



Development of polyvinyl chloride composites with enhanced mechanical properties using modified ceramic particles

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Abstract

The integration of ceramic particles into polyvinyl chloride (PVC) composites offers a promising approach and has garnered significant attention due to their potential for enhancing mechanical properties. This work investigated the development and characterization of PVC composites enhanced with modified ceramic particles. Ceramic particulates, clays, and other mineral rock materials (non-plastics) with activators were processed and incorporated into the PVC matrix at varying weight percentages (5–30 wt%) and particle sizes (40–80 µm). The ceramic–PVC mixtures were synthesized using hot compression molding under specific conditions of 75 MPa pressure and 160 °C temperature. Mechanical properties' testing was conducted using ASTM D3039 standards, covering flexural, tensile, hardness, and impact tests for comprehensive characterization. Microstructural analysis was performed using scanning electron microscopy (SEM). Results indicated that ceramic reinforcement significantly enhanced the mechanical properties of PVC composites, with notable improvements in flexural strength, tensile strength, hardness, and impact resistance. Moreover, the impact of particle size was crucial, as microstructural analysis revealed improved interfacial bonding between ceramic particles and PVC matrix, particularly with finer particle sizes (40 µm), suggesting better stress transfer. The findings demonstrated that including modified ceramic particles can substantially improve the performance of PVC composites, making them suitable as high-strength construction tiles and impact-resistant flooring.

Keywords Polyvinyl chloride · Ceramics · Composites · Mechanical properties · Microstructure

Introduction

Civil and construction industries are among the world's oldest and most essential sectors, with a history as ancient as civilization itself. Today, these industries play a pivotal role in all market economies, leveraging a wide array of

materials, such as cement, concrete, aggregates, polymers, clay, wood, metals, and bricks. The choice of materials depends on their properties and cost, leading to the blending of two or more materials to achieve enhanced properties for specific applications [1–3]. Polymer matrix composites (PMCs) are increasingly being developed by incorporating reinforcements into thermoplastic and thermosetting matrices, resulting in lightweight materials with high stiffness, strength, corrosion resistance, and thermal insulation, alongside acoustic damping and non-magnetic properties. These attributes have broadened their applications in civil and structural industries [4–6].

The modification of PVC has found extensive application in industries, such as construction, automotive, and packaging due to its enhanced mechanical and thermal properties due to its cost-effectiveness, durability, lightweight nature, and resistance to weathering, chemicals, and corrosion [7, 8]. Its applications ranged from pipes, fittings, window frames, and flooring to tiles. While these modifications offer

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numerous advantages, such as improved strength, impact resistance, and longevity, challenges, such as cost implications, process complexity, and environmental concerns, also exist [9, 10]. A balanced approach in adopting these modifications must consider both the benefits and potential drawbacks to ensure industrial feasibility. Thus, the development of PVC composites reinforced with clay-based ceramics presented a novel approach to improving these properties. This work seeks to enhance the mechanical flexibility and durability of PVC for tile applications, where mechanical and thermal resistance are critical, without sacrificing its inherent advantages.

The reinforcement with particulate fillers has proven effective in enhancing PVC mechanical properties. PVC reinforced composites are often favored over fibrous and laminate composites due to their lower cost and ease of fabrication [11, 12]. The selected particulates, which were typically harder and stiffer than the polymer matrix, significantly improved the overall performance, especially the mechanical strength [13–15]. This work introduced clay-based ceramic fillers into PVC to address the stiffness and flexibility limitations of the traditional PVC. Naturally occurring clays like ball clay and kaolin, which are essential in ceramic bodies, undergo physical, chemical, and mineralogical changes during firing, forming new phases depending on the raw materials and sintering temperature [16, 17]. The incorporation of these ceramic components into the PVC matrix enhanced its mechanical properties, making it ideal for tile production in civil and construction applications [18, 19].

