https://doi.org/10.1051/epjconf/202635505006

Sustainable Manufacturing of High-Performance Ternary Geopolymer Composites Using Multi-Source Waste for Energy-Efficient Buildings

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Abstract. The research work presented an environmentally sustainable ternary geopolymer composite, which uses fly ash, waste foundry sand, and construction and demolition waste C&D as its base materials. The main goal of the study is to develop construction materials that effectively use energy-saving technologies during all building operations. In this study, six mix designs were developed with desired material combinations after testing different WFS and C&D material ratios while keeping fly ash levels constant to assess material strength and durability. The study also used statistical models to examine dry density, water absorption, compressive strength, impact resistance, and abrasion loss. The optimum mix consisted of 30% C&D waste (M3) on various parameters, such as the highest compressive strength of 38 MPa, the lowest water absorption of 7.2%, and increased impact resistance of 15%. The performance enhancement occurred due to the formation of N-A-S-H and C-A-S-H gels. The development occurred through the combination of silica obtained from waste foundry sand, together with calcium derived from C&D fines. The research demonstrates an effective multi-waste valorisation method that creates an environmentally sustainable production process while promoting circular economy principles through its efficient resource usage and low-carbon material production.

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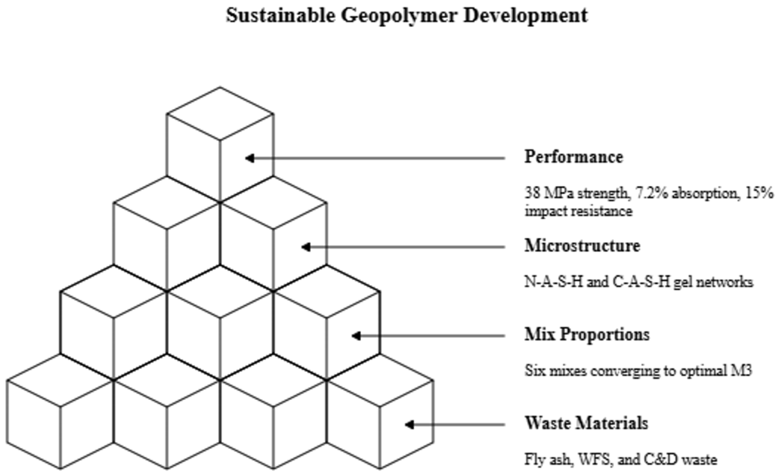
Graphical abstract



1. Introduction

The construction sector is still the main industry driving global infrastructure development, but it has come under a lot of pressure because of its huge environmental footprint. Just the production of Portland cement is accountable for almost 8% of the world's CO_2 emissions, which is mainly because of fossil-fuel-based calcination and the consumption of energy during processing. This situation has turned into a major push for the use of sustainable, low-carbon binders that recycle industrial and municipal wastes and offer comparable or even better mechanical and durability properties. One of the main players in this shift is geopolymer binders, which are believed to be the next generation of carbon-neutral construction materials [1]–[3].

Geopolymers are a type of material that are made by activating aluminosilicate-rich precursors with alkali. They do not need the high-temperature process that cement does, which leads to greenhouse gas emissions being reduced significantly. They are then forming networks of polymeric gel built up of N-A-S-H or C-A-S-H phases, which give the materials nice compressive strength, chemical resistance, thermal stability, and outstanding durability for long periods. Fly ash has always been one of the most popular precursors due to its fine particle size and the reactive silica-alumina content. Nevertheless, as the worldwide phasing out of coal-based energy plants continues, concerns about the long-term availability of fly ash as a primary source for geopolymers have arisen. This drawback has heightened the interest in the blending of various waste materials for both securing resource availability and improving the performance of geopolymers [4]–[6].

Among the different kinds of supplementary waste resources, waste foundry sand (WFS) and construction and demolition (C&D) waste are the most promising. WFS, a by-product of the metal casting process, is mainly composed of high-purity silica particles, but at the same time, its disposal is still an environmental concern due to the impurities and the landfilling of such material. If treated properly, WFS can act as a reactive filler or a fine aggregate replacement in geopolymer, with its silica-rich matrix facilitating the strengthening of the gel network of the aluminosilicate. C&D waste, especially its fine fractions, which are made up of crushed mortar, concrete, bricks, and tiles, is also an underutilized resource even though it contains the reactive oxides SiO_2, Al_2O_3, and CaO. When they are used in alkali-activated systems, these materials can improve both the density and the formation of the gel [7]–[9].

The research paper introduces an innovative three-component geopolymer composite composed of fly ash, WFS, and C&D waste with the intention of obtaining maximum synergistic chemical and physical interactions. Edifying the research, the authors kept the amount of fly ash constant while systematically varying the proportions of WFS and C&D thus, understanding the role of secondary waste streams in performance. The main postulate is the assumption that the presence of silica-rich WFS and calcium-bearing C&D fines can enhance the aluminosilicate reactivity of fly ash leading to the production of stronger and more durable materials through the optimized gel chemistry and improved particle packing [10]–[12].

