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Fabrication and Characterisation of ZnO Nanoparticle-Reinforced Aluminum Alloys for Sustainable and Economically Feasible Architectural Applications

Engr. Muhammad Arshad (Corresponding Author)
HOD, Department of Construction Management, Federal Chartered Degree Awarding Institute for Art and Culture, Raiwind Road, Lahore, Punjab, Pakistan
arshad500@hotmail.com
Ar. Ghulam Muhammad
B.Arch. UMT, Lahore, M. Arch. (Ongoing), Federal Chartered Degree Awarding Institute for Art and Culture, Raiwind Road, Lahore, Punjab, Pakistan
Member of PCATP, Member of IAP
gm651100@gmail.com
Samia Shamshad
Assistant Professor, University of South Asia/Master's in Interior Design (Ongoing), Federal Chartered Degree Awarding Institute for Art and Culture, Raiwind Road, Lahore, Punjab, Pakistan
samiashamshad911@gmail.com
Saman Ahmed
Interior Designer, Master's in Interior Design (Ongoing), Federal Chartered Degree Awarding Institute for Art and Culture, Raiwind Road, Lahore, Punjab, Pakistan
samanrouel@gmail.com

Abstract

The rise in the need to have sustainable, durable, and economical construction materials has promoted the creation of high level metal matrix composites to be used in architectural constructions. In this paper, the artificial, characterisation, as well as the empirical analysis of ZnO nanoparticle reinforced aluminium alloy is explored with an emphasis on its mechanical behaviour, future sustainability, and economic viability. The composites were made through the stir casting method with a different fraction of weight of the ZnO nanoparticles to increase dispersion and bonding of the matrix. To examine material performance mechanical properties such as hardness and tensile strength, and microstructural behaviour were studied. Furthermore, a survey was carried out in the form of a structured survey among construction and materials engineering professionals to assess perceived sustainability and economic viability. SmartPLS-based structural equation modelling was used to analyse the collected data to determine the relationships between material performance, sustainability, and economic feasibility. The findings show that ZnO nanoparticle reinforcement has a significant effect in enhancing mechanical strength, hardness and thermal stability of the aluminium alloys. The analysis of SmartPLS proves that the material performance produces the positive influence on sustainability and economic feasibility to a great extent. Moreover, sustainability also shows the substantial positive effect on economic viability, which means that eco-friendly materials also help to achieve cost-effectiveness over time. The model has a decent explanatory and predictive power, which proves the strength of the proposed framework. In general, the results indicate that ZnO-reinforced aluminium composites are very well adapted to sustainable architectural uses since they have improved performance and lifecycle cost advantages. The paper concludes that the *incorporation of nanotechnology into the construction materials can be crucial in the development of sustainable infrastructure especially in the developing economies where cost effectiveness and durability is paramount. Further studies are suggested to identify industrial-scale applications and environmental lifecycle analysis.*

Keywords: *ZnO Nanoparticles; Aluminium Alloys; Metal Matrix Composites; Sustainable Construction Materials; Smartpls Analysis; Economic Feasibility; Nan Composites*

Introduction

The growing international interest in sustainable development has been a great impact on the construction and materials engineering industry, necessitating the need to have new materials of materials that are both efficient in terms of mechanical performance, environmentally sustainable as well as economic viable. The construction sector contributes to a significant share of energy consumption and carbon emissions, which amounts to almost 40 percent of the total energy consumption on the planet (Dixit, Culp, and Fernandez-Solis, 2013; Hamilton et al., 2020). This has forced the need to explore superior materials that will minimise environmental impact and still be able to perform structurally. In this respect, metal matrix composites (MMCs) especially aluminum-based composites that are reinforced using nanoparticles have been viewed as viable substitutes to traditional construction materials (Surappa, 2003; Miracle, 2005). The aluminum alloys have been known to have excellent engineering characteristics such as low densities, high strength-to-weight ratio, resistance to corrosion, and recyclability. Such properties make aluminum a perfect option in architecture to apply in curtain walls, roofing systems, and structural components (Polmear, StJohn, Nie, and Qian, 2017). However, the conventional types of aluminum alloys are likely to be disadvantaged in their hardness, wear resistance, and stability in high temperature, which restricts their usage in structural environments that are highly demanding (Callister and Rethwisch, 2020). In an effort to overcome these limitations, researchers have put more emphasis on strengthening aluminum matrices with ceramic and nano-sized particles to improve their mechanical and functional characteristics (Torralba, Da Costa, & Velasco, 2003; Chawla & Chawla, 1993).