Several studies have investigated the reinforcement of PVC with various fillers to enhance its mechanical, thermal, and chemical properties. Mahdi and Dean [20] explored the use of glass fibers, reporting improvements in tensile strength and stiffness. Malak [21] studied PVC reinforced with calcium carbonate, which enhanced impact strength and hardness but reduced flexibility. Similarly, Yang et al. [22] reported enhanced composites tensile strength, bending strength, hardness, and density with attapulgite (ATP) in addition to walnut shell (WS) filled PVC. Research work by Rochman et al. [23] on ceramic fillers showed improvements in thermal resistance and mechanical strength, while Li et al. [24] noted enhanced wear resistance and stiffness when using ceramic waste and basalt fiber. Eco-friendly alternatives to conventional PVC by incorporating sustainable materials have also been explored. Akram et al. [25] reported the production of bioplastics using PVC as a matrix with cornstarch (CS) as a biofiller, highlighting its potential as an eco-friendly alternative to traditional polymers. Correa et al. [26] discussed the development of green PVC utilizing fully recycled industrial waste and renewable materials, while Schulze et al. [27] addressed environmental concerns, proposing bioplastics as a solution to the energy crisis. Despite these findings, little attention has been given

to natural, clay-based ceramic particles as reinforcements, particularly modified clays, to improve both flexibility and durability for civil applications like tiles.

While previous studies have focused on reinforcing PVC with inorganic fillers to improve its mechanical and thermal properties, this work is unique in its approach of using modified clay-based ceramics. These ceramic fillers are environmentally sustainable, derived from natural clays, which are abundant and cost-effective [28, 29]. Furthermore, the reinforcement of PVC with ceramic particulates offers a novel method to achieve an optimal balance between flexibility, durability, and cost-effectiveness for tile applications in the civil and structural industry [30, 31]. The novelty lies in the modification of clay-based ceramic particles to enhance their compatibility with PVC, ensuring improved mechanical performance while maintaining the inherent flexibility and ease of processing that PVC is known for them.

This research work aimed to develop PVC composites reinforced with modified clay-based ceramics for tile applications in the civil and structural industry. The focus is to achieve a material that provides the optimal balance of flexibility, durability, and mechanical strength while leveraging sustainable and cost-effective clay-based ceramics as reinforcement.

Experimental

Materials

The materials used for this work were PVC with molecular weight $M_w = 82\,000\text{ g mol}^{-1}$, 0.30 mL caustic soda (NaOH), and 150 mL distilled water, procured from Pascal Chemicals Akure, Nigeria. Other materials used to formulate the reinforcement (Table 1) are Ball clay, stoneware clay, silica sand, limestone, feldspar, frit (Na_2O , $\text{Al}_2\text{O}_3\text{Si}$), coal, and alumina balls were all obtained from Kogi State; kaolin was procured from Okpella, Edo State, and talc was obtained

Table 1 Formulation of the ceramics particulate

Mineral materials	Quantity (g)
Ball clay	31.27
Stoneware clay	15.80
Kaolin	20.80
Talc	5.65
Limestone	0.94
Feldspars	24.40
Frit	0.02
Coal	0.05
Silica	0.47
Alumina balls	600.00

from Madalla, Niger state, Nigeria. Kogi, Edo, and Niger states are in the central region of Nigeria and are known for their sourced in their raw state, then crushed and ground to particle sizes below 100 μm , and rich deposits of the various minerals used in the ceramic formulations.

All ceramic components were treated with caustic soda to enhance the plasticity, dispersion, and bonding characteristics of the clay particles in the PVC composites. The typical treatment involved dissolving the caustic soda in distilled water to create a sodium hydroxide solution, which was then thoroughly mixed with the clay materials for 60 min at room temperature. After treatment, the clay was washed with distilled water to remove excess caustic soda and dried at room temperature. The purity of all materials was assessed to be above 95% after the treatment.

Preparation of ceramics particulates ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, SiO_2 , KAISi_3O_8)

The processing of the ceramic (porcelain) particulates reinforcement involved several steps to ensure the quality and consistency of the final product. Initially, a ceramics slurry was created by using water to blend the mineral materials and additives as presented in Table 1 in a planetary ball mill. This slurry underwent milling to achieve homogenization and particle-size reduction. During the milling process, the impact and friction generated between the ceramic particles, aided by the grinding media in the ball mill, effectively reduced the particle size. The milling was carried out at 150 rpm for 30 min. After milling, the ceramics slurry was sieved to eliminate oversized particles using a mechanical sieve with a mesh size determined based on the desired final particle size. The slurry was poured onto the sieve and agitated to facilitate the separation of finer particles from the coarser ones. The sieving process ensured that only uniformly sized particles progressed to the next stage of processing. The slurry was then subjected to magnetic liquid trap equipment to minimize iron impurities and other ferromagnetic contaminants.

