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Finite Element Simulation of Multi-Storey Structures Reinforced with Sustainable Construction Materials

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Abstract*—*The construction industry's environmental impact necessitates incorporating sustainable construction materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), and recycled concrete aggregate (RCA) in multi-storey structures. This study measured the structural capacity of a ten-level building using FA, GGBS, and RCA according to National Structural Code of the Philippines (NSCP) loading conditions. The finite element analysis in Staad.Pro showed that GGBS concrete achieved the lowest displacement (0.068372 m) and the highest overall stiffness among the three sustainable mixes. While RCA, also performed comparably, it exhibited the highest lateral drift and the lowest natural frequency (0.617 hz), indicating potential limitations in high seismic areas in the Philippines. Overall, all models satisfied NSCP serviceability limits, demonstrating the structural viability of the reinforced eco-friendly concrete for further use in Philippine construction.

Keywords*—*Fly ash, ground granulated blast slug, recycled concrete aggregate, construction materials, STAAD, eco-friendly concrete, sustainable construction.

I. INTRODUCTION

One of the major contributors to the global environmental crisis is the construction industry, which is heavily reliant on concrete for construction of buildings and infrastructure [1]. Increasing rapid urban population growth and rapid development have compounded the already vast amounts of construction material being consumed and, as such, caused a significant increase in the depletion of natural resources, energy usage, carbon dioxide emissions, and the production of solid waste [2][3][4]. All of the above are largely the result of the extraction of raw materials, the manufacture of cement and the transportation and use of construction products, all of which negatively impact ecosystems and contribute to greenhouse gas emissions. Therefore, there is a growing need to implement practices and materials which are more sustainable and to make these methodologies standard practice, especially in developing countries, such as the Philippines, where the rapid urbanization of the population has increased the need for both commercial and residential construction [4][5][6][7].

In response to these challenges, eco-friendly and sustainable construction materials are gaining attention for their potential to reduce environmental impacts while enhancing the energy efficiency and long-term sustainability of buildings and infrastructure [8], [9]. Incorporating industrial and construction waste materials into concrete production is one of the promising strategy which addresses solid waste management concerns while reducing reliance on natural resources, an especially advantageous option for developing economies [2], [10]. Concrete, a composite material composed of cement, aggregates, water, and admixtures, is the second most utilized construction material worldwide after water [2]; however, its production contributes significantly to global carbon emissions, mainly due to Portland cement manufacturing [11]. In order to mitigate these impacts, supplementary cementitious materials like fly ash (FA), ground granulated blast furnace slag (GGBS), and recycled concrete aggregates (RCA) have been increasingly incorporated into concrete mixes [2].

Fly ash is a waste product produced from burning coal in power plants. It has pozzolanic properties that enhance concrete strength and durability through secondary cementitious reactions, while also improving workability, reducing permeability, and increasing resistance to sulfate attack and as well as alkali–silica reaction [12], [13]. Similarly, GGBS, a by-product of ironmaking process, enhance workability, chemical resistance, and long-term durability when used as a partial replacement for Portland cement [14]. Recycled concrete aggregates, from crushed construction and demolition waste, also provide a sustainable alternative to natural aggregates by promoting waste reduction and preserving non-renewable resources [11], [15]. Previous studies have investigated the mechanical properties of concrete incorporating FA, GGBS, and RCA at various replacement levels [16], [17], with fly ash typically used at 15%–30% (and up to 50% in some cases) [18], [19], [20], [21], GGBS at 20%–50% [22], [23], and RCA at 30%–50% replacement of natural aggregates by weight [24], [25].

Current literature on this topic does not provide enough information regarding how these sustainable materials perform structurally, although it does provide good information about the material strength and durability of these materials. Research comparing reinforced concrete (RC) buildings made using Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Recycled Concrete Aggregate (RCA), subjected to simultaneous wind and seismic loads within a context based on the culture, geography, and economy of the Philippines, is extremely limited. The literature also does not provide enough information regarding how the dynamic performance of these materials compares in terms of stiffness, deformation, and stress distribution under NSCP loads. While current literature explores material strength and durability, there is a lack of integrated structural-level evaluation of sustainable concrete materials under combined seismic and wind loads using NSCP-based finite element modelling, which makes the construction industry in the Philippines continues to be sceptical about the reliability and safety of using recycled and waste materials in structural applications [12]. FEA is a method of conducting research that can address this gap in knowledge by allowing researchers to replicate the performance of structures subjected to the effects of seismic load and wind loads; however, to date, there have been few studies comparing the dynamic performance of conventional and sustainable concrete systems based on the NSCP using FEA.

The goal of this study is to evaluate the structural behaviour of multi-storey reinforced concrete structures made with eco-friendly materials through a finite element analysis (FEA). It specifically aims to, (1) To model a multi-storey RC structure using FA, GGBS, RCA, and Pure cement concrete; (2) To analyze structural responses, including node displacement, internal forces, inter-storey drift and natural frequencies; and (3) To compare the performance of these sustainable materials against traditional pure cement concrete structures.