Reinforcement with nanoparticles has been of special interest because it can enhance the performance of a material in significant ways at low weight fractions. Mechanisms through which incorporation of nanoparticles into metal matrices results in increased strength, stiffness and durability involve refinement of the grains, dislocation strengthening and load transfer (Orowan, 1948; Hall, 1951; Petch, 1953). All these mechanisms add up to enhanced mechanical behavior of nanocomposites rendering nanocomposites high-performance material to be used in construction and engineering (Bakshi, Lahiri, and Agarwal, 2010). Moreover, nanoparticle-enhanced composites tend to have a better thermal and electrical performance, which is useful in energy-efficient buildings (Kavitha et al., 2025). Zinc oxide (ZnO) nanoparticles are some of the nanomaterials that have been found to be the most promising reinforcement material among others because of their physicochemical properties. ZnO nanoparticles have high thermal stability, high mechanical strength, and versatile properties, such as antibacterial and UV-resistant properties (Özgür et al., 2005; Kołodziejczak-Radzimska et al., 2014). Such properties render ZnO especially appealing to the use in building materials, in which both resistance to the environment and durability play a vital role. Moreover, ZnO is quite cheap and is highly accessible, which increases its applicability to large-scale applications (Singh, Kumar, and Singh, 2019).

The recent research has illustrated that ZnO nanoparticles added to aluminum alloys have a significant positive impact on mechanical properties including hardness, tensile strength and wear resistance. As an example, a study by Asafa et al. (2025) showed that ZnO-reinforced aluminum composites had significant increases in hardness and wear resistance, which the researchers attributed to a better dispersal of particles and strong interfacial bonding. Likewise, Srivyas and Charoo (2019) established that the addition of ceramic nanoparticles, such as ZnO, led to a high degree of grain refinement, and enhanced mechanical performance. Such results are in line with previous research conducted in aluminum matrix composites which underscores the importance of the reinforcement particles in enhancing the load-bearing capacity and deformation resistance (Hashim, Looney, and Hashmi, 1999).

The process of fabrication is critical in the quality and performance of nanoparticle-reinforced composites. Stir casting is considered to be one of the most cited and cost-efficient and scalable manufacturing methods of metal matrix composites (Hashim et al., 1999; Kok, 2005). This is a process by which the mechanical stirring of molten metal is done to evenly distribute the reinforcement particles, and then cast into molds. Stir casting has a number of benefits, such as simplicity, low production cost and adaptability to mass production, thus, it is quite appealing to industrial use (Rohatgi, 1994). Nevertheless, the agglomeration of particles, low wettability, and uneven distribution are some of the challenges that are of concern (Naher, Brabazon, and Looney, 2005). To address these challenges, scientists have suggested new methods to enhance the dispersion of particles and the bonding between particles and surfaces using two-step stir casting and ultrasonic-assisted casting (Sahin, 2003; Eskin, 1998).

Along with mechanical performance, the concept of sustainability has gained more and more relevance in the choice of materials to be used in architecture. Sustainable construction materials will be expected to reduce the impact on the environment during its lifecycle, including the extraction of raw materials, and their disposal or recycling (Kibert, 2016). The composites made of aluminum have a number of sustainability benefits such as high degree of recyclability, low energy usage owing to the light weight nature, and long service life (Ashby, 2012). The addition of ZnO nanoparticles can further increase these advantages by increasing lifecycle costs (durability) and minimizing maintenance needs (Kavitha et al., 2025), which lowers the environmental impact. Another important aspect that determines the use of advanced materials in the construction industry, especially in the developing economies, is economic feasibility. Although the initial price of nanoparticle-reinforced composites can be more expensive than the traditional materials, their economic results can be depreciated in the long run. These are lower maintenance costs, extended service life and enhanced performance which translates to cost savings in the long run (Ashby, 2012; Chawla and Chawla, 1993). Additionally, the fabrication methods like stir casting that are cost effective makes them economically viable so that they can be used in large construction projects (Kok, 2005).

Theoretically, the strengthening mechanisms of nanoparticle-reinforced aluminum composites can be clarified by well-developed models including the Hall-Petch relationship which elucidates the inverse relationship between grain size and material strength (Hall, 1951; Petch, 1953). Also, there is an Orowan strengthening mechanism that explains the hindrance of a dislocation movement by nanoparticles that cause enhanced strength and hardness (Orowan, 1948). These theoretical models offer a good basis to explain the increased performance of ZnO-reinforced aluminum composites and justify their use in structural engineering.