The granulation of the slurry was accomplished using a BuchiTMMini Spray Dryer, with precise control over air temperatures at the inlet and outlet of the drying apparatus. The drying process involved atomization of the slurry into fine droplets using a high-speed atomizer, followed by the rapid evaporation of water as the droplets passed through a heated air stream. The drying air was maintained at a temperature of 220 $^{\circ}\text{C}$, with a feeding rate of 5 mL/min for the slurry. The atomization process employed a centrifugal atomizer, which ensures uniform droplet formation and effective drying. The granulated slurry was atomized and dried within the drying chamber to produce dried ceramic particulates. Subsequently, the dried particulates were heat-treated in a laboratory muffle furnace at 1100 $^{\circ}\text{C}$ for 30 min



Fig. 1 Photo of the processed porcelain particles

Table 2 Composition of the processed ceramic-reinforced PVC composite samples

Sample code	Composition
Control	100% PVC
5	95 wt% PVC mixed with 5 wt% porcelain
10	90 wt% PVC mixed with 10 wt% porcelain
15	85 wt% PVC mixed with 15 wt% porcelain
20	80 wt% PVC mixed with 20 wt% porcelain
25	75 wt% PVC mixed with 25 wt% porcelain
30	70 wt% PVC mixed with 30 wt% porcelain

to ensure proper sintering and consolidation. Finally, the conditioned ceramic particulates were carefully sieved to obtain three distinct particle sizes (40, 60, and 80 μm), as depicted in Fig. 1. This rigorous sieving process guaranteed uniformity in particle-size distribution, essential for consistent performance in the final composite material.

Synthesis of the processed ceramic-reinforced PVC composites

The composites were synthesized by incorporating processed ceramic particulates, with particle sizes of 40, 60, and 80 μm , in concentrations ranging from 5 to 30 wt%. The mixing process occurred under specific pressure and temperature conditions: 75 MPa and 160 $^{\circ}\text{C}$, respectively, lasting approximately 7 min. Following mixing, the resulting samples were filled into corresponding test sample molds and pressed using a hot compression molding machine under identical operating conditions. Each composite formulation was then subjected to tensile, impact, and flexural tests. Table 2 shows the constituents for each sample, detailing the particle-size variation



Fig. 2 Photo of the developed PVC–porcelain particulate composite samples

(ranging from 40 to 80 μm) of the porcelain particulates. Additionally, Fig. 2 showcases representative samples of the test specimens.

Mechanical properties

Various mechanical tests were conducted to evaluate the properties of the ceramic-reinforced PVC composites. Flexural strength was assessed following ASTM D790 standards using a universal tensile testing machine (Instron series 3369). Specimens, sized $120 \times 15 \times 3 \text{ mm}^3$, underwent three-point bending at a displacement control rate of 10 mm/min over a 65 mm span, with three samples tested per composition.

Tensile tests were performed according to ASTM C1557 on dumbbell-shaped specimens ($90 \times 10 \times 5 \text{ mm}^3$) using the same Instron series 3369 machine at a 5 mm/min crosshead speed. Again, three samples per composition were tested.

Impact resistance was evaluated via Charpy impact testing (ISO179). Samples measuring $80 \times 10 \times 3 \text{ mm}^3$, notched at the center, were tested using a Charpy impact testing machine. Samples were suspended horizontally, with a 60 mm distance between lines of supports. Three test pieces per sample were tested, and average values were recorded.

The hardness of the specimens was determined using a Shore D hardness tester. Samples were placed on the tester stand, and indentation was performed at three locations. Average values were calculated from the obtained hardness readings. These mechanical tests provided comprehensive insights into the strength, impact resistance, and hardness of the ceramic-reinforced PVC composites, which were essential for assessing their suitability for various applications.

Scanning electron microscopic examination

The surface morphology of the processed ceramic-reinforced PVC composites was analyzed using a Tescan VEGA 3 scanning electron microscope (SEM) equipped with an Oxford Instruments detector. Before imaging, all samples underwent carbon coating to enhance conductivity under an operating voltage of 20 kV. SEM micrographs allowed for a detailed examination of the microstructure and surface features of the composites, providing insights into the distribution and interaction of ceramic particles within the PVC matrix.

Results and discussion

Mechanical properties of the porcelain particulate-reinforced PVC composites

Flexural strength, a critical indicator of a material's ability to resist deformation under bending stress, is a key parameter in evaluating the mechanical performance of composites, particularly in structural applications. In this work, the incorporation of porcelain particulates significantly enhanced the flexural strength of PVC composites, as shown in Fig. 3. The flexural strength increased progressively with increase of ceramic particle reinforcement across all particle sizes (40, 60, and 80 μm), peaking at 83.213 MPa for composites with 15 wt% of 80 μm particles. This improvement reflects the strong interfacial bonding between ceramic particles and PVC matrix, which facilitates efficient stress transfer and limits the initiation of cracks under applied loads. The trend suggests that moderate ceramic reinforcement optimally balances rigidity and flexibility, a crucial consideration for applications requiring high mechanical performance, such as flooring and structural panels [32].