The novelty of this study lies in the direct comparison of serviceability, and dynamic response characteristics of these sustainable materials within the same geometry and loading conditions in accordance with the National Structural Code of the Philippines (NSCP). By combining the two types of loading, seismic and wind, this study provides new insights into the relative stiffness, deformation behaviour, and natural frequency response of sustainable concrete systems, offering a practical performance-based application for their adoption in multi-storey buildings.

This research is purely simulation-based, employing three-dimensional beam-frame line elements in STAAD.Pro software. Consequently, detailed finite element analysis involving solid or shell elements with mesh discretization is beyond the scope of this research, and local stress concentrations effects cannot be captured. Due to the unavailability of laboratory setups, no physical testing or experimental validation will occur. No surveys or human respondents were involved in this technical evaluation.

II. MATERIALS AND METHODS

A. Conceptual Framework

Figure 1 shows the Input-Process-Output conceptual framework of the study. The Input consists of secondary mechanical properties data gathered from peer-reviewed literature. The Process involves finite element modelling and analysis in Staad.Pro, and the Output provides a comparative performance evaluation of sustainable materials versus traditional concrete.

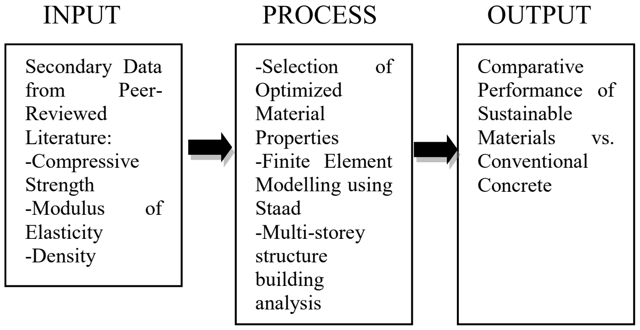

Fig. 1. Conceptual Framework of the Study

B. Secondary Data Selection Procedure

In this study, secondary data on the mechanical properties of concrete incorporating FA, GGBS, and RCA were obtained from peer-reviewed published literature. The dataset includes 28-day compressive strength, modulus of elasticity, density and the corresponding mix designs or replacement ratios. The use of secondary experimental data is appropriate because the primary objective is a comparative structural evaluation of reinforced concrete systems through finite element analysis and not material development or experimental validation.

Material properties were selected based on the optimized compressive strength reported in each source. The data were first grouped by mix design or replacement percentage, and the most commonly used optimized replacement levels were identified. From these mixes, only those with compressive strength falling within the 28-40 MPa range were retained; which is a common strength class for multi-storey residential and office buildings, values outside this interval were excluded. And from the remaining data, the most conservative (lowest) value was selected as final input for the finite element simulation models. This conservative approach ensures simulation results are within safety margin, meaning if the structure performs well with a weaker material it will certainly perform well with the stronger ones.

C. Finite Element Modelling

Structural analysis was carried out using finite element modelling, and was performed on STAAD.Pro License of University Mindanao (UM), a very popular software suite utilized for simulating the response of materials under load.

For the ten-storey RC structure, the geometric dimensions and configuration typically used for these types of buildings were based on the requirements set forth in the National Structural Code of the Philippines (NSCP – Section 418) and standard practice within the Philippine engineering community.

1) *Element Type:* The structure was modelled as a three-dimensional beam-column line elements (two-node frame elements, six degress of freedom per node) which is the only structural element available of the software. Columns (700 x 700 mm) and beams (300 x 500 mm) were modelled as prismatic frame members. Floor slabs (150 mm) were not discretized as plate/shell elements; instead, their self-weight abd the 1.9 kPa live load were converted to member loads on the supporting beams using tributary-area load distribution.
2) *Boundary Conditions:* Fixed supports were applied at the base of every column, restraining all three translational and three rotational degrees of freedom. This is the standard assumption for a preliminary structural comparison where soil-structure interaction is not the focus of the study.
3) *Material Input Procedure:* Four isotropic material definitions (FA, GGBS, RCA, and Pure Cement) were created in the Staad material library, each assigned its own modulus of elasticity and density, with Poisson's ratio held at 0.20 for all four. Then, each material was assigned uniformly to every beam and column in its respective model, and the four cases were run as separate with identical load cases and geometries.

4) *Meshing Assumptions:* Since the model uses line frame elements rather than solid elements, discretization corresponds to member subdivision rather than surface meshing: a node is defined at every beam-column intersection on each of the ten floors, which is the natural and sufficient level of subdivision for linear frame analysis. No further sub-meshing was required, since Staad solves the exact stiffness formulation for prismatic beam elements between nodes rather than an approximate discretized field.
5) *Convergence and Validation Approach:* The analysis uses linear frame elements with a closed-form stiffness matrix, the solution is exact for the given geometry and boundary conditions once the load cases and material properties are defined. Numerical stability was verified through the static equilibrium check, where the applied loads and support reactions were confirmed to balance exactly, with zero net force and moment, for all four material cases.

