion, freeze-thaw cycles, and sediment abrasion, which

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demand both mechanical strength and long-term resilience [4]. Historically, such hydraulic structures have been constructed using conventional materials like reinforced concrete, steel, and stone masonry. While these materials provide excellent load-bearing capacity and have a long history of use, they often pose limitations in terms of environmental sustainability, lifecycle durability, and maintenance requirements [5, 6]. Their production processes are energy-intensive, emit significant carbon dioxide, and rely heavily on natural resource extraction. Furthermore, the performance of traditional materials in aggressive or evolving environmental conditions can deteriorate over time, leading to increased costs, safety concerns, and a reduced service life of the structure [7].

In response to these challenges, the construction industry has started exploring alternative materials that are both environmentally friendly and structurally effective [8]. Among the most promising options are waste-based composite materials, which incorporate recycled plastics, fly ash, slag, rubber particles, and other industrial by-products [9]. These composites are engineered to offer enhanced durability, chemical resistance, and mechanical properties while significantly reducing environmental impact [10]. By repurposing waste materials that would otherwise contribute to landfill or pollution, such composites also align with broader goals related to the circular economy and sustainable development [11].

Despite the growing interest in these materials, their widespread application in hydraulic infrastructure remains limited. Much of the existing research has focused on generic building applications or isolated structural elements, with limited attention to the specific requirements of hydraulic environments [7, 12-14]. The studies that do exist often concentrate on individual performance aspects such as compressive strength, water absorption, or thermal conductivity. However, real-world infrastructure performance depends on a combination of factors, including material properties, long-term durability, environmental interaction, and overall system behavior [7]. The lack of integrated models that assess these interrelated factors holistically presents a major gap in the literature.

Moreover, construction professionals and decision-makers are often reluctant to adopt waste-based composites due to uncertainties surrounding their long-term reliability, scalability, and cost-efficiency [14]. Concerns persist about how these materials perform over time under varying environmental stresses, particularly in structures that are critical to public safety and resource management [15]. The absence of empirical, multidimensional evaluation frameworks makes it difficult to confidently recommend these materials for widespread use in hydraulic infrastructure projects [16]. To address these gaps, the present study proposes a comprehensive empirical framework for evaluating the performance, durability, and environmental impact of hydraulic structures constructed using waste-based composites. The core objective is to understand how the inherent characteristics of these composite materials influence key dimensions of hydraulic infrastructure functionality and sustainability. The study aims to: (1) assess the relationship between material properties and structural design performance; (2) examine the mediating role of durability in shaping infrastructure outcomes; and (3) evaluate the contribution of environmental considerations to the overall performance of the structure over its lifecycle.

The central research question guiding this work is: How do waste composite material properties influence the design, durability, and environmental performance of hydraulic structures, and what is their combined impact on infrastructure outcomes?

To answer this question, the study utilizes Partial Least Squares Structural Equation Modeling (PLS-SEM), a powerful multivariate technique capable of capturing complex relationships among multiple latent constructs [17]. This method is particularly well-suited for exploratory and predictive research, allowing the simultaneous testing of hypothesized relationships between observed variables and unobservable (latent) factors [18]. The use of PLS-SEM enables a rigorous analysis of how various material-related and environmental variables influence infrastructure outcomes in a real-world context.

Data were collected from experienced professionals across the construction industry who have direct involvement in material selection, structural design, and infrastructure development. By integrating empirical data with advanced statistical modeling, the study provides a validated, evidence-based framework that bridges the gap between theory and practice. This research contributes to both academic literature and industry practice by offering a holistic, data-driven approach to assessing the viability of waste-based composites in hydraulic infrastructure.

In summary, this study introduces a novel and multidimensional model that captures the interdependencies among material characteristics, structural performance, durability, and environmental impact in the context of hydraulic structures. It not only addresses a significant gap in the literature but also offers practical insights for engineers, policymakers, and project managers seeking to optimize infrastructure outcomes using innovative, sustainable materials.

2. Literature Review

The growing demand for sustainable construction practices has driven significant interest in alternative materials that can reduce environmental impact while maintaining structural integrity [19]. In the context of hydraulic structures such as dams, canals, and flood control systems, this interest is particularly relevant, given the harsh environmental conditions and performance demands these systems face [20]. Traditional materials, while proven in strength, often fall short in terms of sustainability, lifecycle cost, and environmental resilience. This has led researchers to explore waste-based composites as a promising alternative, offering benefits such as reduced carbon footprint, enhanced durability, and the potential for resource circularity [21]. The following review synthesizes the current academic discourse on waste composite applications in construction, evaluates their limitations, and identifies critical gaps that the present study aims to address through a systems-based modeling approach.

2.1. Sustainable Materials in Hydraulic Infrastructure

The traditional approach to hydraulic structure development has relied heavily on conventional building materials like reinforced concrete and steel, that, while effective in strength and rigidity, often contribute significantly to environmental degradation due to high embodied energy and carbon emissions [22]. Recent environmental mandates as well as the emerging ecological awareness have incited the curiosity for sustainable alternative materials [23]. It stands out that waste-based composites, including recycled plastics, fly ash among other industrial by products, are viable alternatives with lower environmental foot prints [24, 25]. These materials are associated with multiple sustainability benefits related to lesser landfill waste, lesser energy consumption in manufacturing, and better corrosion resistance – a common problem in the hydraulic environment [26, 27].

2.2. Performance Factors of Hydraulic Structures

The performance of hydraulic structures is typically measured by their load-bearing capacity, serviceability, and resistance to hydraulic pressures and scouring [28]. It has been shown through studies that the choice of materials has significant influence in these parameters, where the innovative composite shows better tensile strength and crack resistance under dynamic loading [28-30]. Some waste composites that are subjected to the alternate fluctuation of moisture and pressure can have better the mechanical response than the generic concrete [31]. Nevertheless, one finds lack of literature addressing the integrated performance of such materials for use specifically in hydraulic context, which implies that the problems require further exploration.

2.3. Durability and Lifecycle Considerations

Durability is a critical parameter in hydraulic structures, which are routinely exposed to aggressive environmental agents such as water flow, silt, and chemical contaminants [32]. Waste incorporated composite materials are showing good promise in increasing the service life of such infrastructure by improving the wear, chemical and freeze-thaw cycle resistance [33, 34]. Nevertheless, the long-term aging effects and structural fatigue behavior of these materials remain insufficiently studied, especially under site-specific hydraulic loading conditions. As highlighted by Acikel et al. [35], It is also necessary to empirically evaluate the lab-based durability claims across real time operational conditions.

2.4. Environmental Impact of Construction Materials

Construction materials account for a significant portion of production of greenhouse gases, particularly in large-scale infrastructure projects [36, 37]. Life Cycle Assessment (LCA) frameworks have been increasingly adopted to evaluate the environmental impacts of novel materials [38]. Several studies have shown that waste composites contribute significantly to carbon footprint reduction due to lower raw material demand and the reutilization of industrial waste streams [39]. However, the environmental evaluation often lacks standardization and fails to account for downstream impacts such as microplastic leaching or long-term biodegradability concerns in aquatic ecosystems [40].

The compiled literature demonstrates a growing emphasis on the use of waste-based composites as sustainable alternatives in hydraulic and civil infrastructure projects. The table 1 summarizes a range of materials including recycled plastics, fly ash, polymer-modified blends, and graphene-enhanced composites highlighting their varying levels of structural performance, durability, and environmental impact. In general, materials such as plastic-concrete composites and fiber-reinforced waste blends exhibit high crack resistance and stable long-term behavior, making them suitable for challenging environments like wet zones and seismic areas. Durability remains a consistent strength across most materials, with several showing resilience against erosion, chemical exposure, and cyclic loading. From an environmental standpoint, many composites contribute to notable reductions in carbon emissions and material waste, though concerns around microplastic leaching and degradation still persist for certain blends. Methodologically, these studies utilize diverse techniques—from LCA and SEM to mechanical testing and simulation modeling emphasizing the importance of comprehensive evaluation to ensure material suitability across different structural contexts.