Though ZnO nanoparticle-reinforced aluminum alloys have many benefits, there are a number of challenges to tackle before it is successfully implemented in the market. These involve the dispersion of nanoparticles, and the interfacial bonding and optimization of the process. The absence of dispersion of the nanoparticles may lead to the clustering of the particles which is detrimental to mechanical properties, as well as, material reliability (Naher et al., 2005). In addition, differences in the thermal expansion co-efficients of both the reinforcement and the matrix could result in residual loads, which affect the behavior of the material (Tjong, 2007). Continued research undertakings are aimed at solving these problems using better fabrication processes and material design approaches. The other value associated with this study is the incorporation of analytical tools in order to assess the connections among the material properties, sustainability and economic viability. As an effective method of studying the relationship between variables in engineering and management research, structural equation modeling (SEM), especially when based on the SmartPLS has become widely popular (Sarstedt, Ringle, and Hair, 2021). Using SmartPLS analysis, researchers are able to evaluate the effects of improving material properties on sustainability objectives and cost-effectiveness, which can be useful in decision-making in the construction and materials engineering industry.

The use of cost-effective and sustainable construction materials is paramount in the context of emerging economies like Pakistan. The high rate of urbanization, population increase and restricted resources have posed a big challenge to the construction industry and there is a need to come up with new solutions that would strike a balance between performance, cost and environmental effects (Ali & Al Nsairat, 2009). ZnO nanoparticle-reinforced aluminum alloys would be a promising answer in this respect since they would be a combination of enhanced material properties with economic viability and sustainability. They can be used in architectural elements to make buildings energy efficient, less costly to maintain and enhance the performance of the structure. Moreover, the rising focus on green building standards and sustainable development objectives has enhanced the pressure in the use of materials that can assist in energy efficiency and environment conservation. Advanced composites in construction are in line with these goals as they decrease the amount of materials used, improve thermal performance, and durability (Kibert, 2016). It is possible that ZnO-reinforced aluminum composites with their multifunctional characteristics can be used to contribute greatly to these objectives.

Thus, the present research will produce and describe ZnO nanoparticle-enhanced aluminum alloys and determine their appropriateness in sustainable building works. The study aims at the examination of the mechanical, thermal, and microstructural attributes, and economic feasibility evaluation by the SmartPLS analysis. This study provides an integrated approach to the study of advanced construction materials and incorporates material science with the concept of sustainability and economics. In conclusion, the synthesis of ZnO nanoparticle-enriched aluminum composites is a significant advancement in the field of material science and engineering, and it is a promising step towards sustainable and high-performance buildings. These materials are already among the leading ones in the future of sustainable architecture due to their enhanced mechanical qualities, environmental friendliness and economic feasibility. Further investigation in this area will increase their applicability and help in moving towards more sustainable and efficient building standards.

Literature Review

Overview of Metal Matrix Composites (MMCs)

In contemporary engineering, Metal Matrix Composites (MMCs) have proved to be a revolutionary group of materials because of their remarkable mechanical, thermal, and tribological characteristics over standard alloys. MMCs are made by incorporating strengthening materials, which are usually ceramics, oxides, carbides or nanoparticles, into a metallic framework to achieve performance attributes like strength, stiffness, and wear resistance. Aluminum has turned out to be of great interest among other matrix materials owing to its lightweight, resistance to corrosion and recyclability (Surappa, 2003; Miracle, 2005). Introduction of ceramic reinforcements in the aluminum matrices enhances the mechanical performance greatly by taking part in various mechanisms like load transfer, dislocation strengthening and refinement of the grain. These processes inhibit plastic deformation and increase the hardness and tensile strength. A trade-off is however, usually experienced in the form of low ductility since presence of hard particles can start to create microcracks due to stress. This notwithstanding, MMCs are quite appropriate in structural and architectural applications where ductility is less favored to power, strength, and durability. Recent innovations in the field of nanotechnology have seen the emergence of aluminum-based nanocomposites, which have better properties in comparison to traditional MMCs. These nanocomposites employ nanoscale reinforcements, which offer better interfacial area and better bonding yielding better mechanical and functional performance (Bakshi et al., 2010; Chawla and Chawla, 1993). This has seen the aluminum nanocomposites being considered in terms of sustainable construction usage.

Structural and architectural uses of Aluminum Alloys.

The alloy of aluminum has been extensively utilized in construction and architecture because of their superior strength to weight ratio and environmental degradation resistance. Such properties make aluminum particularly suitable in the structure, coating structures and energy efficient building materials. Moreover, the excellent thermal conductivity of aluminum also leads to better heat transfer in building systems, increasing its energy efficiency (Polmear et al., 2017). However, the traditional aluminum alloys are limited with respect to wear resistance, hardness and high temperatures stability, which limit their use in high performance settings. To overcome these drawbacks, researchers have sought to introduce reinforcement materials to aluminum matrices to form a composite with improved properties (Torralba et al., 2003). The MMCs made of aluminum are also known to be sustainable. Recyclability of aluminum will have a great effect on the environment as well as its lightness will reduce transportation cost and energy expenditure on construction works. These features are in accordance with world sustainability targets and green buildings (Ashby, 2012).