D. Simulation and Analysis

Four separate simulation cases was performed under identical structural geometry and boundary conditions to perform a direct performance comparison:
Case 1: Structural model for the concrete containing optimized FA
Case 2: Structural model for the concrete containing optimized GGBS
Case 3: Structural model for the concrete containing optimized RCA
Case 4: Control model with typical Pure cement concrete

The key metrics generated and analyzed were the following: 1) load distributions of maximum support reaction and maximum beam end force to evaluate the overall structural safety, 2) displacement – including total deformation and inter-storey drift to assess overall stiffness and lateral stability, 3) dynamic response – natural frequency characteristics to assess the structure's vulnerability to seismic and wind excitation.

III. Results And Discussions

A. Objective 1: Modelling of Ten-Story RC Structure

1) *Material Input:* The study successfully modelled four distinct structural cases by defining their unique mechanical properties in Staad Pro. The model utilized optimized replacement levels identified from peer-reviewed literature: 30% for FA, 30% for GGBS, and 25% for RCA.

The optimized material properties in Table I have been used to define the four material types (FA, GGBS, RCA, and Pure Cement) within the Staad material library. Reinforced concrete behavior was simulated using the software's capabilities by modifying composite element properties to ensure appropriate simulation accuracy.

TABLE I. CONCRETE PHYSICAL PROPERTIES

Material	Properties			
	Compressive Strength (Mpa)	Modulus of Elasticity (Gpa)	Density (kg/m^3)	References
FA Concrete	30.33	25.88	2332	[26]
GGBS Concrete	32.44	26.75	2360	[27]
RCA Concrete	28.58	25.13	2417	[28]
Pure Cement Concrete	35.00	27.81	2400	[29]

2) *Structure Geometry:* Figure 2 shows a typical 3D rendering of the ten-storey structure as built in Staad.pro, including its columns, beams, and floor framing.

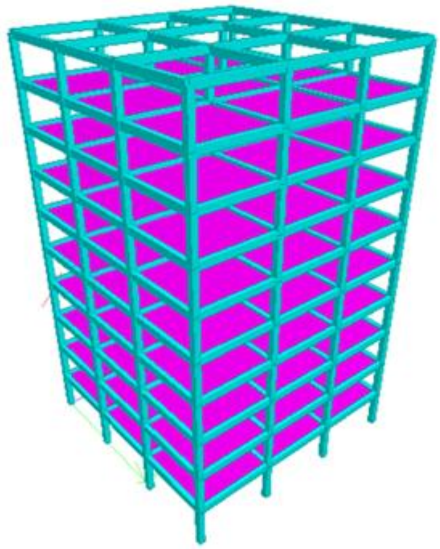

Fig. 2. Typical RC Structure 3D Model

3) *Applied Loads:* The structural parameters for the applied loads in Table II were established based with the latest National Structural Code of the Philippines (NSCP 2015) to ensure local environmental relevance. The Dead Loads (DL) were calculated by combining the software-generated self-weight of the structural elements – using the specific material densities in Table I for FA, GGBS, and RCA, with a superimposed non-structural load of 2.4 kPa as per NSCP Section 204.

TABLE II. APPLIED LOADS

Load Type	Description	
	Applied value/ Parameter	NSCP Basis
Dead Loads (DL)	Self-weight (using densities from Table 1) + 2.4 Kpa for non-structural load	NSCP provisions for typical construction elements Section 204
Live Loads (LL)	1.9 kPa (Uniformly Distributed Load)	NSCP minimum for residential occupancy Section 205
Wind Loads (WL)	Basic Wind Speed of 250 kph	NSCP Section 207 (High Wind Zone)
Seismic Loads (EQ)	Zone 4 Importance Factor (I) = 1 R = 8.5	NSCP Section 208
Loads Combinations	1.2DL+0.5WL, 1.2DL+0.5LL+WL, 0.9DL+WL, 0.9DL+EQ, 1.4DL, 1.2DL+1.6LL, 1.2DL+0.5LL, 1.2DL+0.5WL, 1.68DL+0.5LL+EQ, 1.38DL+EQ, 0.42DL+EQ	NSCP Section 203

Live Loads (LL) were set at a uniform of 1.9 kPa, which represents the minimum requirement for residential occupancy under Section 205. Wind Loads (WL) were modelled based on a basic wind speed of 250 kph, identifying the structure within a High Wind Zone as defined by Section 207. Seismic Loads (EQ) were

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determined using the Static Equivalent Force Procedure for Zone 4, following the seismic provisions of Section 208. Finally, these primary loads were integrated into various Load Combinations following the strength design requirements of NSCP Section 203 to simulate the most critical structural demands.