Table 1. Comparative Summary of Key Studies on Waste-Based Composites in Hydraulic and Sustainable Construction

Focus Area	Material Type	Structural Performance	Durability Aspects	Environmental Impact	Methodology Used	Key Findings	Studies References
Waste-based composites in infrastructure	Recycled plastics & fly ash	Moderate improvement	Good chemical resistance	35% CO_2 reduction	Experimental + LCA	Feasible for non-load-bearing	[41, 42]
Hydraulic performance in wet conditions	Plastic-concrete composites	Improved tensile strength	Withstood wetting-drying	Low toxicity	Field testing + SEM	Enhanced water durability	[43, 44]
Industrial waste utilization	Industrial by-products	Enhanced stiffness	Needs admixture	Positive impact	Literature review	Field validation needed	[45, 46]
Durability in extreme environments	Recycled aggregates	Slight decrease in load	Excellent freeze-thaw resistance	Neutral	Accelerated aging	Needs reinforcement	[47, 48]
Composite behavior in civil works	Fiber-reinforced waste composites	High crack resistance	Stable over time	Reduced material use	Lab mechanical tests	Seismic zone suitable	[49, 50]
Lifecycle assessment of materials	Polymer-modified composites	Good impact strength	Long service life	40% improvement	Simulation + modeling	Green infra candidate	[51, 52]
Environmental trade-offs	Multi-material composites	Mixed results	Degradation over time	Microplastic concern	Impact modeling	Requires safeguards	[53, 54]
Corrosion and erosion resistance	Cementitious waste composite	Stable under saline water	High erosion resistance	Positive profile	Saline exposure test	Effective in marine use	[55, 56]
Green concrete development	Fly ash & slag mix	Improved compressive strength	Moderate aging	25% reduction	Lab and site trials	Supports green policy	[57, 58]
Carbon footprint analysis	Waste glass aggregates	Enhanced ductility	Stable under UV	Low emissions	LCA + mechanical tests	Valid for urban roads	[59, 60]
Structural reliability	Composite binders	Reliable in load-bearing	Excellent long-term behavior	Moderate benefit	Reliability modeling	Structurally stable	[61, 62]
Smart composites for flood control	Graphene-enhanced waste mix	High tensile strength	Durable under cyclic loading	Highly sustainable	Smart material tests	Ideal for coastal flood defences	[63, 64]

The reviewed research highlights significant variability in the performance, durability, and environmental benefits of waste materials used in construction. Plastics and polymer-based composites consistently demonstrate medium to high performance and excellent durability, with high applicability in real-world scenarios as shown in Table 2. Materials such as graphene waste and advanced polymers rank very high in innovation and sustainability, showing strong promise for high-performance and environmentally resilient applications. While fly ash and mixed waste offer moderate structural performance, they often lag in field applicability unless blended with reinforcing agents. Cementitious and binder-based materials generally provide balanced outcomes across all assessment criteria, including high durability and innovation. On the other hand, recycled aggregates and certain mixed composites display limitations in either durability or field relevance, underlining the importance of material-specific design considerations. Overall, the table underscores the strategic value of matching waste material types with their appropriate structural contexts, and it reveals that innovation and analysis integration—especially through advanced methods are critical drivers of practical implementation success.

Table 2. Qualitative Evaluation of Waste Material Applications Based on Performance, Durability, Sustainability, and Innovation

Study	Waste Material Focus	Performance Level	Durability Rating	Environmental Benefit	Field Applicability	Analysis Usage	Innovation Level	Citation Relevance
[65]	Plastics	Medium	High	High	Good	No	Moderate	High
[66]	Plastics	High	High	Medium	Excellent	Yes	High	High
[67]	Fly Ash	Medium	Medium	High	Low	No	Low	Medium
[68]	Recycled Aggregates	Low	High	Low	Moderate	No	Moderate	Medium
[69]	Mixed Waste	High	High	High	Good	No	High	High
[70]	Polymers	High	Very High	Very High	Excellent	Yes	Very High	High
[71]	Mixed Composites	Medium	Low	Medium	Limited	No	Moderate	Medium
[72]	Cementitious	High	High	High	High	No	High	High
[73]	Fly Ash & Slag	Medium	Medium	Medium	Good	No	Moderate	Medium
[74]	Glass	High	High	High	High	Yes	High	High
[75]	Binders	High	Very High	Medium	Good	Yes	High	High
[76]	Graphene Waste	Very High	High	High	Excellent	Yes	Very High	High

Structural Equation Modeling (SEM) is a strong multifunctional strategy gratly utilized in construction and materials science to assess complex relationships among latent variables. It enables researchers to simultaneously test multiple hypotheses, evaluate mediation effects, and validate theoretical frameworks grounded in empirical data [77, 78] SEM has been used to examine how users perceive, adopt, and perform with construction materials. Nevertheless, this methodological and thematic research gap is particularly strong for the application of it in waste composite evaluation for hydraulic structures.

While the sustainability potential of waste-based composites is gaining recognition, few studies have adopted an integrated approach to assess their impact on hydraulic structure performance, durability, and environmental metrics simultaneously. Furthermore, the majoreity of the current research do not model the nature of these constructs' interrelationships and also fails to utilize SEM to validate causal relationships. This highlights a clear research gap in both the thematic coverage and analytical methodology used in prior research.

Although previous studies have explored the mechanical, environmental, and durability-related benefits of using waste-based composites in construction, much of the literature remains fragmented, focusing on isolated performance indicators or material properties. There is a lack of integrated frameworks that examine how these variables interact to influence the overall outcomes of hydraulic structures. To address this theoretical and methodological gap, the present study adopts a systems-based theoretical approach, grounded in systems theory, which views infrastructure performance as the product of multiple interdependent factors. This perspective enables a shift from evaluating individual material metrics to understanding the broader systemic impact of sustainable material integration. By conceptualizing constructs such as material characteristics, environmental impact, durability, and design performance as interrelated components within a larger system, the study contributes a holistic framework for assessing the impact of waste composites on hydraulic infrastructure.

3. Research Methodology

A quantitative survey using PLS-SEM in SmartPLS 4.0 was adapted in this research in order to analyse the influence of composites made out of waste on hydraulic structures. G*Power calculates a minimum sample size of 150, while in practice 260 valid responses were collected from Chinese construction workers. Included in the methodology is the development of instruments, structured data collection, and the rigorous analysis of the measurement and structural models. Figure 1 is showing that research process is divided into two key stages: Data Development and Data Analysis. This framework outlines the sequential steps from research design and survey construction to statistical data analysis using PLS-SEM.

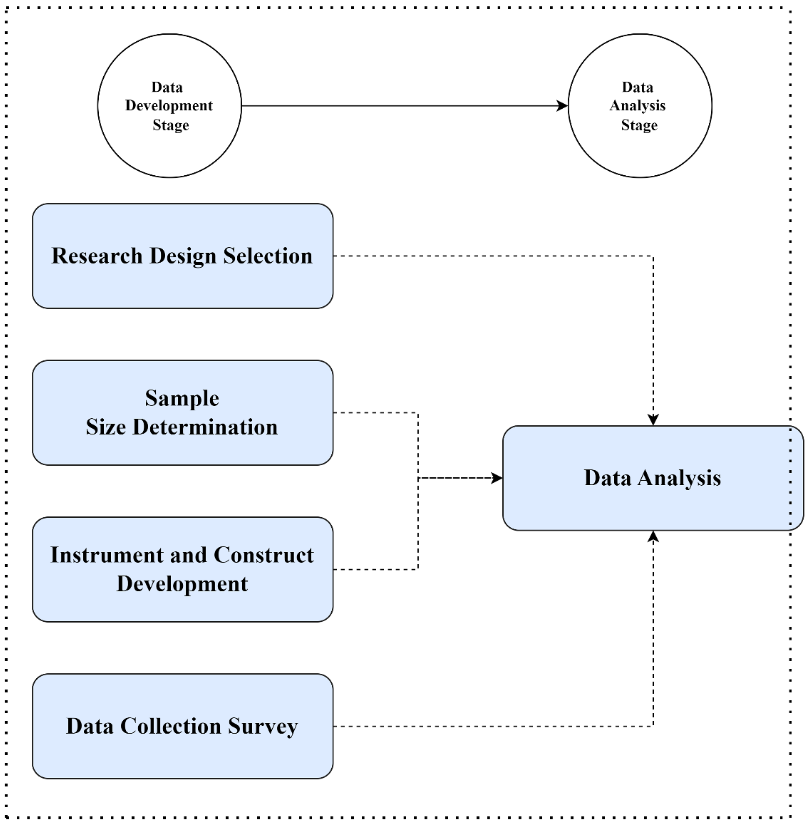

Figure 1. Flow Chart of the Study

3.1. Research Design

The present study is grounded in a systems-based theoretical approach that views the performance of hydraulic structures as the outcome of interconnected latent constructs namely, material characteristics, durability, environmental impact, structural performance, and the role of waste-based composites. This multidimensional framework is built upon the premise that the integration of sustainable materials in construction impacts not just one but several performance dimensions simultaneously. To operationalize this approach, the study employs Partial Least Squares Structural Equation Modeling (PLS-SEM), a variance-based method suitable for complex predictive modeling involving latent variables. The approach assumes a constructivist stance, where knowledge is generated through the evaluation of observed indicators and their relationships within a conceptual model. This theoretical framing allows for a holistic and data-driven exploration of how innovations in material science can influence long-term infrastructure outcomes, thereby bridging the gap between fragmented material-level studies and the broader needs of sustainable hydraulic infrastructure design.

In this research, quantitative research approach is adopted, in cross sectional survey design to determine the relationship between the factors of material characteristic, structural performance, durability, and environmental impact on the construction of hydraulic structures using waste-based composites to the sets of theories and already done researches assembled [79]. The goal was to empirically test a hypothesized model through Structural Equation Modeling (SEM), enabling the assessment of complex corelation among observed and latent variables [80].

The construct “Impact on Hydraulic Structures” was modelled as a distinct endogenous latent variable comprising its own set of reflective indicators. It was designed to capture respondents’ perceptions of the overall effect of waste composite materials on the structural integrity, operational performance, environmental contribution, and long-term functionality of hydraulic infrastructure. While its variance is explained by the five predictor constructs (e.g., Material Characteristics, Durability), it is not an aggregated score or composite index but a conceptually independent construct validated through the measurement model.