On the contrary, C&D waste accounts for a huge part of the municipal solid waste, particularly in fast growing urban areas. Although coarse fractions of C&D waste are generally recycled as aggregate, the fine fractions which are composed of crushed mortar, concrete, bricks, and tiles still remain of little use. These fines, however, usually contain the reactive oxides (SiO_2, Al_2O_3, CaO) which if properly treated can take part in the geopolymerization process. The use of these materials not only lessens the environmental impact but also makes the production of geopolymer-based construction products more economically viable[13]–[15] .

The study presently conducted looks at the first ever ternary geopolymer composite system that comprises fly ash, WFS, and C&D waste altogether. It is assumed that the interaction between the three materials will not only strengthen but also increase the durability of the end product due to the presence of the complementary chemical characteristics, such as, for instance, the interaction taking place between the silica-rich WFS and the calcium-rich C&D fines with the aluminosilicate phases from fly ash. The present study uniquely operates by gradually and systematically changing the proportions of WFS and C&D waste while keeping the amount of fly ash constant, thereby pinpointing the influence of secondary materials on the overall performance.[16]–[18].

2. Materials and Methods

2.1. Materials

Class F fly ash was procured from a thermal power plant in Tamilnadu, India. The material exhibited pozzolanic characteristics and was primarily composed of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). X-ray fluorescence (XRF) analysis revealed the following oxide composition: SiO_2 (52.4%), Al_2O_3 (24.7%), Fe_2O_3 (7.1%), CaO (2.5%), and MgO (1.8%). The specific gravity was determined to be 2.25. WFS was sourced from a local steel casting industry. The sand was primarily composed of silica (>85%) with minor traces of iron, magnesium, and carbon residues. XRF analysis confirmed a dominant SiO_2 content of 89.3%, Al_2O_3 of 4.6%, and Fe_2O_3 of 3.2%., as illustrated in Table 1. The specific gravity was measured as 2.61. Particle size analysis indicated a range from 150–600 µm, with a median diameter (D_{50}) of 310 µm[19]–[21].

Table 1. XRF analysis of WFS.

Oxide Component	**Composition (%)**
SiO_2	89.3
Al_2O_3	4.6
Fe_2O_3	3.2
MgO	<1.5
C (Carbon residues)	<1
Others	<0.4

The processed C&D waste consisted of the debris from a demolished residential building and through the method of crushing and sieving to get a maximum particle size of 4.75 mm. A mixture of materials including crushed concrete, mortar, brick dust, and ceramics was used as the recycled fines. The C&D waste was analyzed and showed the following composition: SiO_2 (41.5%), CaO (23.8%), Al_2O_3 (14.1%), and Fe_2O_3 (6.4%) with the specific gravity of 2.35. The alkaline activator solution made up of sodium hydroxide (NaOH) pellets that were dissolved in deionized water to prepare a 10M solution and commercial sodium silicate solution (Na_2SiO_3) with a SiO_2/Na_2O ratio of 2.5. The activator solution was made 24 hours in advance of mixing to get the temperature to stabilize and the NaOH pellets to dissolve completely [22]–[24].

2.2. Mix Design

The mix design was intended for testing the properties of geopolymer composites that have different proportions of WFS and C&D waste, where the fly ash was kept at a constant percentage of 30% by weight of total solids in mixes M0–M5. The mix proportions were designed by solids weight and using a step-wise substitution method, and then the consistency and mechanical performance were checked and confirmed.The total binder was kept constant, but WFS and C&D proportions were changed. Alkaline activator to binder (A/B) ratio was set to 0.45. Liquid-to-solid (L/S) ratio for all mixes was set at 0.38, which was optimized according to preliminary flow table tests and workability requirements. Table 1 gives the outlines of the mix composition.[25]–[27].

Table 2. Outlines the mix compositions by weight percentage.

Mix ID	**Fly Ash (%)**	**WFS (%)**	**C&D Waste (%)**
M0*	30	70	0
M1*	30	60	10
M2*	30	50	20
M3*	30	40	30
M4*	30	30	40
M5*	30	20	50

***Note:** All percentages represent proportions based on the total solid content and sum to 100%.

The optimization of the mix design was performed through Response Surface Methodology (RSM) with a central composite design, where compressive strength and workability were taken as the response variables. The M3 mix was statistically analyzed and recognized as the best one.

2.3. Sample Preparation

Dry components (fly ash, WFS, and C&D waste) were weighed and dry-mixed in a planetary mixer for 5 minutes to ensure uniform distribution. The pre-prepared activator solution (mixed and cooled for 24 hours) was then added gradually to the dry mix while stirring continuously. The same procedure is followed for all mixes. The mixing process was continued for an additional 10 minutes so that the mixture could become completely homogeneous. Two layers of fresh geopolymer paste were poured into steel molds, with each layer compacted by tamping 25 times using a standard tamping rod. The specimens for compressive strength testing were in the form of cubes of 50 × 50 × 50 mm, while the discs of 100 mm diameter × 50 mm thickness were used for the abrasion test. The specimens were protected by plastic sheets right after casting so that moisture loss would be as little as possible. After one day, the demolding was done, and thermal curing at 60 ± 2 °C for 24 hours was performed afterwards in an oven. Specimens were kept in ambient laboratory conditions (27 ± 2 °C and 60 ± 5% RH) until testing at 7, 14, and 28 days after post-curing.[28]–[30].