4) *Model Verification (Static Equilibrium Check):* A static equilibrium check confirms that the appliled loads and support reactions balance for each model, which is the basic requirement for a numerically sound structural model. Table III demonstrate that all four cases satisfy force and moment equilibrium exactly, with a difference value of zero between applied load and reaction in every case.

Although equilibrium holds for all models, the magnitude of the applied loads differs slightly by material. FA concrete produced the lowest load values, since it has the lowest density among the four materials – about 2332 kg/m^3 versus 2400 – 2417 kg/m^3 for the others – which slightly reduces the total dead load carried by the structure. Pure cement concrete carried the highest applied loads, with RCA close behind; this tracks directly with density, since RCA and Pure cement are the two heaviest mixes. This pattern lines up with the broader relationship between material density and permanent load in reinforced concrete construction: heavier mixes carry a proportionally larger self-weight share of the total demand, a link documented by Sun et al. [31] in their analysis of permanent-to-variable load ratios across reinforced concrete buildings.

Despite these differences, the equilibrium results confirm that all structural models were correctly defined and numerically stable, ensuring the reliability of the subsequent displacement and force analyses.

TABLE III. COMPARISON OF TOTAL APPLIED LOADS

Material	**Load Case**	**Applied Loads**		
		Fx (kN)	My (kN-m)	Mz (kN-m)
FA Concrete	Load Reactions	812.713 -812.713	7948.57 -7948.57	-17374.3 17374.3
GGBS Concrete	Load Reactions	817.504 -817.504	7995.97 -7995.97	-17475.65 17475.65
RCA Concrete	Load Reactions	827.255 -827.255	8092.47 -8092.47	-17681.91 17681.91
Pure Cement	Load Reactions	891.724 891.724	8747.41 -8741.41	-19080.59 19080.59

B. *Objective 2: Structural Response Analysis*

1) *Support Reactions:* Represent the forces and moments transferred from the structure to the supports. Differences in reaction forces reflect how each material affects the stiffness and load distribution within the structural system.

Figure 3 shows one reaction component dominating across all four mixes which is consistent with gravity dead and live loads governing the vertical reactions of a ten-storey frame. The two smaller reaction components, both around 126 kN, are nearly identical to each other for every material because of the structure's plan symmetry, and are consistent in magnitude with the combined lateral wind and seismic effects. FA produced the lowest value of the dominant reaction, at 2506.97, about 1.24% below RCA's 2538.08 kN – the highest of the four – pointing to FA's comparatively lower stiffness and lighter self-weight relative to the other mixes [12],[13]. RCA and Pure cement produced the two largest values of the dominant reaction, which tracks with their higher densities among the four materials. RCA also recorded the highest of the smaller lateral-type reactions, at 126.67 kN – only about 0.08% above pure cement's 126.62 kN and 0.09% above FA's 126.57 kN, differences small enough to be practically negligible, though the ranking is consistent with RCA carrying the greatest lateral demand of the four. This mass-driven pattern in the support reactions mirrors the mass-dependent formulation of seismic demand described by Dominguez et al. [32], who found that reducing a reinforced concrete frame's structural weight directly lowered the forces the structure had to resist.

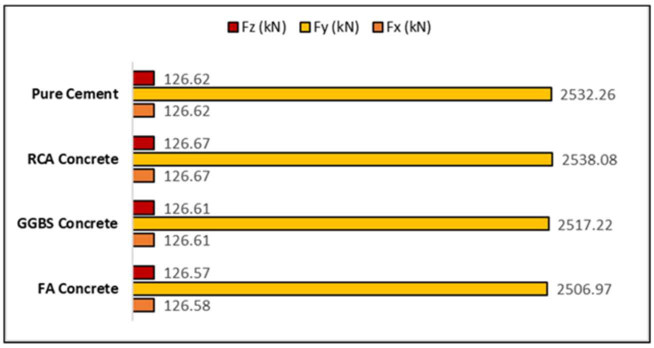


Fig. 3. Force Reaction Comparison

As shown in Figure 4 is the maximum moments reaction at support, Mx and Mz are nearly similar across materials which are located in the outer supports of the structure, while My is zero value for all cases, which further supports the perfect symmetry of the model and the absence of net torsion under the applied loading. Pure Cement produced the highest bending moment values at 445.99 kN-m. GGBS, Fly Ash and RCA recorded nearly the same moment reactions, indicating slightly lower rotational demand at the supports. Overall, the results indicate that Pure Cement and RCA exhibit largest load transfer to the supports, while Fly Ash shows slightly lower reaction forces due to its lower stiffness characteristics. For seismic-mass-sensitive designs, FA's lower self-weight is an explicit structural advantage, independent of it slightly lower stiffness.