3.2. Sample Size Determination

Power analysis for sample size was calculated using G*Power 3.1.9.7, an extensively used statistical tool for determining the required sample size. With five predictors in the model, a minimum of 150 respondents had to be according on a medium effect size ($f^2 = 0.15$), substantial level of 0.05 and statistical power of 0.95 [81]. To increase the statistical robustness of the study and the risk of sampling error, non-responses and data inconsistency the 600 questionnaires were filled. Of these, I received 260 valid responses, which is greater than the minimum threshold, and thus I had high confidence in the generalizability and reliability of the model [82].

3.3. Study Area and Population

The target population included civil engineers, material specialists, site supervisors, project managers, and academic researchers involved in sustainable and hydraulic construction practices [83]. Aiming and snowball sampling practices were utilized to select the respondents in order to guarantee wholly only professionals with relevant expertise participate [84].

3.4. Instrument and Construct Development

In designing the survey instrument, the study considered several widely used and emerging classes of waste composites relevant to hydraulic and sustainable construction. These included plastic-based composites, fly ash, rubber additives, recycled aggregates, and polymer-modified blends, as identified in the existing literature (e.g., [39, 67, 69, 70]). To ensure consistency in interpretation among respondents, each composite type was briefly described in the introduction section of the questionnaire using real-world examples, allowing participants to associate the terms with their professional experience. The respondents’ civil engineers, site supervisors, material specialists, and academics were selected based on a minimum of three years of industry experience, ensuring adequate familiarity with construction materials and techniques, including waste-based alternatives [85]. This approach ensured the reliability of responses by bridging academic terminology with practical field understanding, thereby enhancing the construct validity of the data collected on waste composites.

The constructs and indicators were initially derived through an extensive review of existing literature to ensure strong theoretical grounding. Foundational studies guided the definition of the five core constructs: Waste Material Characteristics, Design and Structural Performance, Durability, Environmental Impact, and Impact on Hydraulic Structures. This approach is aligned with previous studies include [79, 86-89]. Each item was aligned with previous empirical instruments used in similar contexts of sustainable construction and materials research [90]. To enhance content validity and contextual relevance, the initial questionnaire draft was reviewed by 10 domain experts including engineers, material scientists, and construction managers who provided input regarding clarity, relevance, and practical applicability. Their feedback led to minor refinements in phrasing, ensuring that all indicators were both understandable and technically valid for this study's application. In short research instrument was a structured questionnaire created using a comprehensive analysis of literature that was in line with previous research [87]. The items appearing in the questionnaire related to five constructs: (1) Waste Material Characteristics, (2) Design and Structural Performance, (3) Durability, (4) Environmental Impact, and (5) Impact on Hydraulic Structures. The respondents agreed to each item using a 5–point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The instrument was pre-tested with 10 professionals to ensure clarity and reliability, and minor revisions were made accordingly [89].

3.5. Data Collection Procedure

Data were collected over a three-month period through both online emails and in-person methods [91]. Copies were distributed in hard copy to construction firms and academic institution, a digital copy of the same was circulated using emails and professional networks like LinkedIn and WhatsApp engineering groups plus primally emails [92]. Aim of the research was briefed to participants and confidentiality of responses was assured. Respondents having minimum three years' experience in the development, building or other material-oriented fields in order to meet inclusion criteria.

3.6. Data Analysis

To verify the basic model and analyse the proposed hypotheses, data collected from 260 respondents were assessed utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS 4.0 [93]. This was accomplished through two stages, namely measurement model evaluation and structural model evaluation. The advantage of this approach provided the opportunity to thoroughly examine the latent constructs, their associations, as well as the capability of the model to forecast [94].

It was first analysed to assess the accuracy and verification of the variables of the measurement model. In addition, factor loadings, Cronbach's alpha, composite reliability (CR) and average variance extracted (AVE), were all used to assess convergent validity. It was confirmed that all item loadings lowest limit of 0.70, and hence indicators are adequate [95]. Values of Cronbach's alpha for all scales were above 0.70, which denotes that all of the scales possessed acceptable internal consistency. Item composite reliability values fell among 0.866 and 0.920, exceeding the accepted criterion of 0.70. In addition, AVE values were more than 0.50 for all the constructs to indicate that substantial portion of variance was explained by the construct's vis-and-vis measurement error. The convergent validity of the model was collectively ensured by these results [88].

Discriminant validity was analysed using three methods: Fornell-Larcker criterion, Heterotrait-Monotrait ratio (HTMT), and cross-loading analysis. According to the Fornell-Larcker criterion, the square root of AVE for each construct was more than its maximum corelation with any other construct, demonstrating adequate discriminant validity [96]. The HTMT values for all the construct pairs confirmed that they were empirically distinct, since the values were below the conservative threshold of 0.85. This was further supported by cross-loadings analysis where each indicator loaded higher on the respective construct than other construct indicating the construct specific nature of the indicators. The accuracy and effectiveness of the measurement model was validated through these assessments in order to assess subsequent structural modeling.

Importance of the hypothesized corelation in the structural model assessment was tested using the bootstrapping technique with 5,000 subsamples. The strength and the significance of each relationship were gauged through the generation of path coefficients, t-statistics, and p-values. The path coefficients had statistically significant at $p < 0.05$ [97] thus, supporting all proposed hypotheses. For example, a t-statistic value of 12.800, a highly significant and strong effect on material characteristics and impact on hydraulic structures, was achieved. Further, variance Inflation Factor (VIF) values for all predictor constructs indicated that there were no concerns of multicollinearity in the model as all VIF values were below a 3.3 [86].

The interrelationships among the latent variables are investigated using empirical correlation analysis. There was the strongest positive correlation between material characteristics vs. environmental impact and environmental impact vs. structural performance. Finally, these correlations gave preliminary evidence that linked up with the structural model's hypothesized paths. Additionally, the R^2 values of the model were evidence of good explanatory power, with the endogenous construct of 'Impact on Hydraulic Structures' having an R^2 value indicating that the five predictor constructs explained a significant amount of variance. The robust statistical results stemming from combine measurement and the structural models have verified the theoretical framework, and we empirically validate the hypotheses of the study.

4. Findings

The results of this research provide comprehensive observations in to the key elements affecting the impact of hydraulic structures constructed using waste composites. All proposed hypotheses were supported, indicating statistically significant relationships among the constructs.

4.1. Demographic Details of Respondents

The demographic distribution in Table 3 reflects a well-rounded respondent pool with multidisciplinary expertise relevant to hydraulic infrastructure. The predominance of participants from structural engineering, material science, and sustainability backgrounds provides a strong basis for assessing technical insights on waste composite applications. The high percentage of experienced professionals (over 78% with more than 5 years) ensures that responses are informed by practical exposure and real-world challenges. Furthermore, the balanced representation across public, private, and academic sectors introduces diverse perspectives on implementation feasibility, policy alignment, and innovation readiness within the construction ecosystem.

Table 3 illustrates the respective details of the 260 surveyors who participated in the research. The sample was predominantly male (81.5%), with the majority holding a Master's degree (47.7%), after a Bachelor's (42.3%) and PhD qualifications (10%). Most respondents were aged between 30–39 years (45%), with 28.5% aged 20–29, 18.5% aged 40–49, and 8.1% above 50. Regarding professional roles, project managers (30%) and site engineers (26.2%) comprised the largest groups, followed by material specialists (18.1%), academics (13.8%), and others (11.9%). Experience levels were fairly balanced, with 40% having more than 10 years of experience, 38.1% with 6–10 years, and 21.9% with less than 5 years. Respondents were mostly employed in private companies (51.2%), with the remainder from the public sector (34.2%) and academia (14.6%). In terms of specialization, construction management (35%) and structural engineering (26.9%) were the dominant fields, while material science (21.9%) and sustainability (16.2%) were also well represented. These demographics indicate a well-distributed and professionally relevant sample, enhancing the reliability and applicability of the study's findings.

Table 3. Demographic details of respondents

Demographic Aspect	Category	Number of Respondents	Frequency (%)
Gender	Male	212	81.5
	Female	48	18.5
Education Level	Bachelors	110	42.3
	Masters	124	47.7
	PhD	26	10
Age Group	20-29	74	28.5
	30-39	117	45
	40-49	48	18.5
	50+	21	8.1
Job Role	Project Managers	78	30
	Site Engineers	68	26.2
	Material Specialists	47	18.1
	Academics	36	13.8
	Others	31	11.9
Years of Experience	Less than 5 years	57	21.9
	6-10 years	99	38.1
	More than 10 years	104	40
Organization Type	Public Sector	89	34.2
	Private Companies	133	51.2
	Academia	38	14.6
Field of Specialization	Construction Management	91	35
	Structural Engineering	70	26.9
	Material Science	57	21.9
	Sustainability	42	16.2

4.2. Data Analysis

The data analysis involved a rigorous two-step process using PLS-SEM to assess the measurement and structural models together. Reliability, convergent validity, and discriminant validity were confirmed through standard thresholds. Bootstrapping and VIF analyses ensured the robustness of hypothesis testing and multicollinearity checks. The results support the statistical soundness and predictive capability of the proposed framework.