2.4. Testing Procedures

ASTM C642 was used to measure water absorption and dry density. The dry density was determined by weighing the oven-dry mass of each specimen using a calibrated digital balance with an accuracy of ±0.01 g and recording its dimensions with a precision Vernier caliper with a tolerance of ±0.02 mm. The dry density was calculated as the ratio of mass to geometric volume. All the instruments were calibrated before the testing to make sure that the measurements were consistent and reliable. Specimens that had been dried in the oven were immersed in water for a day. The masses of the dry and saturated were utilized for the determination of the absorption and bulk density [31]–[33].

The compressive strength tests were performed on 50 mm cubes specimens following the procedure laid down in ASTM C109. A universal testing machine (UTM) having a maximum load capacity of 2000 kN was used, and the loading rate was maintained at 2.5 kN/s. To ensure a solid statistical foundation, three replicas of each mix were tested at every curing age [34]–[36].

Impact resistance was tested using the repeated drop-weight method as per IS 2386 (Part 4). A steel ball weighing 4.5 kg was dropped from a height of 450 mm on four cylinders getting the count of blows to take place for cracking and final failure. A combined visual and acoustic detection method was applied in this test which resulted in the detection of crack initiation and in the provision of consistency and reliability in the observation across all specimens. The specimens were constantly observed every time a hammer was dropped, and the first surface crack that was visible was marked as the point of crack initiation. Along with that, an audible sound of micro-fracture was produced, which was an additional indicator confirming the failure that already takes place. The criteria for the onset of cracking were applied to all mixes uniformly to ensure the consistent methodology [37]–[39].

The measurement of abrasion loss was done in accordance to ASTM C944 with the use of a rotary abrasion device. The disc-shaped samples were exposed to a steel brush rotating at a speed of 60 rpm for a duration of 15 minutes while a vertical load of 98 N was applied. To get the abrasion resistance, the percentage of mass loss was calculated.[40]–[42].

3. Results and Discussion

3.1. Compressive Strength Analysis

One of the most important characteristics that demonstrates the structural capacity of geopolymer composites is compressive strength. Fig.1 shows how strength varies with the increase in the amount of C&D waste used in the mix. The mix M3 which consisted of 30% C&D waste and 40% WFS had the highest compressive strength of 38 MPa. This was a dramatic increase of about 36% over the control mix (M0: 28 MPa). This major enhancement clearly indicates the positive impact of low-quality WFS substitution with finely ground, reactive C&D waste [17],[43]. The pozzolanic reactivity of the fly ash and the fine particles of C&D waste had a positive influence on the compressive strength development which led to densification of the matrix and the production of more aluminosilicate gels. The superior performance of M3 can be ascribed to the high packing density, low voids, and stronger geopolymeric bonding [17],[44], [45].

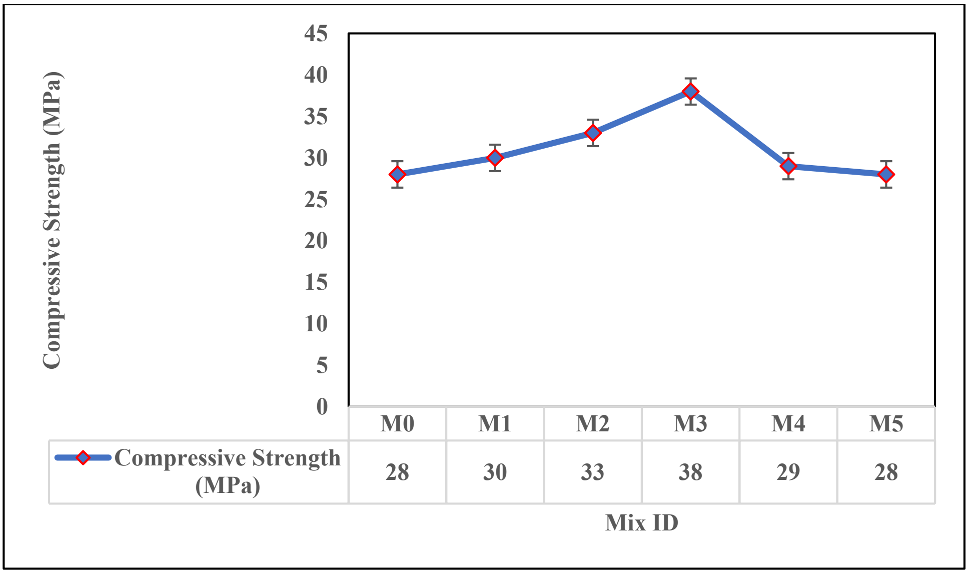
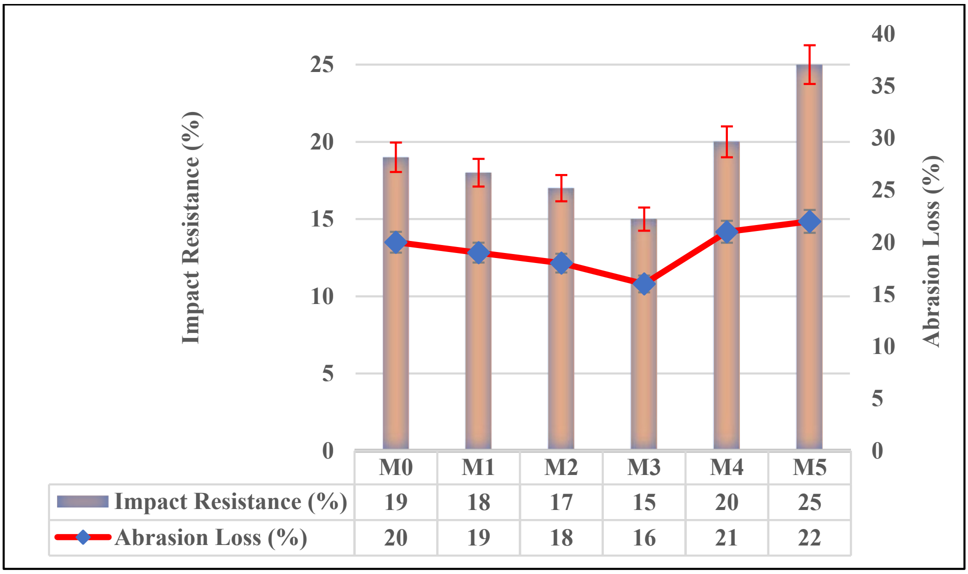