However, increase in flexural strength was not linear beyond certain thresholds. While smaller particle sizes (40 and 60 μm) exhibited increased flexural strength up to 25

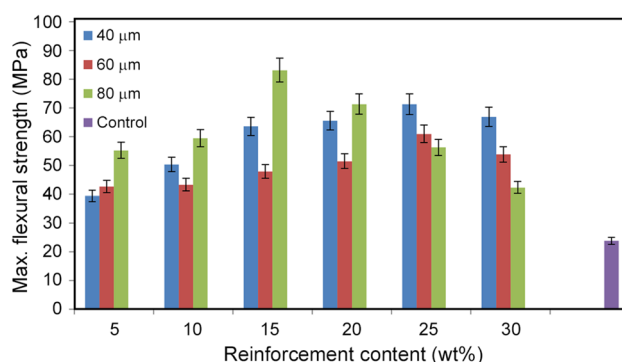


Fig. 3 Effects of porcelain particulate reinforcement content and particle size on the flexural strength of the PVC composite samples

wt%, the larger 80 μm particles reached their optimal performance at 15 wt% of ceramic particles, after which flexural strength declined to 42.35 MPa at 30 wt% of them. This decline was attributed to particles agglomeration, which disrupted the uniform stress distribution within the PVC matrix, weakening the material [25]. Additionally, larger particle sizes tend to offer reduced surface area for bonding, leading to weaker interaction with PVC matrix. Higher concentrations of ceramic particles (above 20 wt%) have been reported in various works often led to a decreasing trend in mechanical properties such as flexural strength. Akram et al. [25] observed that beyond 20 wt% of biofiller reinforcement, the mechanical properties of PVC-based biocomposites declined due to agglomeration and reduced interfacial interaction. Similar findings were reported by researchers such as Rajesh Kanna et al. [33] who noted that at higher filler contents, the increased viscosity of the composite mixture resulted in poor particle dispersion and weak bonding, leading to a reduction in flexural strength and overall mechanical performance.

These results highlighted the significance of controlling both particle size and weight fraction to prevent adverse effects on the mechanical properties of material, corroborating findings from previous studies [34, 35]. Maintaining an optimal balance ensures that the composite exhibits enhanced flexibility and strength, making it suitable for structural and industrial applications where both properties are critical.

The flexural modulus, which represents a material's ability to resist bending or flexing under an applied load, is a crucial property for structural and mechanical applications, especially for materials used in flooring, construction, and other load-bearing components. This parameter is significant when evaluating the suitability of composite materials for applications that require rigidity and resistance to bending.

Figure 4 illustrates the flexural modulus behavior of PVC composites reinforced with porcelain particulates at various weight fractions (5–30 wt%) and particle sizes (40, 60, and 80 μm). The graph shows that the flexural modulus

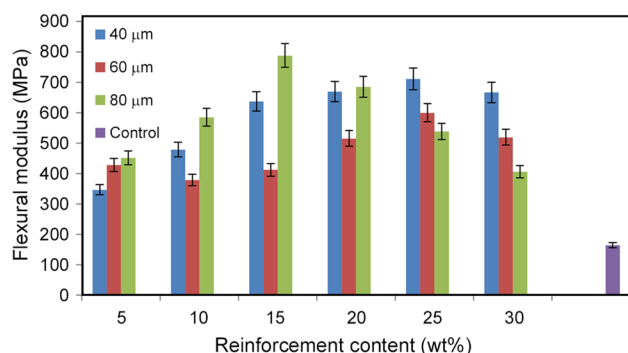


Fig. 4 Effects of porcelain particulate reinforcement content and particle size on flexural modulus of the PVC composite samples

increased with ceramic content up to a certain point for all particle sizes, followed by a decline as the weight percentage increased beyond the optimal value. Notably, the highest flexural modulus was observed at 15 wt% reinforcement for 80 μm particles, achieving a value of approximately 787 MPa. This increase in stiffness indicates that at moderate reinforcement levels, the ceramic particles effectively enhanced the modulus by improving the composite's load-bearing capacity.