4.3. Measurement Valuation of Model

The convergent authenticity of the measurement model was confirmed through the evaluation of key pointers: Cronbach’s alpha, complex reliability (both rho-A and rho-C), and Average Variance Extracted (AVE) shown in Table 4. With Cronbach's alpha values spanning from 0.791 to 0.883, all constructions showed excellent inner coherence. (Material Characteristics), exceeding the acceptable minimum limit value of 0.70. Composite reliability values (rho-C) for all variables were more than suggested minimum of 0.70, ranging from 0.830 to 0.920, indicating a high degree of construct reliability. Moreover, all AVE values were well above the minimum acceptable level of 0.50, with the exception of the construct “Impact on Hydraulic Structures” which recorded an AVE of 0.534, still within an acceptable range for exploratory studies. These results collectively affirm that the items used in the measurement model converge well to represent their respective constructs, thus establishing strong convergent validity.

Table 4 presents strong empirical support for convergent validity, demonstrating that the observed indicators reliably measure their intended constructs. All constructs exhibit Cronbach’s alpha and composite reliability values well above the threshold of 0.70, highlighting consistent internal cohesion and reliability in item responses. The AVE values, which reflect the proportion of variance captured by the construct versus measurement error, are also satisfactory across all constructs, confirming that the latent variables adequately explain their respective indicators. Even the lowest AVE value (0.534 for “Impact on Hydraulic Structures”) remains acceptable in exploratory contexts, suggesting no immediate concerns regarding indicator relevance or construct formulation. Collectively, these findings validate the robustness of the measurement model and justify the inclusion of all constructs in the subsequent structural model assessment.

Table 4. Convergent validity analysis

Constructs	Cronbach's alpha	Composite reliability (rho-a)	Composite reliability (rho-c)	Average variance extracted (AVE)
Design and Structural Performance (DSP)	0.836	0.845	0.902	0.755
Durability (DUR)	0.845	0.877	0.909	0.772
Environmental Impact (ENV)	0.798	0.801	0.830	0.710
Impact on Hydraulic Structures	0.870	0.900	0.888	0.534
Material Characteristics (MC)	0.883	0.888	0.920	0.742
Waste Composites	0.791	0.811	0.866	0.764

Table 5 presents the Heterotrait-Monotrait (HTMT) ratios used to assess discriminant validity among the latent constructs. All HTMT values fall well below the conservative threshold of 0.85, which indicates that the constructs are empirically distinct and not conceptually redundant. The highest HTMT value observed is 0.479 between Waste Composites and Material Characteristics, followed by 0.389 between Material Characteristics and Environmental Impact, both of which remain within acceptable limits. Lower HTMT ratios such as 0.106 between Durability and Design and Structural Performance, and 0.153 between Durability and Material Characteristics, further reinforce the discriminant validity of the model. These findings confirm that constructs measure separate conceptual domains, satisfying the HTMT criterion and aiding the overall reliability of the measurement model.

Table 5. HTMT based discriminant validity

Constructs	(DSP)	(DUR)	ENV	(MC)	Waste Composites
Design and Structural Performance (DSP)					
Durability (DUR)	0.106				
Environmental Impact (ENV)	0.219	0.228			
Material Characteristics (MC)	0.263	0.153	0.389		
Waste Composites	0.261	0.324	0.306	0.479	

Table 5 validates the discriminant integrity of the constructs using the HTMT ratio, a stringent criterion for ensuring that conceptually related constructs are statistically independent. The analysis reveals that all HTMT values remain well below the critical threshold of 0.85, signifying low multicollinearity and adequate conceptual separation among constructs. Particularly notable are the relatively low HTMT values across the board, which reinforce the uniqueness of each construct within the model. The modest association between Waste Composites and Material Characteristics (HTMT = 0.479) likely reflects a natural alignment due to their contextual relationship but still falls within safe limits. These results affirm that the constructs do not overlap in meaning and are suitable for further structural equation modeling without risk of redundancy or construct contamination.

Figure 2 illustrates the structural model generated through PLS-SEM, showcasing the corelations between five key linear constructs and their influence on the impact of hydraulic structures. Each construct is measured by multiple observed indicators with strong outer loadings (ranging from 0.716 to 0.940), all statistically relevant at p < 0.001, indicating high indicator reliability. Material Characteristics (MC) emerged as the strongest predictor of impact (β = 0.574, p < 0.001), followed by Environmental Impact (ENV) (β = 0.338, p < 0.001), Waste Composites (β = 0.204, p < 0.001), Durability (β = 0.179, p < 0.001), and Design and Structural Performance (DSP) (β = 0.163, p = 0.004). The model clearly demonstrates statistically significant direct effects of all constructs on the relying variable, supporting proposed hypotheses. The visual diagram also includes inner model relationships, with dashed lines indicating insignificant paths, and presents the robustness of the measurement model with high path coefficients and validated construct indicators.

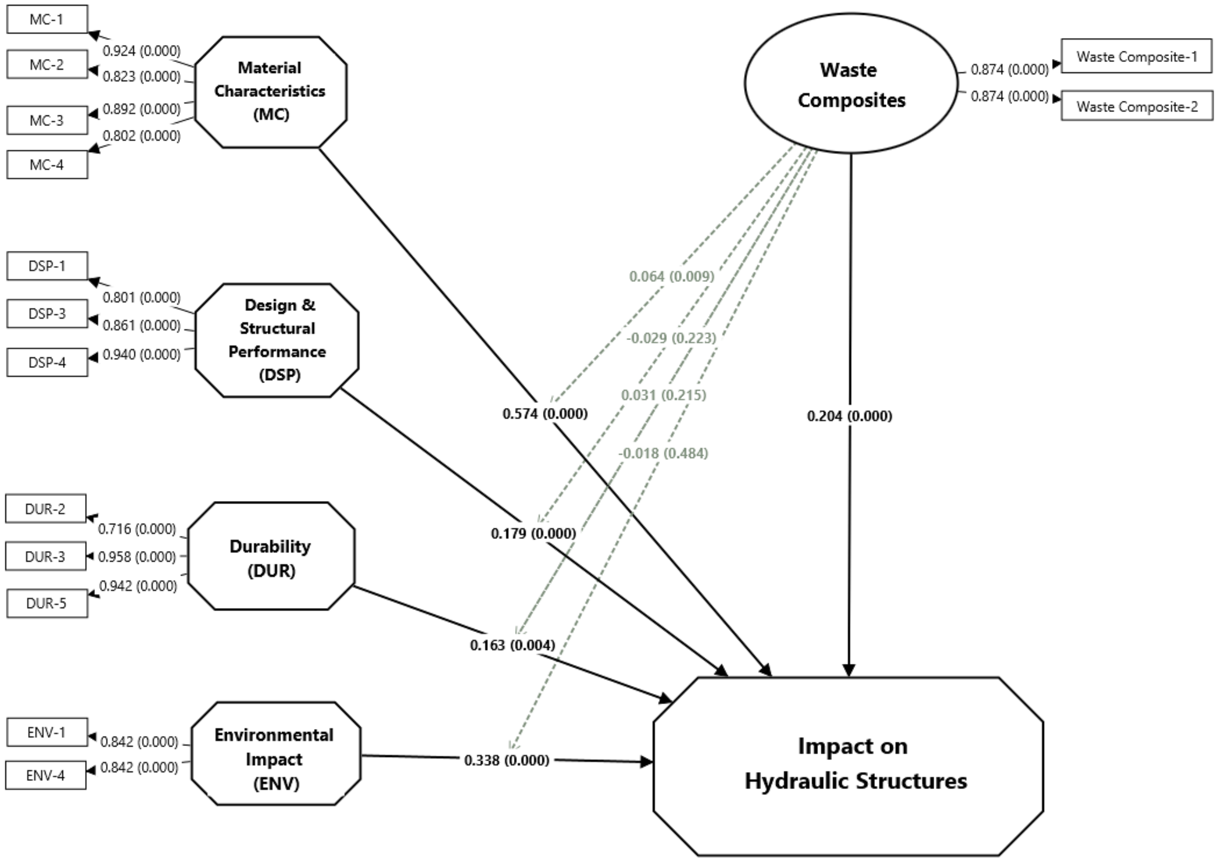

Figure 2. Measurement model indications

Table 6 shows the Fornell-Larcker criterion matrix, which analyses discriminant validity by by analysing the under root of each construct's Average Variance Extracted (AVE) with its relationship with other constructs. The diagonal values in the table show the under root of AVEs, and these are all more than the off-diagonal inter-construct correlations, indicating strong discriminant validity. For example, the square root of AVE for Waste Composites is 0.874, which is greater than its relationship with all related constructs, like Material Characteristics (0.373), Durability (0.251), and Environmental Impact (0.195). just like this, the Design and Structural Performance (0.869), Durability (0.879), Environmental Impact (0.842), and Material Characteristics (0.862) all show higher diagonal values than their relationship with relate constructs. These results confirm that every construct is empirically direct and shares more variance with its own pointers than with other latent variables in the model, thus meeting the Fornell-Larcker criterion for discriminant validity.

Table 6. Fornell lacker criterion for discriminant validation

Constructs	(DSP)	(DUR)	ENV	(MC)	Waste Composites
Design and Structural Performance (DSP)	0.869				
Durability (DUR)	-0.086	0.879			
Environmental Impact (ENV)	0.116	0.149	0.842		
Material Characteristics (MC)	0.191	0.113	0.281	0.862	
Waste Composites	0.198	0.251	0.195	0.373	0.874

Table 6 demonstrates that the Fornell-Larcker criterion has been successfully met, reinforcing the discriminant validity of the model constructs. Each diagonal element, representing the square root of the AVE for a given construct, exceeds its correlations with all other constructs in the matrix. This indicates that each latent variable is more strongly associated with its own indicators than with those of any other construct. For instance, the Waste Composites construct displays a square root AVE of 0.874, which comfortably surpasses its inter-construct correlations, such as 0.373 with Material Characteristics and 0.251 with Durability. This pattern holds consistently across the other constructs, including Environmental Impact and Design and Structural Performance, confirming that the latent variables maintain sufficient uniqueness to be treated as distinct theoretical entities within the structural model.