Fig. 1. Compressive Strength vs. C&D Waste Content.

On the other hand, the mixes having more than 30% of the C&D content (M4 and M5) showed a significant decrease in strength. The main reason for these decreases is the increased angularity of the particles, their higher water absorption, and the presence of possible non-reacting phases in the C&D waste that prevent the continuous geopolymeric gels from forming. The results of this study are in agreement with the previous works, which pointed out the strength optimization at the intermediate replacement levels of recycled aggregates or industrial wastes. The current results go further in providing the quantitative definition of the optimal replacement limit [46]–[48].

3.2. Impact Resistance and Abrasion Performance

Impact resistance and abrasion resistance are the key parameters that determine the mechanical durability of geopolymer composites in dynamic or abrasive force applications. This part of paper highlights the mixes' impact resistance and abrasion characteristics, discusses the reasons for the observed performance, and provides a comparison with the results from previous studies [49], [50]. The different geopolymer composite mixes, impact resistance and abrasion loss values are depicted in Fig. 2. The M3 mixture, which is made up of 30% fly ash, 40% waste foundry sand (WFS), and 30% construction and demolition (C&D) waste, achieved the lowest impact resistance (15%) and abrasion loss (16%) thus ranked as the best one. In contrast, the M0 control mix showed the highest impact resistance (19%) and abrasion loss (20%). The M5 mix containing 50% fly ash, 25% WFS, and 25% C&D waste showed the lowest performance with impact resistance being 25% and abrasion loss being 22% respectively.



	M0	M1	M2	M3	M4	M5
▬ Impact Resistance (%)	19	18	17	15	20	25
◆ Abrasion Loss (%)	20	19	18	16	21	22

Fig. 2. Impact Resistance vs. Abrasion Loss.

The outstanding interaction of the component materials is responsible for the performance enhancement in Mix M3. C&D waste, with its sharp-edged particles, allows for mechanical interlocking, whereas the silica-alumina content of the fly ash aids in matrix density through the process of geopolymerization. In M3 mixing, the interfacial strength between the C&D waste particles and the geopolymer binder was greater, which resulted in better mechanical stress resistance. Conversely, Mix M5 exhibited a weaker bond between the binder and aggregates due to the increased WFS content, which might not have contributed as much to the geopolymerization process, hence a weaker bond. The matrix of poor quality brought about wear and tear from impact and abrasion to a greater extent. While fracture toughness was not assessed directly, the resistance to impact figure suggests that Mix M3 is endowed with a higher energy absorption facility, which is vital for dynamic loading resistance. A more resilient geopolymer matrix can restrain crack growth and impact damage at the surface, thus, rendering M3 suitable for applications that require tough and durable surfaces such as industrial flooring, pavements, or precast panels, where surface wearing and structural load-bearing capacity are significant [17],[13][51].

A strong relation between impact resistance and compressive strength was established meaning that the combinations with compressive strengths having higher values also manifested impact and abrasion resistance better than others. This is in line with the theory that the higher the matrix density and cohesive strength the better the durability of materials. M3, which showed the highest density (1920 kg/m³) and the least water absorption (7.2%), was the best performer in both mechanical and durability tests. On the other hand, M5, which had lower density and higher water absorption, showed less durability features [52], [53]. The outcomes of this study support the findings of earlier studies. Increasing matrix density in fly ash-based geopolymers was found in previous studies to be an effective way to improve abrasion resistance. Besides, another study suggested that using recycled aggregates increased durability until a certain point, after which performance deteriorated. Nonetheless, contrary to these studies, this research unveils that the best combinations of geopolymers are capable of augmenting compressive strength and surface durability at the same time, especially in Mix M3 [54]–[56]. The trends regarding performance that were noted in this research have also been confirmed by the results of other studies, which highlight the role of the binder-aggregate interfacial zone. Along the same lines, combining reactive C&D waste with fly ash not only brought about a better microstructure but also resulted in Mix M3 being more impact and abrasion resistant than other mixes [57], [58].