The decreasing trend observed beyond 15 wt% for 80 μm particles, as well as beyond 25 wt% for 40 and 60 μm particles, might be attributed to particle agglomeration, which impaired stress transfer and reduced overall stiffness. Agglomeration resulted in non-uniform stress distribution within the matrix, weakening the composite's structure. Larger particles, i.e., 80 μm , though initially were more effective at lower concentrations, might offer less surface area for bonding at higher weight fractions, leading to diminished reinforcement effects.

The ultimate tensile strength (UTS) is a crucial property of materials, representing the maximum stress that a material can withstand while being stretched or pulled before breaking. UTS is particularly significant in evaluating the mechanical integrity of composites for load-bearing applications, such as structural panels and flooring materials. Figure 5 shows the effect of porcelain particulate reinforcement at varying weight percentages (5–30 wt%) and particles sizes (40, 60, and 80 μm) on the ultimate tensile strength of PVC composites. The graph reveals a general declining trend in UTS as the weight percentage of reinforcement increased for all particle sizes. The UTS was the highest for samples with 5 wt% reinforcement, where the composites containing 40 μm particles achieved approximately 60 MPa, and those with 60 μm and 80 μm particle sizes exhibited similar strengths around 58 MPa. However, as the reinforcement content increased beyond 5 wt%, a steady decrease in UTS can be observed. For example, at 30 wt% reinforcement,

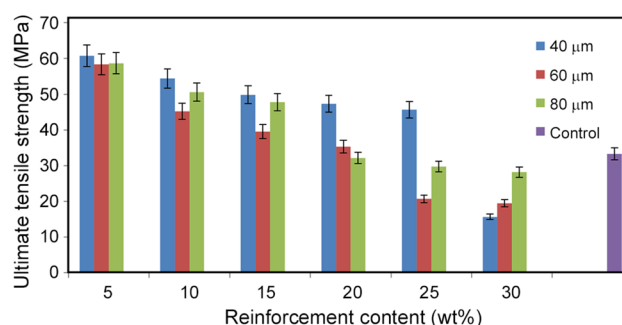


Fig. 5 Effects of porcelain particulate reinforcement content and particle size on the ultimate tensile strength of the PVC composite samples

the UTS dropped significantly to around 15 MPa for 40 μm particle size.

This declining trend in UTS can be attributed to the increasing content of the ceramic particles, which can hinder the even and effective load transfer between PVC matrix and reinforcing particles at higher concentrations. Excessive reinforcement content often leads to particle clusters, creating stress concentration points that weaken the composite structure and reduce tensile strength. Particles with greater size, such as 80 μm , tend to exhibit weaker performance at higher reinforcement levels due to their reduced surface area for interfacial bonding with the matrix, which corroborated findings by Ashraf et al. [36] that emphasized on the negative impact of particle agglomeration and weak interfacial adhesion on tensile strength. As the ceramic content increased, the PVC matrix might become overly rigid, losing its inherent flexibility and ductility, which are necessary for maintaining high UTS values. Rahman and Putra [37] noted that increasing reinforcement content beyond an optimal threshold diminished the tensile properties of the composites due to reduced polymer chain mobility and inadequate stress transfer.

Tensile modulus, or Young's modulus, is a key parameter that determines a material's stiffness and its resistance to elastic deformation under tensile stress. This property is crucial for assessing the mechanical performance of materials in applications where rigidity and structural integrity are vital. Figure 6 shows the tensile modulus response of PVC composites reinforced with porcelain particulates at varying weight percentages (5–30 wt%) and particles sizes (40, 60, and 80 μm). Interestingly, the tensile modulus of the control (unreinforced PVC) was around 189.16 MPa, and most reinforced samples exhibited lower modulus values, except for the PVC composite sample reinforced with porcelain particulates of 40 μm . This porcelain particulates-reinforced PVC composite showed an enhanced modulus, reaching a peak value of approximately 217.16 MPa at 5 wt% of reinforcement. The enhancement in modulus over the control was sustained up to 25 wt%, where the modulus

remained at around 195 MPa. However, beyond 25 wt%, the tensile modulus of the 40 μm reinforced samples declined to around 153 MPa at 30 wt%, a value lower than that of the control PVC sample. The larger particle sizes (60 μm and 80 μm) showed consistently lower tensile modulus than the control sample, with values ranging from 140 to 180 MPa across the reinforcement levels.