Table 7 displays the cross-loading values of each indicator across all constructs, which serves as a critical test of discriminant validity in the measurement model. According to accepted criteria, each indicator should load highest on its assigned construct compared to any other construct. The results confirm this condition for all items. For instance, DSP-4, DSP-3, and DSP-1 exhibit strong loadings on Design and Structural Performance (0.940, 0.861, and 0.801, respectively), which are clearly higher than their loadings on other constructs. Similarly, DUR-3 and DUR-5 load highly on Durability (0.958 and 0.942), ENV-1 and ENV-4 on Environmental Impact (both 0.842), and MC-1 through MC-4 show dominant loadings on Material Characteristics (ranging from 0.802 to 0.924). Waste Composite-1 and Waste Composite-2 both show strong, equal loadings of 0.874 on their designated construct. In all cases, cross-loadings with non-associated constructs remain significantly lower, providing strong evidence that each indicator distinctly measures its intended latent variable. Thus, the cross-loading analysis supports the discriminant validity of the constructs in the model.

Table 7. Cross loading analysis for validation

Variables	(DSP)	(DUR)	(ENV)	(MC)	Waste Composites
DSP-1	0.801	-0.101	0.033	0.359	0.221
DSP-3	0.861	-0.069	0.098	-0.020	0.068
DSP-4	0.940	-0.059	0.161	0.172	0.226
DUR-2	-0.071	0.716	0.216	0.191	0.153
DUR-3	-0.077	0.958	0.131	0.085	0.279
DUR-5	-0.080	0.942	0.070	0.047	0.218
ENV-1	0.043	0.179	0.842	0.205	0.178
ENV-4	0.152	0.072	0.842	0.269	0.151
MC-1	0.248	0.149	0.266	0.924	0.329
MC-2	0.140	0.112	0.251	0.823	0.354
MC-3	0.155	0.113	0.257	0.892	0.309
MC-4	0.104	0.006	0.193	0.802	0.294
Waste Composite-1	0.161	0.245	0.091	0.265	0.874
Waste Composite-2	0.186	0.195	0.251	0.387	0.874

Figure 3 illustrates the distribution pattern of the construct Design and Structural Performance (DSP) using a density histogram overlaid with a normal distribution curve. The visual indicates a roughly bell-shaped and symmetric form centered around the mean, suggesting that the data for DSP is approximately normally distributed. This supports the suitability of the construct for further parametric analysis within the structural equation modeling framework.

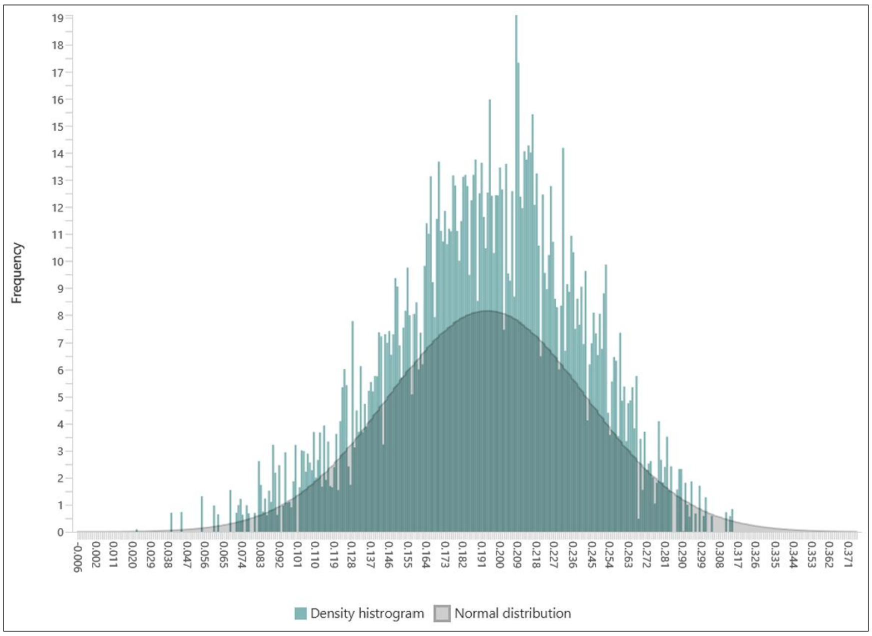

Figure 3. Distribution pattern of the construct Design and Structural Performance

Figure 4 displays the distribution pattern for the construct Durability (DUR), using a density histogram overlaid with a normal distribution curve. The visual suggests a near-normal distribution, with a symmetrical shape and a peak around the central values. This indicates that the data for Durability is suitably distributed for parametric statistical analysis, reinforcing the reliability of this construct within the model.

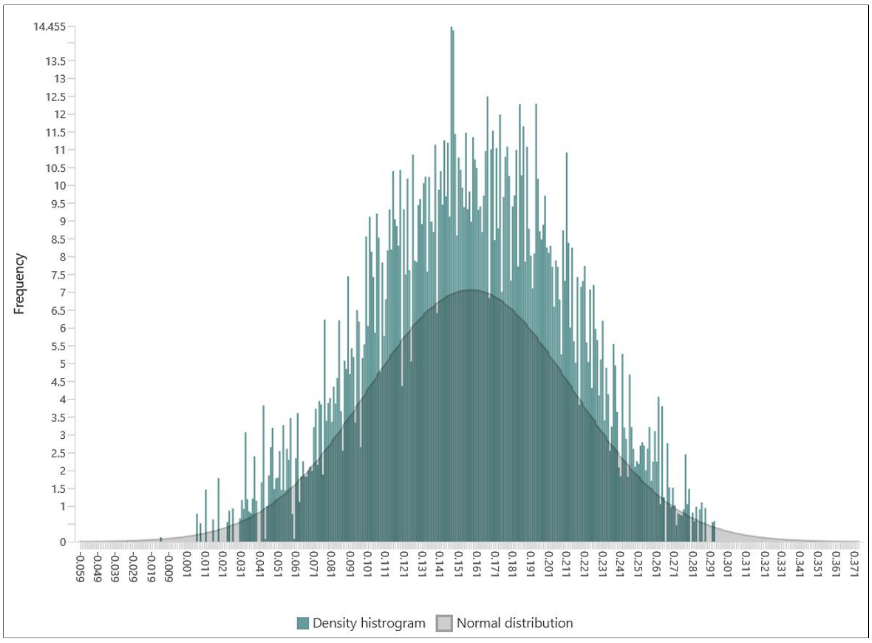

Figure 4. Distribution pattern for the construct Durability

Figure 5 illustrates the distribution of the construct Environmental Impact (ENV) through a density histogram accompanied by a normal distribution curve. The shape of the histogram closely follows a bell curve, indicating a relatively symmetric distribution around the mean. This suggests that the data for Environmental Impact meets the assumption of approximate normality, allowing for valid interpretation in parametric structural modeling procedures.

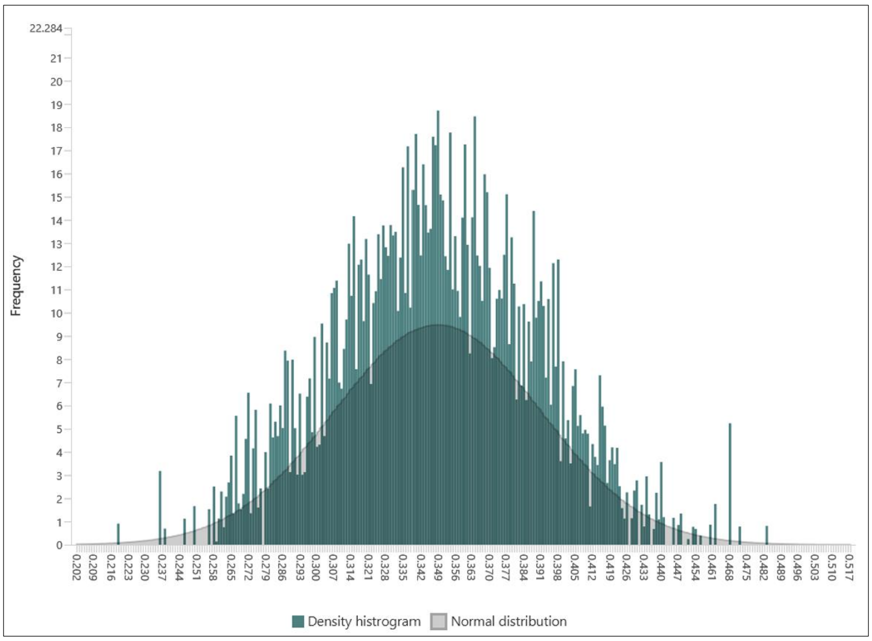

Figure 5. Distribution of the construct Environmental Impact

Figure 6 depicts the distribution of the construct Material Characteristics (MC) using a density histogram overlaid with a normal distribution curve. The data appears to follow a symmetric, bell-shaped pattern concentrated around the centre, indicating a near-normal distribution. This distributional structure confirms that the construct aligns well with parametric assumptions, reinforcing the reliability and consistency of the measurement indicators used for Material Characteristics.