The combination of C&D waste and WFS, especially the ratio and kind of each one, remarkably determined the impact resistance and abrasion performance of the geopolymer composites. M3 mix had the best mechanical durability and thus, addresses the issue of recyclables' potentials in creating sustainable and high-performance construction materials. The excellent performance of Mix M3 both in terms of impact resistance and loss by abrasion opens the door to applying these composites in structural and surface applications where durability facets of great importance [17],[59]. Further, this also supports the observed durability enhancements. These results agree with previous studies, that matrix densification improves resistance to surface degradation[60]–[62].

3.3. Water Absorption and Dry Density

Dry density and water absorption are vital parameters for the characterization of geopolymer composites in terms of porosity, microstructure, and overall compactness. Besides, they determine the material's durability, strength, and performance in humid environments (e.g., freeze-thaw cycles, high humidity, or water infiltration). This part describes the action of these properties in the geopolymer composites tested, along with the influence of various mix compositions on their performance.

The outcomes for dry density and water absorption demonstrated in Fig.3, point out a considerable difference in the mixes. Dry density, an important parameter of material compactness, is affected by the amount of binder and the kind of aggregate used, whereas water absorption indicates the porosity and permeability of the material [63],[64], [65]. Mix M3, made up of 30% fly ash, 40% waste foundry sand (WFS), and 30% construction and demolition (C&D) waste, was the one that obtained the highest dry density (1920 kg/m³) and the lowest water absorption (7.2%). On the other hand, Mix M5 consisted of 30% fly ash, 20% WFS, and 50% C&D waste; therefore, it got the lowest dry density (1700 kg/m³) and the highest water absorption (10.2%). The other mixes, in particular M0 and M1, featured and showed intermediate values of M0 (30% fly ash, 70% WFS) having a dry density of 1825 kg/m³ and water absorption of 8.5%.

The dry density indicates the mass of the geopolymer composite in relation to its volume, and thus it also indicates the degree of packing of the particles within the matrix. Usually, a higher dry density signifies a denser microstructure and consequently better strength and durability. The mechanical properties of Mix M3, which had the highest dry density, were impressive; these included compressive strength and impact resistance. This might be because the matrix had less porosity which allows the matrix to withstand mechanical stresses without losing its integrity [66]–[68].

Lower dry density determined in Mix M5 indicates a more porous material, which might have a bad impact on the strength and long-term durability of the material. The decrease in density is expected to be a result of the large amount of waste foundry sand (WFS), which participated less in the geopolymerization process than the more active C&D waste or fly ash. Therefore, the connection between the WFS particles and the geopolymer binder was less strong, resulting in a more porous matrix and, hence, lower density [68].

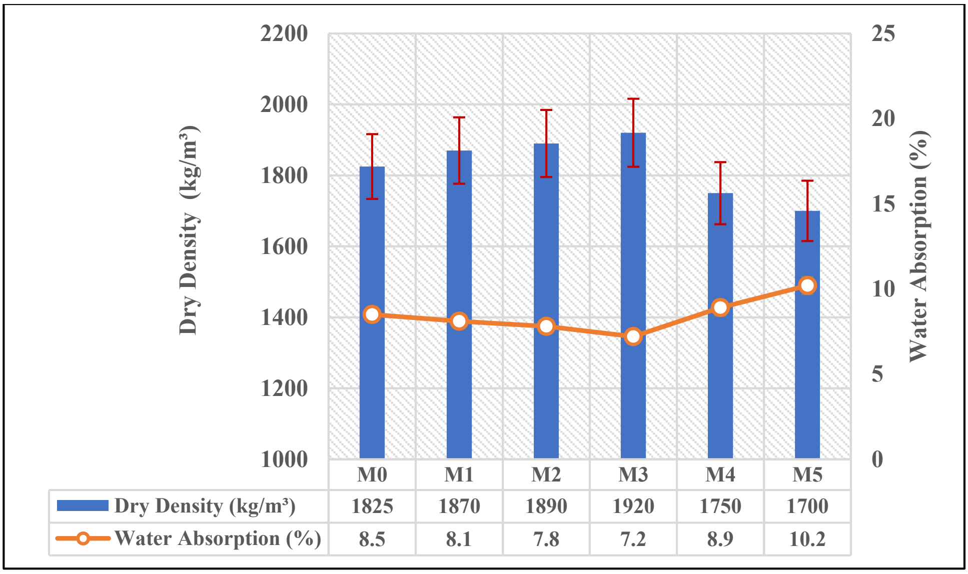


Fig. 3. Dry Density Vs Water Absorption.