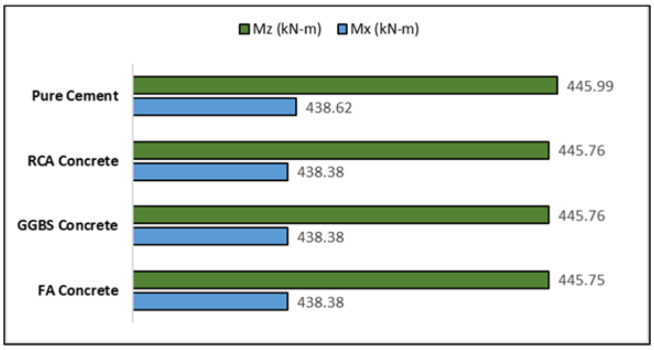


Fig. 4. Moment Reaction Comparison

2) *Node Displacement:* The maximum displacement in every case occurred at the top corner joints of the structure

which is expected location for a laterally loaded frame. Figure 5 shows a clear separation in stiffness between the four materials. GGBS produced the smallest maximum displacement, 0.068372 m, while RCA produced the largest, 0.072780 m – a difference of 6.45% between the two. That gap lines up well with what has been reported by Fan et al. [28] that recycled aggregates tend to have reduced stiffness and more variable quality compared with natural aggregate, and Yang et al. [30], that modelling a recycled-aggregate-concrete-filled steel tube frame under seismic loading, found that raising the RCA replacement ratio measurably reduced structural stiffness and increased lateral displacement, the same softening pattern seen here even though the structural system is different. On the other side, GGBS's superior performance is consistent with Cahyani and Rusdianto [23], who found that slag-based concrete offers enhanced long-term durability and mechanical stability.

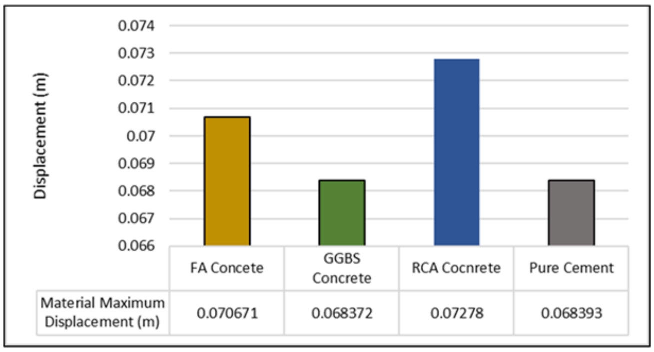


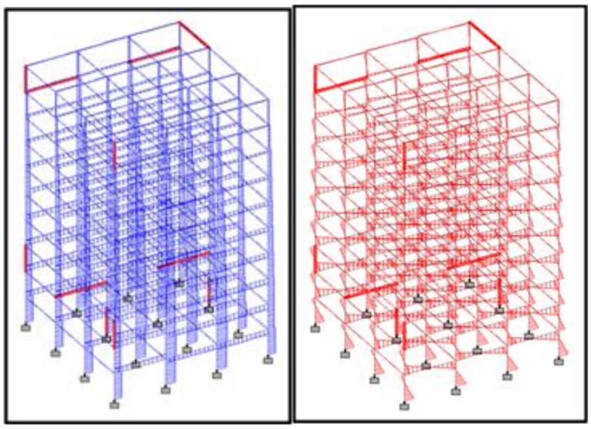
Fig. 5. Maximum Displacement Comparison

FA came in at 0.070671 m – about 3.4% higher than GGBS but 2.9% lower than RCA – putting it in a middle position: moderately stiff, but with slightly more deformation than GGBS. Pure cement, despite attracting the largest seismic forces of the four cases, recorded 0.068393 m, essentially tied with GGBS (0.03% apart) and clearly better than both FA and RCA. Attracting more seismic force does not automatically translate into more displacement, because displacement also depends on how that force is resisted by the frame's stiffness.

Overall, the displacement results place GGBS as the best-performing material for deformation control with RCA producing the largest structural movements of the four under combined seismic loading. For lateral-deflection-governed designs, GGBS replacement is effectively a drop-in stiffness-equivalent substitute for pure cement, while RCA should be assumed to need supplementary lateral stiffening if used above low-rise heights.

3) *Internal Forces:* Figure 6 represent the typical shear and moment diagrams from Staad.Pro at the beam locations that recorded the highest internal forces – the same locations across all four cases. Bending moments, shear forces, and axial forces that arise as a result of applied loads are among these factors.

Table IV shows that the largest axial beam force (Fx) was recorded in the RCA model at 2538.08 kN, about 1.24% above FA's 2506.97 kN – the lowest of the four – and closely followed by pure cement at 2532.26 kN. RCA also produced the highest shear forces of the four materials, while Pure cement carried the highest bending moment, 445.991 kN-m, indicating the highest bending demand among the cases.



a) *b)*

Fig. 6. Typical Beam End Force Staad Diagram, a.) Shear Diagram, b.) Moment Diagram

Fly ash consistently produced the lowest internal force values, followed by GGBS, which suggests that the FA structure distributes load slightly more evenly and develops lower force concentrations at the beam ends. FA tends to have lower internal stress demand, whereas RCA and Pure cement tend to develop higher internal beam forces when combined. This is the same mass-dependent mechanism already noted for the global support reactions [32]: a lighter mix transmits proportionally smaller forces through every part of the load path, from the foundation up to the individual beam ends.