This behavior, where the tensile modulus of the reinforced composites was lower than that of the control PVC in most cases, can be attributed to the distribution and interfacial bonding between ceramic particles and PVC matrix. While small particles (40 μm) improved the modulus at moderate reinforcement levels (5–25 wt%), the larger particles (60 and 80 μm) were less effective due to poor dispersion and weak interfacial bonding. As larger particles offer less surface area for bonding, the stress transfer between matrix and particles is less efficient, leading to reduced stiffness. The decline in tensile modulus at higher reinforcement levels, especially at 30 wt% could be attributed to the reduction in matrix continuity, where an excess of ceramic particles disrupted the matrix network, impeding its ability to uniformly distribute stress and thus lowering stiffness [38].

Figure 7 illustrates the variation of impact strength of the reinforced PVC composites with porcelain particulates of 40, 60, and 80 μm particle sizes alongside the control sample. It can be observed from the bars chart that all the developed composites exhibited improved impact energy compared to the control sample. The impact energy of the composite samples increased as the ceramic content increased to a certain proportion before decreasing. This gradual decrease in impact energy was attributed to increased ceramics content, which may have led to partial agglomeration of the porcelain particles within the PVC matrix. This behavior suggests improved particle–matrix adhesion, indicating proper transfer of loads from the matrix to the reinforcements. This observation was aligned with the findings of Jimoh et al. [16] and de Macedo Neto et al. [17] which suggested that

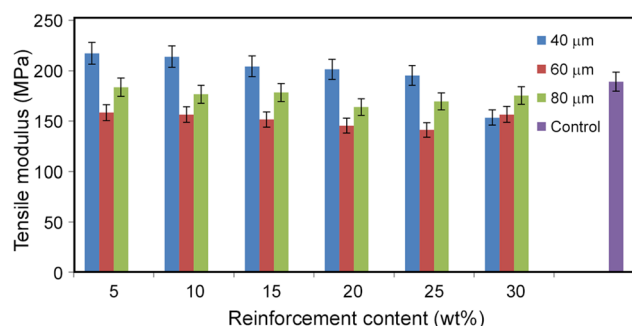


Fig. 6 Effects of porcelain particulate reinforcement content and particle size on the tensile modulus of the PVC composite samples

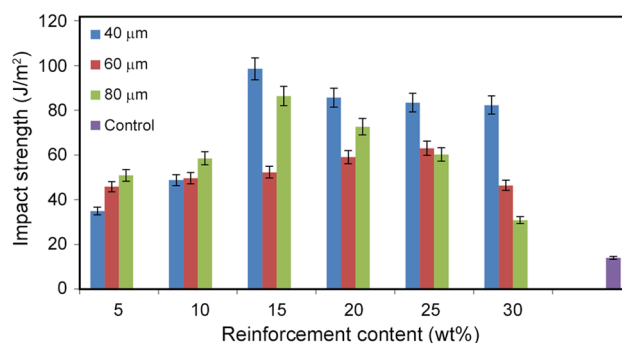


Fig. 7 Effects of porcelain particulate reinforcement content and particle size on the impact strength of the PVC composite samples

fibers played a crucial role in impact strength by impeding crack propagation and serving as a load transfer medium.

The maximum impact strengths obtained in this work were from the reinforced PVC composites with 40 μm ceramic particle size at 15 wt%, followed by 15 wt% of 80 μm ceramic particulate with values of 98.56 Jm^{-2} and 86.40 Jm^{-2} , respectively. Considering the impact properties of the reinforced composites, it was noted that adding ceramics to the PVC matrix improved the impact energy of the composites up to a certain point before the values diminished.

The surface hardness of the composites is a critical factor directly influencing wear resistance. As depicted in Fig. 8, composite samples with low-weight fractions of ceramic particles demonstrated improved resistance to surface indentation (hardness) compared to the control. Introducing ceramics into the matrix at low volume particle loading

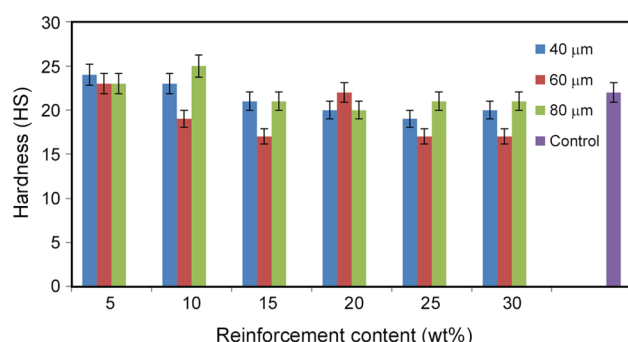


Fig. 8 Effects of porcelain particulate reinforcement content and particle size on the hardness of the PVC composite samples

increased hardness, with an optimal value of 25 Hardness Shore (HS) observed at 10 wt% of 80 μm particle sizes. This enhancement could be attributed to improved alumina fiber–matrix interfacial adhesion facilitated by physical surface modification of the clay materials through NaOH treatment [18]. The hardness properties of the composites at low-weight percentage ceramics particles were enhanced due to decreased flexibility and increased stiffness, supporting findings from previous research work [19]. However, further addition of ceramics particles resulted in a decline in hardness, similar to findings reported elsewhere [20] where, the addition of 19, 43, and 52%vol of kenaf fiber to phenol–formaldehyde composite led to a linear increase in hardness with increasing fiber volume until 43 wt%, followed by a progressive decrease.