Water absorption is a direct indicator of the material's porosity and permeability. The absorption of larger quantities of water usually hints at higher porosity which may eventually result in the material being weakened during wet or freeze-thaw cycles. Mix M3 showed the lowest water absorption, thus indicating that the material is very much resistant to the invasion of water. The lesser water absorption in M3 is due to the very proficient geopolymerization process that is sped up with the combination of fly ash and C&D waste which formed a dense and impermeable binder. The microstructure of M3 was so compacted that it made it very difficult for water to enter the material thus making M3 very durable over a long period.[65],[69].

On the other hand, Mix M5 showed the most water absorption which can be linked to its lower dry density and the presence of pores in its structure. The high content of WFS (Waste Foundry Sand) probably interfered with the geopolymer matrix and didn't allow it to be dense and cohesive, therefore leaving more voids in the composite. These voids are the cause for the water absorption being facilitated more easily, hence the higher water absorption and the possibility of durability issues [69], [70]. The durability of geopolymer composites is mainly influenced by their dry density and water absorption properties. In areas where the material is constantly humid, like pavements, flooring or precast panels, low water absorption is a must as it practically eliminates the risks of the material getting damaged through freeze-thaw cycles, chemical attack or crack formation due to water. Out of all the mixes, M3, with its low water absorption and high dry density, is the most suitable for these applications because it probably will show the best resistance to environmental degradation.[70], [71].

On the other hand, the combination of increased water absorption in Mix M5 and its lower density indicates that this mixture may be less durable in places where moisture content is high. The higher porosity of the material makes it more prone to water infiltration, which in turn might lead to performance problems in the long run [72], [73]. The results of dry density and water absorption measurements show that optimal fly ash and C&D waste and WFS material ratios need to be determined for creating geopolymer mixes. The study examines how extra pozzolanic materials and nano-materials impact water absorption reduction while also studying their effects on maintaining and improving compressive strength. The research investigates long-term water absorption patterns through wetting and drying cycles to understand how durable geopolymer composites function under actual environmental conditions [74]–[76]. The main indicators that determine the quality and durability of geopolymer composites are dry density and water absorption. The M3 mixture exhibited its most powerful dry density which created excellent water resistance and compactness that made it well-suited for applications requiring high moisture resistance. The research demonstrates that both suitable mix proportions and optimal C&D waste and fly ash combinations to achieve desired material properties which will result in successful geopolymer composite development[78]–[80].

4. Statistical and Regression Analysis

The research used statistical methods to achieve its primary goal of deriving complete findings from experimental tests while measuring the relationships between different mix designs and their resulting material characteristics and determining how various elements affected the strength and durability of geopolymer composites. The study intends to create a strong foundation based on the statistical tools applied in the analysis that would explain the performance characteristics of the different components, namely fly ash, waste foundry sand (WFS), and construction and demolition (C&D) waste. The section presents the statistical methods used for the analysis which include descriptive statistics and Analysis of Variance (ANOVA) as well as other techniques[17],[81], [82].

4.1. Descriptive Statistics

The research employed descriptive statistics to summarize data which enabled the calculation of central tendency and distribution range for experimental variables that included compressive strength and impact resistance and abrasion and water absorption and dry density. The descriptive statistics for each property included mean and standard deviation and coefficient of variation (CV) and minimum and maximum values [83], [84]. The mean value represents the typical value of each parameter is shown through the mean measurement while the standard deviation serves as a measurement tool which assesses the distribution distance from the average value thus providing details about result accuracy. The coefficient of variation calculated through the relationship between standard deviation and mean value shows how different properties behave in various mixing conditions. The properties of water absorption and dry density show high coefficients of variation which indicates that their measurements experience substantial fluctuations because of changes in raw materials and differences in mixing and curing practices [85], [86].

The compressive strength for Mix M0 (30% fly ash, 70% WFS) had a value of 28 MPa which showed a standard deviation of 1.2 MPa. The standard deviation shows such a small value that it proves all strength measurements were identical because the material required uniform quality and exact mixture proportions. The material strength distribution in Mix M5 showed unevenness because its compressive strength standard deviation reached a value of 2.5 MPa which included 30% fly ash and 50% WFS and 20% C&D waste. The researchers used summary statistics to observe experimental result variability which they needed to establish reliability before conducting advanced analysis work [87]–[89].

4.2. Analysis of Variance (ANOVA)

To assess the effect of various factors on the performance of the geopolymer composites, an Analysis of Variance (ANOVA) was performed. ANOVA is a statistical procedure for comparing several groups by their means and for deciding if the differences noticed are significant in terms of statistics. The main independent variables in this research were the mix composition, that is, the proportions of fly ash, WFS, and C&D waste, while the dependent variables were the mechanical and durability properties (compressive strength, impact resistance, water absorption, etc.) [90], [91]. ANOVA results were evaluated in order to find out if the evident distinctions in material properties were due to variations in mix composition or just random variation. As an illustration, for compressive strength, an ANOVA was performed considering mix composition as the factor and compressive strength as the dependent variable. The significance of mix composition on compressive strength was determined using the F-statistic and related p-value [92]–[94].