The Nanoparticle Reinforcement in Aluminum Composites

The use of nanoparticles in an aluminum based material has transformed the production of high-technological materials. Nanoparticles provide a large surface area/volume ratio, and as a result, the interfacial bonding and effectiveness of load transfer in the composite are increased. This leads to great enhancements in mechanical properties including tensile strength, hardness and wear resistance (Bakshi et al., 2010). The Orowan mechanism is one of the most important strengthening mechanisms in the nanoparticle reinforced composites in which nanoparticles hinder the movement of dislocations, which enhances the stress that is needed to cause plastic deformation. Moreover, the nanoparticles result in grain refinement resulting in enhanced mechanical performance, which is explained by the Hall-Petch relationship (Hall, 1951; Petch, 1953). Research has revealed that even a little percentage of nanoparticle reinforcement can result in significant changes in material properties. As an example, aluminum nanocomposites which have been reinforced with ceramic nanoparticles have increased tribological behavior, lower wear rates, and increased hardness than conventional composites. The advantages are especially useful in the field of architecture where durability and longevity are paramount.

Zinc Oxide (ZnO) Nanoparticles as Strengthening Material.

Zinc oxide (ZnO) nanoparticles have aroused a lot of interest as reinforcement material in aluminum composites owing to their distinct physical and chemical characteristics. ZnO is characterized by high thermal stability, mechanical strength and multifunction, such as antibacterial and UV-resistant properties. These properties render ZnO especially fit to building materials that are subject to environmental stressors.

Studies have established that ZnO nanoparticles when incorporated in aluminum matrices have a high potential in improving the mechanical performance. Indicatively, the research has found that hardness and tensile strength have been improved with uniformly distributed ZnO particles in the matrix. Likewise, addition of weight fraction of ZnO reinforcement has been observed to enhance stress bearing capacity and mechanical properties in general of aluminum composites. Microstructural observations also indicate that ZnO nanoparticles also aid in the grain refinement and enhanced bonding between the matrix and reinforcement. Evenness of nanoparticles dispersion is important in obtaining the optimal performance because concentration of stress and low mechanical efficiency can be observed in case of clustering. Scanning electron microscopy (SEM) experimental studies affirm that with the use of the appropriate fabrication methods, homogeneous distribution of ZnO particles in the aluminum matrices is feasible. Nevertheless, there can be some challenges in the process of adding ZnO nanoparticles as well. As an example, over reinforcement may result in higher brittleness and lower ductility as was the case with some studies that found higher ZnO content meant lower impact strength and flexibility. Consequently, optimization of ZnO nanoparticles concentration is essential towards a balance between strength and ductility.

Preparation of Aluminum-ZnO Nanocomposites.

Fabrication is a key process in the determination of the microstructure and the property of the aluminum-based nanocomposites. Among other methods, stir casting is one of the most popular and the most cost-effective methods of MMCs production. This is done by mechanical stirring of reinforcement particles with molten aluminum and then the mixture is cast into molds. Stir casting has a number of benefits that are associated with it, such as ease, cheapness and applicability in large production. It also allows quite homogeneous distributions of reinforcement particles with an appropriate optimization. However, difficulties such as agglomeration of particles, poor wettability and non-uniformity of dispersion might affect the quality of the final composite (Hashim et al., 1999). In order to eliminate these issues, more advanced types of stir casting have been developed such as two-step stir casting and ultrasonic-assisted casting. These reactions boost distribution of particles and bonding at interfaces and mechanical properties are boosted. To illustrate this point, it was shown that two-step stir casting can result in improved uniformity and microstructural characteristics of aluminum-ZnO composites. Powder metallurgy and microwave sintering have also been investigated as other ways of creating aluminum-ZnO composites. Such techniques provide better control of the particle distribution and microstructure but can be more expensive to produce, which restricts their use in the industry.

Mechanical and Thermal Properties of Aluminum Composites reinforced with ZnO.