The pattern mirrors the density-driven trend from support reactions results, since beam end force under gravity-dominant load combinations scales with self-weight; the seismic contributions adds a secondary stiffness-driven component consistent with GGBS and Pure Cement's higher elastic modulus. Because Pure cement attracts the highest bending demand while GGBS achieves nearly the same stiffness at a lower moment demand (445.755 vs 445.991 kN-m) and lower seismic mass, GGBS beams can be expected to require comparable reinforcement relative to Pure cement.

TABLE IV. BEAM END FORCE COMPARISON

Material	Maximum Beam End Force				
	Fx (kN)	Fy (kN)	Fz (kN)	My (kN-m)	Mz (kN-m)
FA Concrete	2506.97	115.322	116.424	445.754	445.754
GGBS Concrete	2517.22	115.324	116.426	445.755	445.755
RCA Concrete	2538.08	115.329	116.430	445.757	445.757
Pure Cement	2532.26	115.259	116.363	445.991	445.991

4) *Dynamic Response Characteristics:* Modal analysis was used to obtain the natural frequencies and dynamic response characteristics of the structure. Figure 7 compares the first three natural frquencies across all four models. Results revealed that modes 1 and 2 are nearly identical for each material, confirming the building's symmetry in plan. Mode 3 are frequencies that are higher, indicating a torsional or

vertical mode. The Pure Cement model had the highest young's modulus, and thus, also exhibited a corresponding highest fundamental frequency of 0.649 Hz. GGBS followed closely at 0.640 Hz – only about 1.39% below Pure Cement – even though the seismic mass and elastic modulus assumed in the model would suggest a noticeably higher spectral accelaration for pure cement. In effect, GGBS achieves nearly the same stiffness as Pure cement while carrying a more favorable modulus-to-weight ratio: its density (2360 kg/m3) sits between FA and RCA, but its modulus of elasticity (26.75 GPa) is the highest of the three sustainable mixes, giving it the best stiffness-to-mass balance of the group.

RCA, by contrast, had the lowest fundamental frequency of the four at 0.617 Hz – about 4.9% below pure cement and 3.6% below GGBS – making it the most dynamically flexible model in the study. This result is consistent with the broader literature on recycled-aggregate structures by Yang et al. [30] reported that increasing the recycled-aggregate replacement ratio in a composite steel-concrete frame reduced the structure's natural grequency by roughly 2% to 5% under seismic loading depending on the replacement level.

In Philippines Seismic Zone 4, a lower fundamental frequency generally means a longer natural period, which shifts the structure's spectral acceleration demand and can increase displacement demand under a design spectrum RCA's combination of reduced stiffness and increased density is therefore the least favorable combination for seismic-force-controlled design among the three sustainable mixes.

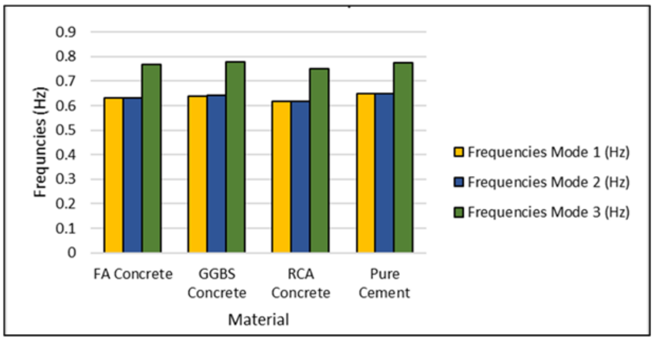


Fig. 7. Natural Frequecy Comparison

5) *Inter-Storey Drift:* Drift ratios (drift/storey height) as presented in Figure 8 were calculated by subtracting lateral displacement between adjacent floors. All four models maintained ratios significantly below the NSCP serviceability limit of 0.0042 and the strength limit of 0.020. GGBS's drift ratio (0.003378) was only about 3.4% above pure cement's (0.003268), confirming its high lateral rigidity – a result consistent with the literature suggesting that supplementary cementitious materials can maintain structural serviceablity effectively when optimized at replacement levels around 30% [25]. RCA recorded the highest drift of the four at 0.003597 – about 10.1% above Pure cement and 6.5% above GGBS – consistent with the reduced stiffness already identified for RCA in this study's displacement and dynamic response results [7], [28] – while FA sat in between at 0.003497, about 7.0% above pure cement.