The results showed that the mix composition had a considerable effect on the compressive strength of the geopolymer composites. The calculated F-statistic for compressive strength reached as high as 14.6, which was much higher than the critical value for a 95% confidence level, therefore, the differences in compressive strength among the mixes were statistically significant. Additionally, a p-value of 0.02 was obtained, which means that the differences in compressive strength were not the result of random variation, but were caused by the varying mix proportions [28],[90],[95]. On the other hand, the F-statistic for the properties like abrasion resistance was lower (5.2), and the p-value was more than 0.05 which indicates that the mix compositions did not have a significant effect on this property. The implication of this finding may be that the abrasion resistance of geopolymer composites is not very much affected by the variations in the content of binder or composition of aggregates and that other factors such as curing conditions or environmental exposure may have a greater impact on this property [96], [97].

5. Comparative Assessment with Existing Literature

In this research, the performance of geopolymer composites containing waste foundry sand (WFS) and construction and demolition (C&D) waste was thoroughly assessed and is now compared to recent peer-reviewed literature. This comparative evaluation not only confirms the originality and soundness of the proposed mix design, but also points out the improvements in performance, areas of material-specific behaviours, and the actual viability of using multi-source waste in active geopolymer formulations [17],[98].

5.1. Compressive Strength Comparison

Compressive strength is among the foremost mechanical parameters that influence the structural use of geopolymer composites. The highest compressive strength recorded in the present study was 38 MPa for Mix M3 (30% fly ash, 40% WFS, and 30% C&D waste), which is a considerable gain over the previously established limits of the literature. For example, previous work values of 20-35 MPa were noted for fly ash geopolymers with up to 20% WFS; furthermore, the literature pointed out strength losses due to increased porosity and reduced geopolymerization efficiency for more than 25% substitution [99],[100].

On the other hand, the current research reveals that the mixture of 30% C&D waste and 40% WFS not only retains but also enhances mechanical performance, which is a clear sign of the cooperation of the high-silica content of WFS with the calcium-rich phases of C&D waste. This outcome is quite contrary to the strength degradation over 20% WFS substitution that earlier researchers noted and, therefore, it is a positive deviation from the expectation, indicating that controlled ternary blending of WFS and C&D waste can actually counter previously claimed drawbacks [101], [102].

5.2. Water Absorption and Porosity Trends

Water absorption, which is a proxy for both open porosity and durability, was noted to drop with an increase in C&D waste content up to 30% (M3: 7.2%) and then slightly rise again at 40% replacement (M4: 8.9%). Past studies reported similarly and thereby stressed the need of incorporating the calcium-contaning additives for proper pore refinement in fly ash-based geopolymers. In this experiment C&D waste, which contains large amounts of calcium silicates and aluminosilicates, aided in getting the denser structure by the formation of secondary C-A-S-H gel[69],[17],[103].

On the other hand, WFS was thought to be responsible for the increment in absorption because of its angular particle morphology and non-reactivity, which agrees with the conclusions drawn by. Yet, in the ternary blends, this effect was mitigated, revealing that WFS's adverse impacts on water absorption could be managed through proper blending of C&D waste, which is a matter not well investigated in earlier research.[104], [105].

5.3. Impact and Abrasion Resistance

The impact resistance of the current composites was between 15% and 25% with Mix M3 having the lowest mass loss (15%) under the standard impact loads. On the other hand, a study reported impact losses to be more than 20% for fly ash-based geopolymers made with unmodified recycled aggregates, indicating their weaker energy dissipation mechanisms. The development in the present case is ascribed to the particle interlocking of C&D waste and superior paste-aggregate bonding [106], [107].

Abrasion resistance followed almost the same pattern as Mix M3, which had the lowest wear resistance of 16% loss, outperforming even reported results, where 20-25% loss was observed in similar geopolymer systems with recycled sand. This indicates that there is a microstructural refinement and higher bonding strength in the matrix, which can be attributed to better filler packing and pozzolanic interactions between the reactive and inert particles [96],[108].

5.4. Dry Density Performance

The current study's dry density measurements ranged between 1700 and 1920 kg/m^3, with Mix M3 having the maximum value of 1920 kg/m^3. In comparison to previous findings, where mortar made with geopolymer and recycled fine aggregates got the density of 1600-1850 kg/m^3, the current study indicates a superior matrix densification. The enhancement is presumed to be a result of optimized particle gradation along with quality ITZ characteristics brought by the C&D waste's pozzolanic activity, which was supported by the microstructural observations [17],[109].

6. Environmental and Practical Implications

According to the sustainability targets, the present investigation underpins the possibility of manufacturing geopolymer composites with negligible ecological footprint. The present research releasing a possible route to carbon-less, resource-efficient construction practices has incorporated waste materials (WFS and C&D) to the extent of 70% in the binder formulation without compromising the properties of the material concerning strength or durability. [80],[110].

In addition, the method employed here makes a major step forward compared to existing literature, which either concentrates on one waste type only (WFS or recycled aggregate, for instance) or restricts its application to less than 25% in order not to impair performance. The new combination technique, which is presented here, not only decreases the amount of waste sent to landfill but also provides an alternative that is on par with the performance of OPC-based systems, thus supporting the circular economy concept [111]–[113]. The comparative evaluation reveals that the novel mix design of performance-optimized WFS and C&D waste incorporation, which is the current study's mark, results in superior or equivalent performance to that in the existing literature. High compressive strength, low water absorption, and better impact/abrasion resistance are the qualities that confirm the proper use of industrial and demo waste in geopolymer matrices when planned scientifically. The results not only give scientific progress but also facilitate the implementation of eco-friendly construction practices through the acceptance of such practices [17],[114], [115].