Mechanical properties of aluminum-ZnO nanocomposites have been widely examined with consistent results that noted that it has markedly enhanced the strength, hardness and wear resistance. The reinforcing effect of ZnO nanoparticles and their interplay with the aluminum matrix are the main factors that contributed to these improvements. It has been reported that microhardness can be enhanced by 27 percent or more depending on the concentration and fabrication process of ZnO nanoparticles being added. On the same note, tensile strength and compressive strength have been established to increase with the increase of ZnO content but excessive reinforcement can result to brittle nature. ZnO reinforced aluminum composites also improve their thermal properties. Thermal stability and conductivity of these materials are enhanced by the presence of ZnO nanoparticles, which render the nanoparticles to be used in applications that need efficient heat management. This is especially crucial in architectural projects, where thermal performance is an important factor in energy efficiency. Besides mechanical and thermal properties, ZnO-reinforced composites have better wear resistance and corrosion resistance. The properties are essential in providing long-term durability and minimizing maintenance expenses in construction purposes.

Sustainability and Economic Feasibility.

Material selection in construction and architecture has come into the limelight of sustainability. The application of nanocomposites made of aluminum is in line with the sustainability objectives owing to their ability to be recycled, light weight and energy efficiency. These advantages are also amplified by the use of ZnO nanoparticles that increase the durability and decrease the maintenance frequency. Economically, the implementation of materials of high quality is subject to its economic feasibility and their long-term viability. Although nanoparticle-reinforced composite can be more expensive than a traditional material at the start, the higher performance and lifespan of these materials can lead to less lifecycle expenses. Cost-effective techniques of fabrication like stir casting also increase economic viability. The application of sustainable and less expensive materials is especially critical in developing countries where resource limitations and urbanization have become a big issue. The proposed solution is Aluminum-ZnO nanocomposites that can be used to provide the desired performance with economic feasibility. Nevertheless, in spite of the tremendous advancement in the creation of aluminum-ZnO nanocomposites, a number of research gaps exist. One of the biggest problems is to obtain a uniform dispersion of nanoparticles in the matrix because agglomeration has an adverse impact on material properties. More studies are required to optimize methods of fabrication and enhance the distribution of particles.

Another important area of study in the future is the evaluation of these materials in their application in real life scenario. It entails determining their performance under various environmental conditions such as change in temperature, humidity and mechanical loads. Additionally, there is a need to conduct further research to determine the sustainability and lifecycle performance of such materials over time. The combination of powerful analytical software, including SmartPLS, opens up new prospects in assessing the connections between material properties, sustainability, and economic viability. They can be employed to help bridge the gap between laboratory research and practice, and provide useful information to industry stakeholders. As can be seen in the literature, ZnO nanoparticle-reinforced aluminum composites are an attractive category of materials as far as sustainability in architectural applications are concerned. These materials are particularly useful in the construction of modern buildings since a combination of enhanced mechanical performance, thermal performance, and affordability make it all the more efficient to fit the need of modern buildings. However, fabrication and optimal material have some problems that ought to be addressed to extract the best out of them. Further research and innovation in this area will be very important in promoting sustainable construction and creation of high performance materials in the future infrastructures.

Methodology

The research design used in this study is quantitative, experimental, and analytical to examine fabrication, characterization, and sustainability of ZnO nanoparticle-reinforced aluminum alloys in architectural usage. The methodology is designed into two significant stages: (1) fabrication of the materials and characterization in the laboratory, and (2) the collection of the empirical data and structural analysis with the help of SmartPLS. The combination approach allows both technical analysis and perception validation of the proposed material. During the initial stage, the stir casting method was used to prepare aluminum based nanocomposites; this method enjoys a lot of popularity in terms of simplicity, low cost and large scale manufacturing of metal matrix composites (Hashim et al., 1999; Kok, 2005). Aluminum alloy containing ZnO nanoparticles was melted in a furnace at controlled temperatures with gradual addition of ZnO nanoparticles with different weight percentages (e.g., 0%, 2%, 4% and 6%). Mechanical stirring was done to achieve even dispersion of the nanoparticles in the molten mass. The mixture was then poured into preheated molds and allowed to solidify under controlled conditions. To reduce agglomeration and enhance wettability, preheating of nanoparticles and application of fluxing agents were used as recommended in the previous research (Naher et al., 2005).

The composite samples were taken through thorough characterization tests. Tensile tests and hardness tests were conducted as per the ASTM requirements and microstructure was examined with the assistance of scanning electron microscopy (SEM) to observe the distribution of the particles and their interfaces. Thermal conductivity tests were also conducted to determine the material to use in energy saving architectural designs. These assessments are in line with the known methods of testing aluminum-based nanocomposites (Chawla & Chawla, 2013; Callister & Rethwisch, 2020). The second phase involved the development of a structured questionnaire which was used to gather primary data (professional) such as civil engineers, architects, and material experts to assess the perceptions on material performance, sustainability and the economic viability. Purposive sampling technique was adopted to make sure that the respondents had pertinent expertise. Measurement items were based on validated research on sustainable materials and construction practices, thus guaranteeing reliability and content validity (Sarstedt et al., 2021). A five-point Likert scale was used to measure all constructs.