Microstructural analysis of the porcelain particulate-reinforced PVC composites

Figure 9 shows the SEM micrographs of porcelain particulate-reinforced PVC composites, illustrating the dispersion of particles of different sizes (40 and 80 μm) and reinforcement levels (5 to 20 wt%) at a magnification of 100 $\times$. These microstructures provide insights into the particle distribution and interfacial bonding within the PVC matrix, which directly influence the mechanical properties of the composites. In Fig. 9a and b, representing the PVC composite samples with 40 μm particles at 5 and 10 wt% reinforcement contents, respectively, the particles appeared well dispersed with minimal signs of agglomeration. The smooth dispersion suggests that the smaller particle size facilitated better interaction with PVC matrix, enhancing the interfacial bonding

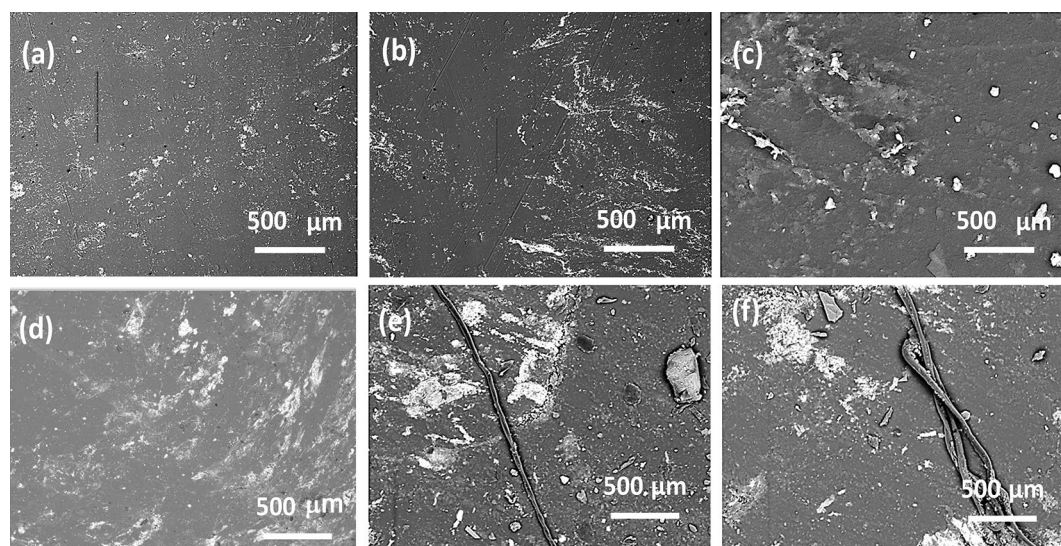


Fig. 9 SEM Micrographs showing dispersion of porcelain particulate particles of: **a** 40 μm , 5 wt%; **b** 40 μm , 10 wt%; **c** 80 μm , 5 wt%; **d** 80 μm , 10 wt%; **e** 80 μm , 15 wt%; **f** 80 μm , 20 wt% in the reinforced PVC composite samples

and contributing to improved mechanical performance, as discussed in the previous sections. Smaller particles increase the surface area available for stress transfer, which enhances the composite's strength and stiffness. Similar observations were reported by Kuan et al. [38] that found smaller ceramic particles in polymer composites typically resulted in improved mechanical properties due to effective stress transfer and uniform particle distribution.

In contrast, as the particle size increased to 80 μm , particularly at higher reinforcement levels (15 and 20 wt%), there was clear evidence of particle agglomeration (Fig. 9c–9f). The larger particles tend to cluster together, leaving gaps or voids in the matrix, which did not compromise the stress transfer between the reinforcement and matrix. These voids act as stress concentration points, leading to reduced mechanical performance. Kundie et al. [34] similarly observed that the larger ceramic particles in polymer composites often lead to clustering, which weakens the composite's overall stiffness and strength due to poor stress distribution.