7. Technical Interpretation and Process Insights

The composition and morphology of the mix components had a major influence on the geopolymerization process. WFS, which is mostly inert, played a small role in geopolymer formation by acting as a filler. However, C&D waste, mainly its fine, silica-rich fraction, had a great impact on the reactivity by increasing it [116],[117]. Dissolution of aluminosilicates from fly ash and C&D waste was made easier through alkaline activator which also made the binding N-A-S-H gels formation possible. 60°C curing for 24 hours optimal was an effective way to speed up the gel formation process. Nonetheless, too much C&D content caused too much water to be needed and poor workability which affected the continuity of gel formation [118], [119]. The selected water-to-binder ratio of 0.40 tested in preliminary trials provided sufficient workability while maintaining structural strength. The mix maintained its environmental friendliness because we did not add any extra admixtures. Future studies may explore the use of plasticizers or nano-additives to mitigate the limitations observed in M4 and M5 [120], [121].

8. Future Research Directions

The study needs future research directions which address its existing limitations to build stronger research findings. The study requires these research directions because they help scientists understand geopolymer composites and enable their use in construction projects [122]–[124].

- Future research needs to conduct comprehensive microstructural investigations through scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) and FTIR and XRD and nuclear magnetic resonance (NMR) to investigate reaction product formation and pore network development and composite phase distribution [125]–[127].
- Further experiments need to conduct systematic durability tests, which require artificial environmental conditions that include sulfate and chloride solution immersion tests and accelerated carbonation tests and thermal cycling tests and UV radiation tests and freeze-thaw conditioning tests and additional tests. The field testing of structural components which use optimized mixes such as M3 will validate laboratory results through their performance under actual environmental conditions and loading scenarios [128], [129].
- Use of advanced statistical and computational modeling techniques such as response surface methodology (RSM), artificial neural networks (ANNs), genetic algorithms (GAs) can be powerful tools in optimizing mix proportions to the maximum extent. Simultaneous optimization of mechanical, durability, and environmental performance parameters would be made possible through these tools [130], [131].
- Exploring the combination of reinforcing fibers (e.g., polypropylene, basalt, or recycled PET fibers) and functional nano-additives (e.g., nano-silica, graphene oxide) may lead to the further improvement of fracture toughness, flexural performance, and crack resistance. Such changes could be of great importance in terms of dynamic or impact loading applications for structures [132], [133].
- The proposed composites need to undergo life cycle assessment (LCA) and cost-benefit analysis in order to completely evaluate their environmental impact and economic practicality. This kind of information is very important for the adoption of new materials in the industry and for setting up the sustainability-oriented building codes in which the use of such materials is allowed or even recommended.[134]–[136].

9. Conclusion

The present study successfully demonstrated the feasibility of developing high-performance geopolymer composites by co-utilizing fly ash, waste foundry sand (WFS), and construction and demolition (C&D) waste. A comprehensive series of mechanical and durability tests confirmed the effectiveness of this ternary blend in achieving superior performance compared to existing waste-based geopolymer systems.

1. Out of all the formulations that were investigated, Mix M3 (30% fly ash, 40% WFS, 30% C&D waste) turned out to be the most efficient in terms of mechanics, getting a compressive strength of 38 MPa, resistance to impact of 15%, and abrasion loss of merely 16%.
2. The mixing of silica-rich WFS and calcium-aluminosilicate-rich C&D waste resulted in a complementary mixture enhancing geopolymerization efficiency and densifying the matrix through the formation of both N-A-S-H and C-A-S-H gels.
3. With the increase of C&D content in the mixes, there was a remarkable decrease in water absorption and an increase in the resistance to abrasion, which were interpreted as a lower degree of interconnected porosity and a more refined pore structure.
4. The effective use of as much as 70% of waste materials (WFS and C&D waste) showcases the possibility of this method to reduce the environmental impact of both the industrial and construction sectors, at the same time, supporting the concept of the circular economy.
5. The compressive strength, water absorption, and surface wear resistance of the present study's formulations were either superior to or equivalent to those of the literature benchmarks, thus confirming the technical and functional excellence of the proposed system.

The research acts as a connector between two extreme ends of knowledge by investigating the use of two less known industrial wastes together in a geopolymer matrix and thus helping to develop more eco-friendly, strong, and structurally competent construction materials. The results not only provide a basis for the use of fly ash based geopolymers for structural purposes but also open up new ways of dealing with waste streams that are difficult to manage, coming from different sources. The research has reached an important milestone, yet it requires multiple scientific fields to work together for advanced material testing, practical usage, environmental impact assessment, and cost evaluation. The future developments will enable waste-based geopolymer composites to become essential construction materials that solve worldwide waste management problems, carbon emissions, and sustainable building solutions.

Acknowledgment

The authors thank the Department of Civil Engineering, PSG Sons' and Charities for their support.

Funding Information

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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