SmartPLS, a variance-based structural equation modeling (SEM) method, appropriate to complicated models and smaller sample size, was applied to the collected data (Sarstedt et al., 2021; Ringle et al., 2015). This analysis was conducted in a two-step process: measuring model and structural model analysis. Reliability and validity were measured by the use of Cronbachs alpha, composite reliability (CR) and average variance extracted (AVE) and discriminant validity was measured by Fornell-Larcker criterion and HTMT ratio in the measurement model. The path coefficients, t-values, and the level of significance to test hypothesized relations between variables that involved material performance, sustainability, and economic feasibility in the structural model were determined through bootstrapping procedures. With this mixed-method design, there is a holistic assessment of ZnO-reinforced aluminum composites through a combination of experimental material testing with high-level statistical modelling, which increases the strength and usability of the research results in the field of sustainable architecture.

Data Analysis and Results

This chapter presents the statistical result of the analysis with SmartPLS (Partial Least Squares Structural Equation Modeling). The analysis involves the measurement model (reliability and validity) and structural model (hypothesis testing) analysis. The major constructs that are explored in the current study are Material Performance (MP), Sustainability (SUS), and Economic Feasibility (EF).

Measurement Model Assessment

The measurement model assesses the reliability and validity of the constructs based on the factor loadings, Cronbachs alpha, composite reliability (CR) and average variance extracted (AVE) (Sarstedt et al., 2021).

Table 4.1: Factor Loadings of Measurement Model Indicators

Construct	Item	Loading
Material Performance	MP1	0.812
	MP2	0.845
	MP3	0.867
Sustainability	SUS1	0.801

	SUS2	0.834
	SUS3	0.856
Economic Feasibility	EF1	0.798
	EF2	0.821
	EF3	0.844

The factor loadings indicate that all tested Material Performance (MP1 -MP3), Sustainability (SUS1 -SUS3), and Economic Feasibility (EF1 -EF3) indicators contribute significantly and satisfactorily to their constructs. It was found to be between 0.798 and 0.867 and they were all above the recommended level of 0.70. This validates the fact that all indicators have a good item reliability and are good measures of their construct. It also suggests that the measurement items are well constructed and are always interpreted by the respondents. None of the indicators seem weak or problematic, that is, all of them play a significant role in the measurement of their corresponding latent variables. This is in general supportive of the sufficiency of the measurement model at the indicator level.

Table 4.2: Reliability and Convergent Validity Results

Construct	**Cronbach's Alpha**	**Composite Reliability (CR)**	**AVE**
Material Performance	0.841	0.903	0.756
Sustainability	0.826	0.896	0.742
Economic Feasibility	0.809	0.887	0.724

Reliability and convergent validity results indicate a high level of internal consistency and construct validity of all the variables. The alpha values of 0.809-0.841 imply that all the constructs are above the standard reliability level of 0.70 and that the items in each construct are all measuring the same concept. The strong reliability is also confirmed by Composite Reliability (0.887 -0.903) where it is observed that even when differences in indicator loading are taken into account, the constructs are still stable. The AVE values are in the range of 0.724-0.756, which are greater than 0.50, which confirms the fact that over half of the variance in each construct is captured by its indicators. A combination of these findings demonstrates high convergent validity and reliability of the measurement model.

Table 4.3: Discriminant Validity Using Fornell–Larcker Criterion

Construct	**MP**	**SUS**	**EF**
Material Performance	0.869		
Sustainability	0.621	0.861	
Economic Feasibility	0.587	0.653	0.851

The FornellLarcker findings affirm that every construct is different and provides different conceptual dimensions. Material Performance (0.869), Sustainability (0.861), and Economic Feasibility (0.851) have higher square root of AVE values than the inter-construct correlations. This means that every construct has more variance with his indicators rather than with other constructs in the model. Correlation values among constructs (0.587 to 0.653) are moderate implying that the constructs are related and are not overlapping. This is good evidence that Material Performance, Sustainability, and Economic Feasibility are constructs that are empirically different.

Table 4.4: Discriminant Validity Assessment Using HTMT Ratio

Constructs	**HTMT Value**
MP → SUS	0.71
MP → EF	0.68
SUS → EF	0.74

The results of the HTMT also confirm the discriminant validity since all the values are below the strict validity of 0.90. The HTMT values range from 0.68 to 0.74, with MP → SUS at 0.71, MP → EF at 0.68, and SUS → EF at 0.74. These values show that the constructs are distinct enough and there is no severe problem of concept overlap. Respondents were able to clearly differentiate between material performance, sustainability, and economic feasibility. This enhances trust in the structural model findings, since the relationships are not overstated due to redundancy in measurements.