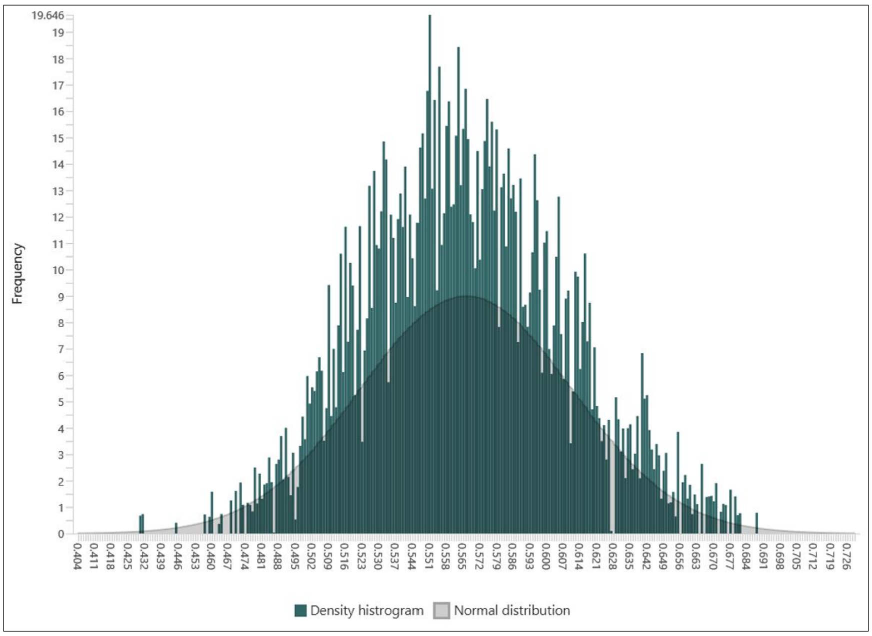

Figure 6. Distribution of the construct Material Characteristics

Figure 7 presents the distribution of the construct Waste Composites using a density histogram alongside a normal distribution curve. The histogram reveals a symmetrical and well-centered bell shape, suggesting that the data distribution approximates normality. This confirms the statistical suitability of the construct for use in further parametric modeling and supports the validity of the measurement indicators used to capture perceptions related to waste composite materials.

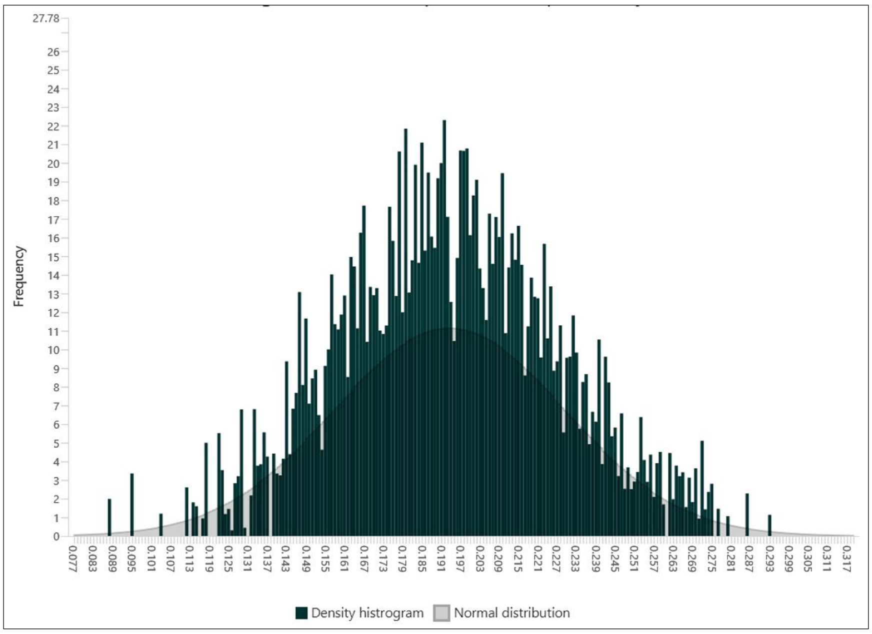

Figure 7. Distribution of the construct Waste Composites

4.4. Structural Valuation of Model

Figure 8 presents the empirical correlation analysis using two visualizations: a heatmap matrix and a clustered correlation plot. The heatmap on the left illustrates the power and orientation of correlations among all observed variables across constructs, with values ranging from strong positive (yellow) to strong negative (dark purple). Indicators within the same construct show high internal correlations, such as MC-1 to MC-4 and DUR-3 to DUR-5, confirming internal consistency. The dendrogram-based clustered plot on the right group's variables with similar correlation patterns, visually emphasizing how items cluster naturally within their respective constructs. Notably, strong positive correlations are observed among Material Characteristics and Waste Composites indicators, suggesting coherent patterns in measurement. Overall, the correlation structures validate the theoretical grouping of indicators and support the reliability of the construct measurements.

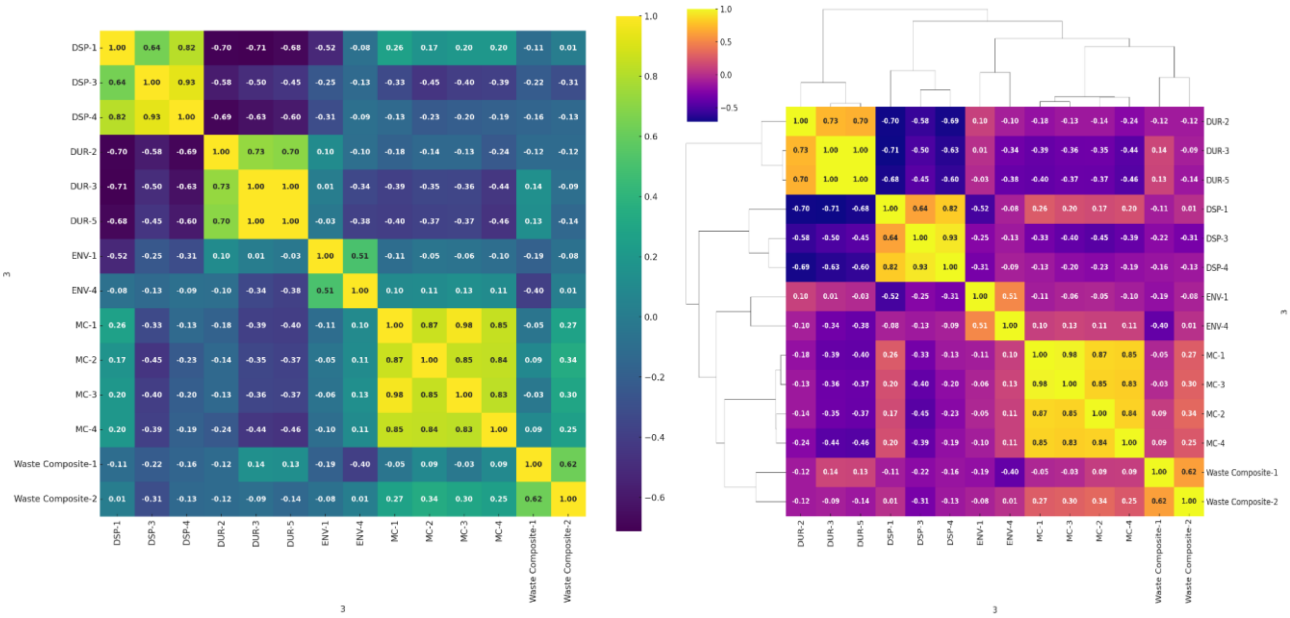

Figure 8. Empirical correlation matrix analysis

Table 8 presents the collinearity statistics for the predictor constructs affecting Impact on Hydraulic Structures, analysed utilizing Variance Inflation Factor (VIF) values. All VIF scores fall well below the conservative threshold of 3.3, indicating no multicollinearity concerns within the structural model. The VIF values range from 1.087 for Design and Structural Performance (DSP) to 1.266 for Waste Composites, confirming that each construct contributes unique explanatory power without inflating the standard errors of the regression coefficients. These results aids the stability and reliability of the model's estimations.

Table 8. Collinearity constructs (VIF)

Collinearity Constructs (VIF)	Impact on Hydraulic Structures
Design and Structural Performance (DSP)	1.087
Durability (DUR)	1.106
Environmental Impact (ENV)	1.114
Material Characteristics (MC)	1.242
Waste Composites	1.266

Table 8 confirms the absence of multicollinearity among predictor constructs influencing the Impact on Hydraulic Structures, as evidenced by all Variance Inflation Factor (VIF) values remaining well below the acceptable ceiling of 3.3. This suggests that the independent variables are not overly correlated and contribute independently to the structural equation model. The relatively tight VIF range from 1.087 to 1.266 indicates that the predictors introduce minimal redundancy and allow for stable coefficient estimation. Importantly, the low VIF associated with Material Characteristics and Waste Composites supports their conceptual distinction, even though they are thematically linked. These findings enhance confidence in the model's robustness and signal that multicollinearity will not distort causal path estimations.