A notable observation in Fig. 9e and f is the presence of a thread-like feature in the matrix. Upon closer inspection, this feature seems to be an impression or defect in the PVC matrix rather than a characteristic of the particles' dispersion. Such defects are often introduced during processing and can create weak spots in the composite material. These defects can disrupt the continuity of the matrix, leading to a reduction in the mechanical properties by promoting crack initiation or facilitating easier deformation under applied stress. The thread-like impressions could result from the extrusion or casting process, where incomplete matrix filling around the reinforcement particles created surface imperfections. The presence of these impressions, particularly as shown in Fig. 9e and f, suggests that defects in the PVC matrix may contribute to the reduction in tensile modulus and strength at higher reinforcement levels. Studies by Sokołowski and Kamiński have shown that defects or imperfections in polymer composites can significantly degrade their mechanical performance by acting as failure initiation sites [39].

Bonding mechanisms in PVC composites reinforced with porcelain particulates

The interface characteristics between the porcelain particles and PVC matrix also differ with particle size, impacting the overall mechanical performance of the composites. The increased bonding area in larger particles (80 μm) enhanced the flexural properties due to more effective stress distribution, even if the interfacial interactions were not as optimal as in the case of smaller particles. However, in terms of tensile performance, the smaller 40 μm particles provide a more effective load-bearing network due to their higher specific

surface area, which enhanced the bonding with PVC matrix [2, 40]. Moreover, the distribution of these porcelain particles within the PVC matrix is crucial; a more homogeneous distribution of the 40 μm particles helped prevent localized weaknesses, leading to higher tensile strength and impact performance [41].

The volume fraction of the porcelain particles played a pivotal role in determining mechanical properties, with 15 wt% emerging as the optimal reinforcement level for maximizing overall performance, as excessive reinforcement could lead to agglomeration and diminish mechanical effectiveness [36, 42]. Ultimately, the choice of particle size and distribution must be tailored to specific performance requirements, balancing the strengths of both finer and larger particles to achieve the desired mechanical behavior in PVC composites.

The interfacial bonding between the PVC matrix and porcelain particulate reinforcement plays a critical role in the mechanical performance of the composites. In the current system, the primary type of bonding expected at the interface is physical rather than chemical due to the nature of both the polymer matrix and ceramic reinforcement [43]. Van der Waals forces are likely to dominate the interaction, as these weak intermolecular forces are common in polymer–ceramic composites, promoting adhesion between the matrix and particles [44]. In addition to Van der Waals forces, physical interlocking may occur, particularly with the irregular surface morphology of the porcelain particles. The rough surface structure of the particles enhanced mechanical anchoring within the PVC matrix, thereby improving load transfer under mechanical stress [6]. This phenomenon was especially significant in composites with smaller particles sizes, where the increased surface area of the particles provided more opportunities for effective load transfer and bonding [45].

Mechanical bonding through this interlocking mechanism may help explain the improved mechanical properties observed at moderate reinforcement levels (5–25 wt%). However, beyond this level, the potential for particle agglomeration could lead to reduced interfacial bonding and, consequently, a decline in mechanical performance, as discussed in earlier sections. These findings were consistent with those of previous research works on polymer–ceramic composites, where similar bonding mechanisms were observed [9, 18].

Conclusion

This work presented promising results for developing PVC composites reinforced with modified ceramic particles, particularly for tile industry applications. The ceramic reinforcement led to significant improvements in

mechanical properties, with the flexural strength increasing from 23.82 MPa (control) to 83.21 MPa at 15 wt% ceramic reinforcements, and the flexural modulus rising from 163.72 MPa to 787.66 MPa at the same reinforcement level. Ultimate tensile strength (UTS) increased from 33.31 MPa to 60.78 MPa at 5 wt% reinforcement, while the tensile modulus improved from 189 to 217 MPa at 5 wt%. Impact strength showed a 14.16% enhancement at 15 wt% and 40 μm particulate ceramic reinforcement, and surface hardness reached 25 HS at 15 wt% of the same reinforcement. Microstructural analysis revealed improved interfacial bonding between ceramic particles and PVC matrix, indicating potential for enhanced durability and performance in tile applications. These findings lay the foundation for further research and optimization of ceramic-reinforced PVC composites, offering improved strength, impact resistance, and wear resistance specifically tailored for tile manufacturing.

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Declarations

Conflict of interest The authors affirm that they have no known financial interests or personal relationships that could have influenced the impartiality of the work presented in this paper.

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