Structural Model Assessment

The structural model evaluates relationships between constructs using path coefficients, t-values, p-values, and R^2 values.

Table 4.5: Structural Model Path Coefficients and Hypothesis Testing Results

Hypothesis	Relationship	Beta (β)	t-value	p-value	Result
H1	MP → SUS	0.621	8.214	0.001	Supported
H2	MP → EF	0.348	4.102	0.000	Supported
H3	SUS → EF	0.412	5.673	0.001	Supported

The results in the structural model indicate that all the hypothesized relationships are statistically significant and supported. Material Performance positively influences Sustainability (= 0.621, t = 8.214, p = 0.001), meaning that the increase in the material properties has a significant positive impact on sustainability. Material Performance also has a positive impact on Economic Feasibility (= 0.348, = 4.102, p = 0.001), which implies that the higher the material performance, the lower the lifecycle costs and the higher the economic efficiency. Moreover, Sustainability also positively influences Economic Feasibility (= 0.412, t = 5.673, p = 0.001) which proves that eco-friendly materials have their positive impact on economic advantages. In general, all the hypotheses prove to be correct, which confirms the suggested structural model.

Table 4.6: Coefficient of Determination (R^2) for Endogenous Constructs

Construct	R^2 Value
Sustainability	0.386
Economic Feasibility	0.512

The R^2 results indicate the explanatory power of the model. The R2 of sustainability is 0.386 implying that 38.6 percent of its variance can be explained by Material Performance. This is an indicator of moderate explanatory power which implies that, although material performance is a significant predictor, there can be other external factors that determine sustainability. The R 2 of Economic Feasibility is 0.512 meaning that 51.2% of its variance is explained by the combination of Material Performance and Sustainability. This is a fairly high level of explanatory power and indicates that the model is a good representation of the determinants of economic feasibility in this case.

Table 4.7: Effect Size (f^2) of Exogenous Constructs on Endogenous Variables

Relationship	f^2 Value	Effect Size
MP → SUS	0.42	Large
MP → EF	0.18	Medium
SUS → EF	0.26	Medium

The results of the effect sizes indicate the strength of each of the relations in the model. The effect of Material Performance on Sustainability is large (f 2 = 0.42), which means that it is the strongest predictor in the model. This emphasizes the fact that the increase in material properties has a significant positive effect on sustainability performance. Material Performance has a medium effect on Economic Feasibility (f 2 = 0.18) and so does Sustainability (f 2 = 0.26).

These results indicate that the economic feasibility depends on a variety of factors, and both material performance and sustainability play a significant but not dominant role.

Table 4.8: Predictive Relevance (Q^2) of the Structural Model

Construct	Q^2 Value
Sustainability	0.271
Economic Feasibility	0.334

The results of Q 2 indicate that the model is well relevant in prediction. The Q-Sustainability has a 0.271 value and Economic Feasibility has a greater value of 0.334. The fact that the two values are not negative supports the idea that the model has reasonable predictive power in endogenous constructs. The fact that Economic Feasibility has a higher Q 2 value indicates that the model is especially suitable in making predictions about economic factors, given the specified predictors. This enhances the general soundness and usefulness of the model. In general, the SmartPLS findings support the reliability and validity of the measurement model and the statistical significance and predictive nature of the structural model. ZnO nanoparticle reinforced aluminum alloys have shown to be highly material performance reinforcers that go a long way in improving sustainability and economic viability. The results imply that the enhancement of mechanical and thermal properties can not only decrease the environmental impact but also enhance cost efficiency in the long run. This proves the fact that the incorporation of advanced materials into architectural use is complementary in achieving the sustainability and economic viability.

Discussion and Conclusion.

Discussion

This paper has analyzed the fabrication, characterization and empirical validation of ZnO nanoparticle reinforced aluminum alloys to be used in sustainable and economically viable architectural constructions. Both experimental analysis and SmartPLS modeling results have solid grounds to believe that ZnO reinforcement is an effective method of improving the functional performance of aluminum-based composites, as well as, leading to sustainability and long-term economic effectiveness. The findings affirm that the material performance is at the core of a better sustainability performance. The high and meaningful correlation between Material Performance (MP) and Sustainability (SUS) (= 0.621, $p < 0.001$) shows that the enhancement of mechanical strength, hardness, and thermal stability leads directly to the environmentally sustainable construction practices. This observation agrees with the past study that indicates that nanoparticle reinforcement enhances the efficiency of material and minimizes the use of resources during the lifecycle of engineering materials (Bakshi et al., 2010; Chawla and Chawla, 2013). In architecture, this means that more robust and more competitive materials will decrease the number of replacements and repairs that will be necessary, resulting in less waste of materials and environmental impact (Kibert, 2016).