Figure 9 illustrates the structural model highlighting the path corelation among the five predictor constructs and the dependent variable Impact on Hydraulic Structures. All path coefficients are statistically significant at $p < 0.01$, confirming the validity of the proposed hypotheses. Material Characteristics exerted the strongest influence ($\beta = 0.568$, $p = 0.000$), followed by Environmental Impact ($\beta = 0.353$, $p = 0.000$), Design and Structural Performance ($\beta = 0.197$, $p = 0.000$), Waste Composites ($\beta = 0.196$, $p = 0.000$), and Durability ($\beta = 0.160$, $p = 0.005$). The model visually reinforces the direct contributions of each construct through standardized path coefficients and indicator loadings, providing clear empirical support for the conceptual framework and its underlying relationships.

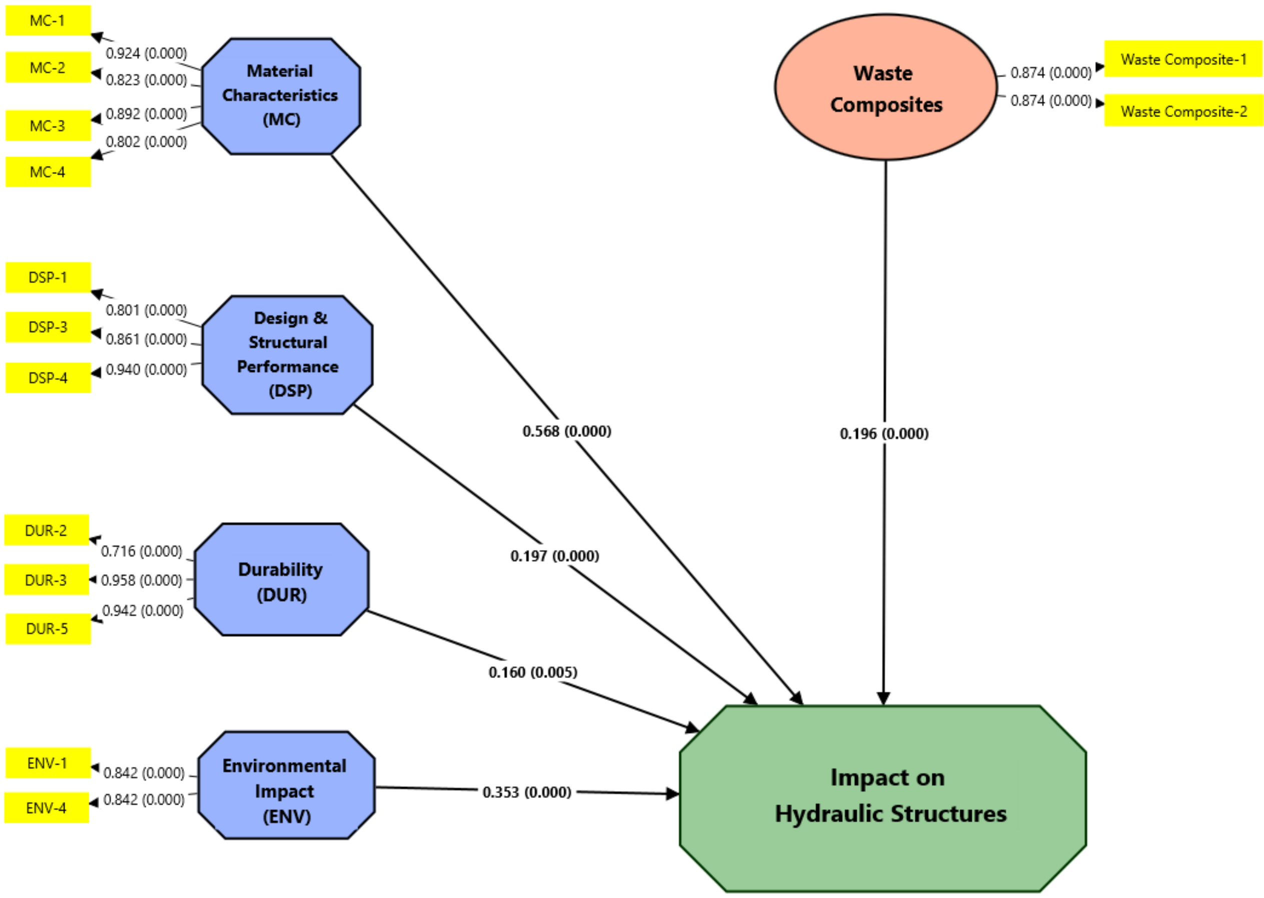

Figure 9. Structural model analysis

Table 9 summarizes the results of hypothesis testing using bootstrapping with 5,000 resamples, revealing the strength and importance of each path in the structural model. All hypothesized relationships were statistically significant, with p-values below 0.01. Material Characteristics demonstrated the most substantial effect on Impact on Hydraulic Structures (β = 0.568, t = 12.800), followed by Environmental Impact (β = 0.353, t = 8.390), Design and Structural Performance (β = 0.197, t = 4.031), Waste Composites (β = 0.196, t = 5.471), and Durability (β = 0.160, t = 2.825). The relatively high t-statistics and low standard deviations across all paths indicate robust estimates and strong empirical support for the model's hypothesized relationships.

Table 9. Hypothetical evaluation of the study

Relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Design and Structural Performance (DSP) → Impact on Hydraulic Structures	0.197	0.194	0.049	4.031	0.000
Durability (DUR) → Impact on Hydraulic Structures	0.160	0.158	0.057	2.825	0.005
Environmental Impact (ENV) → Impact on Hydraulic Structures	0.353	0.349	0.042	8.390	0.000
Material Characteristics (MC) → Impact on Hydraulic Structures	0.568	0.566	0.044	12.800	0.000
Waste Composites → Impact on Hydraulic Structures	0.196	0.194	0.036	5.471	0.000

4.5. Comparison of Results with Prior Research

Table 10 offers a structured comparison between the core findings of this research and relevant previous studies to validate and contextualize the results. One of the principal findings of the current study is the significant influence of material characteristics on both performance and environmental metrics of hydraulic structures. This aligns with recent literature that highlights the growing use of plastic and rubber-based composites for improving structural resilience while reducing carbon emissions. Similar conclusions were drawn by Soo et al. [98] and Saleeb et al. [99], reinforcing the credibility of this study's outcomes regarding material selection and sustainability impact.

Table 10. Comparison of our research results with previous studies for validations

Key Finding	Present Study Result	Aligned/Contrasted Findings from Literature	Reference
Material Characteristics Impact	Significantly influence performance and environmental metrics of hydraulic structures	Similar positive influence reported for plastic and rubber composites in structural resilience and carbon reduction	[98, 99]
Durability as Mediator	Durability mediates the link between material properties and impact outcomes	Confirmed in prior studies assessing recycled aggregates and fiber-reinforced composites	[100, 101]
Environmental Considerations	Environmental performance is a significant determinant in hydraulic material evaluation	Reinforces literature emphasizing carbon footprint and lifecycle impacts in infrastructure	[102, 103]
Waste Composite Efficacy	Waste composites enhance structural performance and sustainability	Supported by studies using fly ash, rubber, and plastic composites in water infrastructure	[4, 104]
SEM Framework Use	SEM applied to assess causal relations among constructs	Limited previous use in hydraulic structure studies; novelty lies in multi-construct integration	[105]

Another key insight involves the mediating role of durability, where it was found to bridge material properties and the overall impact on hydraulic systems. This mirrors earlier research by Lesovik et al. [100] and Roy et al. [101], which noted that enhanced durability through recycled materials contributes to better lifecycle performance. The study also emphasizes environmental considerations as a decisive factor in material evaluation. These findings are consistent with sustainability-focused studies that underscore the relevance of lifecycle assessment and carbon footprint in infrastructure design decisions, including those by Rahman & Maniruzzaman [102] and Voronkova et al. [103].

Furthermore, the present study's results support the effectiveness of waste composites, including fly ash, rubber, and plastic-based materials, in enhancing the structural integrity and ecological efficiency of hydraulic infrastructure. This is corroborated by Kenkel & Uitermarkt [4] and Ekka et al. [104]. A unique aspect of this research lies in its application of Structural Equation Modeling (SEM) to analyze causal relationships among key constructs—an approach rarely employed in previous studies focusing on hydraulic structures. The integration of SEM not only strengthens the analytical depth but also adds a novel methodological contribution to the field, as indicated by recent advanced modeling applications in construction materials research [102, 103].

5. Discussion

This research focuses on analysing the impacts of various elements—including design and structural performance, durability, environmental impact, material characteristics, and waste composites on the overall impact of hydraulic structures. Using PLS-SEM analysis on data collected from 260 professionals, all proposed hypotheses were supported, confirming the theoretical framework's robustness. The constructs demonstrated strong internal reliability and predictive validity, reinforcing their relevance in the context of sustainable infrastructure. The empirical evidence provided by this research adds to in depth knowledge of how waste-based construction materials can improve the long-term effectiveness of hydraulic structures.

The hypothesis that DSP significantly influences hydraulic structures was supported ($\beta = 0.197$, $p < 0.001$). This results corelates with prior studies indicating that superior structural design enhances load distribution, integrity, and operational lifespan in water-based infrastructures. Studies by Lee et al. (2002) [106] and Ţăranu et al. (2013) [44] similarly emphasized that well-engineered composite designs directly affect system resilience, especially in environments subjected to hydraulic pressure variations.