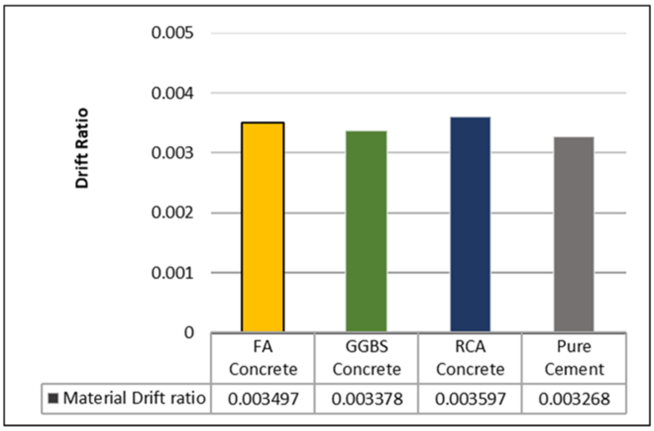


Fig. 8. Maximum Storey-Drift Ratio Comparison

C. Objective 3: Comparative Performance Evaluation

1) *Overall Comparison:* In summary, Pure Cement concrete is the stiffest and produces the lowest drifts, but attracts the highest seismic base shear and overturning moments – mirroring the mass-dependent seismic demand as discussed for the support reactions [32]. This would translate into larger foundation sizes, heavier lateral-force-resisting elements, and higher construction costs, with no meaningful improvement in displacement control over GGBS concrete.

GGBS concrete (Case 2) was determined to be the best performing due to superior serviceability results overall. It exhibits the smallest maximum displacement (0.068372m), drift ratio only marginally higher than Pure Cement, and a natural frequency very close to that of Pure Cement. Critically, its seismic base shear is on par with the lightweight FA and RCA concrete, not with pure cement. This combination of high stiffness and low seismic demand makes GGBS the most structurally efficient and economical choice. Research by Ahmad et.al [3] and Al-Mansour et.al [14] supports this by characterizing GGBS as a high-performance cement replacement that benefits from secondary cementitious reactions which enhance long-term strength beyond that of standard FA mixes.

FA concrete provides a middle-ground performance: lower self-weight and lower seismic force generation – the same mass-dependent relationship noted for the static loads and support reactions above [31], [32] – but moderately higher displacement and drift than GGBS. It remains a viable sustainable alternative, particularly if absolute drift limits are not critical.

RCA met all NSCP serviceability requirements, but it also produced the largest displacement, the largest lateral drift, and the lowest natural frequency of the four. Designs that lean on RCA may therefore need additional lateral stiffness – beyond what FA or GGBS would require – to meet mode demanding dynamic performance targets, and its flexibility could create serviceability concerns in the Philippines' high-seismic regions. This is consistent with published structural-engineering guidance recommending limited RCA replacement ratios or supplementary lateral detailing for primary structural elements in taller, higher-seismicity buildings [33].

2) *Parameter Sensitivity:* The four material cases in this study effectively double as a small parametric comparison, since they isolate the effect of density, modulus of elasticity, and compressive strength while holding geometry and loading constant.

Modulus of elasticity has the most direct relationship with displacement and drift: a stiffer material (higher E) generally deforms less under the same load. That is why RCA, with the lowest modulus of the four (25.13 GPa), produced the largest displacement and drift, and why pure cement, with the highest modulus (27.81 GPa), produced the lowest drift.

Density, however, works against modulus in the seismic load case, because higher density means more seismic mass, and seismic force scales with mass. This is the mechanism behind GGBS's strong overall performance: at 2,360 kg/m³, its density sits well below pure cement's (2,400 kg/m³) and even below RCA's (2,417 kg/m³), while its modulus of elasticity (26.75 GPa) is close to pure cement's. The result is that natural frequency, which scales roughly with the square root of stiffness over mass, favors GGBS more than a simple comparison of modulus values alone would suggest — GGBS gets nearly pure-cement stiffness without carrying pure-cement mass.

RCA sits at the opposite end of this trade-off: it combines the lowest modulus of elasticity (25.13 GPa) with the highest density (2,417 kg/m³) of the four materials — a reduction consistent with published findings on the characteristically lower elastic modulus of recycled aggregate concrete relative to natural-aggregate concrete of comparable strength [34], which is the least favorable stiffness-to-mass combination in the study and explains why it consistently ranks lowest across displacement, drift, and natural frequency.

Compressive strength, meanwhile, tracks less tightly with the serviceability results than modulus and density do, largely because the models stay within the linear-elastic range under NSCP loading, where stiffness governs deformation rather than ultimate strength. RCA's 28.58 MPa is the lowest compressive strength of the four, and it still comfortably met the NSCP strength limit of 0.020 for drift — its serviceability limitations show up in displacement and drift, well before strength becomes a controlling factor.

Table V shows the performance ranking of each material. The ranking is based purely on the three stiffness/ serviceability indicators and does not account for seismic base shear or foundation cost which is why pure cement ranks best even though GGBS identifies as the more structurally efficient overall choice once seismic demand and cost are factored in.