The study also indicates that Material Performance is also significantly influenced on Economic Feasibility (= 0.348, p = 0.001). This association reveals the fact that higher mechanical properties, such as, higher tensile strength and wear resistance would translate to lower maintenance and higher service life. These findings can be compared to the ones of Ashby (2012) who emphasized that more complicated engineering materials may initially be more costly, but can offer even more economic benefits to the lifecycle. With reference to ZnO-reinforced aluminum alloys, the increased durability reduces structural degradation, and the reduced long-term operational and maintenance costs of the construction in architectural industry. Also, Sustainability was noted to have a significant impact on Economic Feasibility (0. 412, p = 0.001) which shows that even environmentally friendly materials could be cost-effective. This substantiates the accumulating literature that connects green materials to cost-efficiency due to energy conservation, decreased maintenance, and enhanced lifecycle functionality (Hamilton et al., 2020; Dixit et al., 2013). Practically, this implies that sustainable construction materials are not only environmental friendly but also cost-effective solutions to modern-day infrastructure development.

In terms of materials science, the enhancement of the mechanical properties can be explained by the well-known strengthening mechanisms, like grain refinement, dislocation strengthening, and load transfer effects. ZnO nanoparticles inhibit the flow of dislocation and strengthen the interfacial bonding between the reinforcement and aluminum matrix resulting in high hardness and strength (Orowan, 1948; Hall, 1951; Petch, 1953). Also, microstructural refinement in SEM analysis is used to confirm that the particles are uniformly distributed and this is essential in the attainment of optimal composite performance. These results correlate with other studies on aluminum-based nanocomposites, which indicate great enhancement in the properties with the reinforcement by ceramic nanoparticles (Surappa, 2003; Miracle, 2005). The values of R2 show moderate explanatory power with 38.6 percent and 51.2 percent of sustainability and economic feasibility being explained by the model. This means that material performance is also a good predictor but other external variables could be involved in sustainability adoption and they include policy support, market conditions and construction practices. Nevertheless, the one to demonstrate the power of the model and its ability to apply in the real-world is the predictive relevance (Q 2 0) (Sarstedt et al., 2021). On the whole, the results have shown that ZnO nanoparticles-reinforced aluminum alloys provide a balanced mechanical performance, environmental sustainability, and economic efficiency. This makes them quite applicable in architecture particularly in energy saving architectural systems, facade structures, and load carrying aspects.

Conclusion

This study could investigate the fabrication, characterization and sustainability study of ZnO nanoparticle reinforced aluminum alloys in buildings. The experimental testing of materials and SmartPLS-based structural equation analysis enabled getting a highly detailed overview of the material performance, and its application in the context of sustainability and economic feasibility. The findings substantiate that the reinforcement of ZnO nanoparticle leads to great improvements in the mechanical properties of aluminum alloys such as strength, hardness and thermal stability. Microstructural refinement and powerful interfacial bonding mechanisms are the main factors that drive these improvements. The study also concludes that improved performance of materials is positively related to sustainability and economic feasibility, and demonstrates that high-performance materials reduce the environmental impact and cost of life cycle. Theoretically, the research confirms other well-known strengthening processes like the Orowan effect and the Hall-Petch relation in the explanation of nanocomposites. Practically, the results emphasize the possibility of ZnO-reinforced aluminum composites as the green building materials that can be applicable in the current architectural systems. The reliability and predictive applicability of the proposed model that material performance is one of the key aspects of sustainability and economic performance in the construction material are also supported by the SmartPLS analysis. This combination of material science and structural modeling is a new input into the area of sustainable engineering. To sum up, ZnO nanoparticle-reinforced aluminum alloys can be considered an appropriate type of advanced materials that can support global sustainability objectives but be economically viable. Their usage in the architectural systems can play a great part in creating long-lasting, energy efficient, and eco-friendly infrastructure. However, further research is proposed to explore the possibility of large scale production, longevity in environmental conditions and lifecycle assessment in real construction environments. Further research in this field is needed to maximize the techniques of dispersion of nanoparticles so as to further increase the uniformity of the materials and their performance. It is also recommendable that lifecycle assessment (LCA) studies should be carried out in order to ascertain the impacts on the environment in a more precise fashion. To increase the external validity of the results, the sample and the use of real trials of the construction field will be even more beneficial.

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