Durability also showed a positive and visible impact ($\beta = 0.160$, $p = 0.005$), confirming that long-lasting materials contribute to structural reliability and reduced maintenance. These findings are concurrent with results by Chou et al. (2012) [48] and Hagen et al. (2009) [47], who highlighted that materials resistant to chemical degradation and freeze-thaw cycles have a crucial part in the life-cycle performance of hydraulic installations.

Environmental Impact emerged as a strong predictor ($\beta = 0.353$, $p < 0.001$), suggesting that eco-friendly material choices not only benefit the environment but also improve overall project outcomes. This supports prior studies ~~(e.g.,~~ Mehraein et al. (2020) [58]; Pereira et al. (2020) [107]) which indicated that the integration of low-carbon, recyclable materials enhances sustainability performance while maintaining structural efficiency.

Material Characteristics was the influential factor of all ($\beta = 0.568$, $p < 0.001$), demonstrating that the physical and mechanical characteristics of waste composites—like ductility, resistance to water, along bonding ability—are crucial determinants of structural success. This result aligns with Walker & Thies (2022) [72], who emphasized the role of advanced composite behavior in shaping infrastructure outcomes.

The latent impact of Waste Composites was also major ($\beta = 0.196$, $p < 0.001$), validating their practical utility as a sustainable construction material. This finding echoes earlier works by Sulaiman et al. (2023) [69], which showed that recycled waste materials can provide both environmental and engineering advantages when properly integrated into infrastructure projects.

The study offers strong empirical support for the use of waste-based composites in hydraulic construction. Among all factors, Material Characteristics and Environmental Impact had the most pronounced effects, indicating the need for careful material selection and environmental evaluation in the design phase. These insights advance the theoretical and practical understanding of sustainable construction and offers action taking guidance for engineers and policymakers searching to optimize the performance of hydraulic structures using eco-innovative materials.

6. Implications of the Study

This study offers multiple implications across theoretical, practical, managerial, and policy dimensions, contributing meaningfully to both academic literature and real-world practice in the domain of sustainable hydraulic infrastructure.

6.1. Theoretical Implications

The findings provide empirical validation of a comprehensive model that integrates material characteristics, structural performance, durability, environmental impact, and the role of waste composites. By applying Structural Equation Modeling (PLS-SEM), the research adds to the idea and knowledge of how these variables interact to influence the ability of hydraulic structures. This contributes in filling the voids among sustainability-focused material knowledge and infrastructure performance Modeling, offering a replicable framework for future researchers.

6.2. Practical Implications

From an engineering and construction standpoint, the results highlight the practical viability of using waste-based composite materials in hydraulic applications. The significant impact of material characteristics and environmental factors suggests that project stakeholders must give priority when choosing the materials not only according to strength and durability but also environmental performance. These insights can support engineers and project designers in adopting more sustainable construction practices without compromising on quality or structural integrity.

While this study emphasized structural, environmental, and material performance, the importance of economic feasibility in material adoption decisions cannot be overstated. In practical construction settings, the selection of waste-based composites often hinges on their cost-effectiveness, availability, and long-term financial benefits. Although economic variables were not modelled in this study, future research should explore cost-performance trade-offs by integrating constructs such as life cycle cost (LCC), procurement challenges, and return on investment (ROI). This would enable a more financially grounded assessment framework, enhancing the practical utility of waste composite applications in hydraulic infrastructure development.

The authors also recognize the value of real-time performance monitoring to validate and enhance the use of waste composites in hydraulic structures. Future studies are envisioned to incorporate sensor-based systems that measure strain, durability factors, and environmental conditions over time. These sensors can be integrated into the structural elements to capture live data streams, which can then be processed within a digital twin environment. Digital twins—virtual replicas of physical infrastructure would allow for predictive performance modeling, early fault detection, and lifecycle optimization. This technological integration would complement the survey-based insights by offering continuous empirical validation of material behavior under real-world operational stresses.

6.3. Managerial Implications

For construction managers and decision-makers, the study underscores the importance of investing in materials that exhibit strong performance across multiple dimensions. The demonstrated influence of environmental impact and durability on infrastructure outcomes suggests that lifecycle assessments should be embedded into material procurement and planning decisions. Managers should also ensure continuous training and awareness among technical teams regarding the benefits and performance metrics of sustainable materials.

6.4. Policy Implications

At the policy level, the strong empirical evidence supporting the benefits of waste composites provides justification for integrating these materials into public infrastructure guidelines and building codes. Policymakers may consider creating incentive programs or regulations that promote the adoption of eco-efficient construction materials, especially in water infrastructure projects. Additionally, standards for the evaluation of material characteristics—such as recyclability, environmental safety, and mechanical resilience—should be updated to align with emerging sustainable technologies.

In summary, the study supports a multidimensional shift in how materials are selected, assessed, and implemented in hydraulic infrastructure encouraging a transition from conventional practices to sustainability-driven decision-making grounded in data and proven performance.

7. Conclusion

This study provides a holistic analysis of the critical factors influencing the impact of hydraulic structures when constructed using waste-based composite materials. Drawing insights from 260 professionals across construction, material science, and sustainability domains, and applying Partial Least Squares Structural Equation Modeling (PLS-SEM), the research confirms the strong influence of five key constructs: design performance, durability, environmental impact, material characteristics, and composite waste utilization. Notably, material characteristics and environmental considerations emerged as the most dominant predictors, reinforcing the necessity for engineers and decision-makers to prioritize both structural integrity and sustainability in infrastructure planning. These findings reflect a growing trend toward integrated material evaluation that supports both functional performance and environmental responsibility.

The validated model contributes valuable empirical evidence supporting the adoption of waste composites in sustainable construction. By uncovering statistically significant interrelations among core sustainability indicators, the study offers actionable insights for industry stakeholders. In doing so, it highlights the transformative potential of recycled materials such as fly ash, rubber, and plastics to enhance the performance and lifecycle quality of water infrastructure systems. Ultimately, the research calls for a paradigm shift in materials selection from narrow, traditional metrics to a comprehensive framework that includes structural, environmental, and long-term viability assessments. These insights pave the way for innovation in green construction technologies and set a foundation for future research focused on real-time performance monitoring and cost-effectiveness of sustainable composites in hydraulic applications.

7.1. Limitations and Future Directions

Despite the robustness of the methodology and statistical analysis, this study is subject to many shortcomings Initially, the research was geographically limited to key cities within china, that doesn’t completely illustrate the divergent nature of construction practices, environmental regulations, or material availability in other regions or countries. As such, the findings should be interpreted with caution when applied to broader or global contexts. Secondary, the research is based on self-reported sets of data, gathered through structured questionnaires, that may lead to social wishes bias or perceptual inaccuracies, especially when respondents estimate the long-term impact or environmental performance of materials. Third, the constructs were assessed cross-sectionally, limiting the ability to observe changes or causal effects over time. Fourth, while the model included five critical constructs, other potentially influential factors such as cost-efficiency, regulatory barriers, or organizational readiness were not addressed. Lastly, the study focused solely on hydraulic structures; hence, generalization to other types of infrastructure (e.g., roads, bridges, or buildings) should be made cautiously.

Building on the insights from this study, future research can be expanded in several meaningful directions. First, comparative studies across different countries or regions especially those with contrasting climates, construction standards, or regulatory environments can increase the outer validation of model. Second, incorporating a longitudinal research design would allow for the assessment of changes in material performance and stakeholder perceptions over the life cycle of hydraulic structures, providing a deeper understanding of long-term sustainability. Third, future studies could integrate actual field performance data, such as sensor-based monitoring or degradation testing, to complement perception-based responses and reduce potential bias. Fourth, researchers may expand the current model by including additional constructs such as economic feasibility, government incentives, stakeholder resistance, or digital technologies (e.g., BIM or IoT integration) to offer a more holistic framework. Lastly, the methodology can be extended to other types of infrastructure projects, such as flood control systems, wastewater treatment plants, or green stormwater management, to evaluate the broader applicability and benefits of waste composites in sustainable construction.

Furthermore, while the study sample encompassed professionals involved in a wide range of hydraulic infrastructure projects such as dams, irrigation channels, and flood management systems, sectoral distinctions (e.g., hydropower vs. irrigation) and regional differences were not explicitly coded or analyzed in the structural model. As such, potential variations in perception or applicability of waste composites across infrastructure types were not statistically tested. Future research should consider incorporating sectoral and geographic variables into the research design to enable multigroup analysis or moderation testing, which could reveal critical differences in material performance expectations and adoption barriers across various hydraulic domains.

8. Declarations

8.1. Author Contributions

Conceptualization, M.U.G. and Z.Y.; methodology, M.U.G.; software, M.U.G.; validation, M.U.G., Z.Y., and K.A.; formal analysis, M.U.G.; investigation, M.U.G.; resources, Z.Y.; data curation, M.U.G.; writing—original draft preparation, M.U.G.; writing—review and editing, B.N.K.R. and Z.Y.; visualization, M.U.G.; supervision, Z.Y.; project administration, Z.Y.; funding acquisition, K.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

8.4. Conflicts of Interest

The authors declare no conflict of interest.

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