TABLE V. PERFORMANCE RANKING

Indicator	Material			
	FA	**GGBS**	**RCA**	**Pure Cement**
Maximum displacement	0.070671 (3rd)	0.068372 (1st)	0.072780 (4th)	0.068393 (2nd)
Inter-storey drift ratio	0.003497 (3rd)	0.003378 (2nd)	0.003597 (4th)	0.003268 (1st)
Fundamental frequency	0.632 (3rd)	0.640 (2nd)	0.617 (4th)	0.649 (1st)
Rank	3rd Place	2nd Place	4th Place	1st Place

3) *Engineering Implications of Sustainable Concrete Adoption in the Philippines:* All four material cases satisfied both the NSCP 2015 serviceability drift limit (0.0042) and strength limit (0.020). GGBS offers the widest safety margin among the sustainable mixes because it combines high stiffness with comparatively low seismic mass; RCA, while still code-compliant here, carries the least margin of the four and would benefit from added lateral stiffening in any Zone 4 design. This precaution is consistent with published structural-engineering guidance on RCA's seismic applications, which recommends limited replacement ratios or supplementary detailing for primary lateral-force-resisting elements under higher seismic demand [33]. Pure cement's higher stiffness comes at a price, attracting the highest seismic base shear and overturning moment generally means larger foundations and heavier lateral-force-resisting elements, which raises construction cost. GGBS and FA reduce seismic mass relative to pure cement, which can translate into smaller foundations and lighter lateral systems – a real cost advantage on top of their sustainability benefit. This trade-off between member size, reinforcement demand, and overall cost has been documented in published cost-and-encvironmental-impact optimization studies of reinforced concrete structural design [1], [25]. RCA's raw material cost is typically the lowest of the three sustainable options, since it reuses demolition waste, but any additional reinforcement needed to offset its lower stiffness in seismic zones would need to be weighed against that saving on a project-by-project basis.

FA, GGBS, and RCA all reduce reliance on virgin raw material and Pure cement content, which lowers the embodied carbon of the structure and supports a more circular use of industrial and demolition waste in the Philippine construction sector.

Based on these results, GGBS is well suited to mid-rise and high-rise residential and commercial buildings in Zone 4, where both high lateral rigidity and low seismic demand matter. FA is a reasonable choice where reducing structural weight and internal force demand is the priority and where drift control is not the governing constraint. RCA is best suited to lower rise construction, or to elements outside the primary lateral-force-resisting system, unless it is paired with additional reinforcement or stiffening measures adequate for high-seismic conditions, an approach consistent with published guidance on matching recycled-aggregate-concrete use to building height and seismic exposure [33].

IV. Conclusions and Future Works

This study set out to do three things: model a ten-storey reinforced concrete building using FA, GGBS, RCA, and Pure cement concrete; analyze displacement, internal forces, drift, and natural frequency across the four cases; and compare the structural performance of the three sustainable materials against the conventional concrete control. The findings against each objective are summarized below.

A ten-storey reinforced reinforced concrete building was successfully modelled in STAAD.Pro under NSCP 2015 loading conditions, using optimized replacement levels of 30%

fly ash, 30% GGBS, and 25% RCA. All four models satisfied static equilibrium exactly, with zero net force and moment imbalance, confirming that the models were correctly defined and numerically stable before any comparative analysis was carried out.

Across the four cases, GGBS produced the lowest maximum displacement (0.068372 m) and the second-lowest drift ratio (0.003378, about 3.4% above pure cement's 0.003268), while its natural frequency (0.640 Hz) sat only 1.4% below pure cement's (0.649 Hz). RCA produced the largest displacement (0.072780 m, 6.45% above GGBS), the largest drift ratio (0.003597, 10.1% above pure cement), and the lowest natural frequency (0.617 Hz, 4.9% below pure cement) of the four materials. FA produced the lowest internal beam forces of the group, indicating the most even load distribution among the four mixes.

GGBS is the most structurally efficient of the three sustainable materials: it delivers stiffness close to pure cement while carrying a seismic demand closer to the lighter FA and RCA mixes, a combination that favors both structural safety and construction economy. RCA, while fully code-compliant here, is the most dynamically flexible material of the four and would need additional lateral stiffening to meet more demanding seismic performance targets under Philippine Zone 4 conditions.

On this basis, GGBS is recommended for multi-storey residential and commercial buildings where high lateral rigidity and tight displacement control are required. Where reducing structural weight and internal force demand is the priority and drift limits are not governing, FA concrete is a reliable substitute. Where RCA is used, especially in Zone 4 designs, it should be paired with refined reinforcement detailing or enhanced lateral-force-resisting elements to meet stricter dynamic performance requirements — or reserved for lower-rise or non-seismic-critical applications.

Because the modelling proved successful under NSCP parameters, standardized local design guidelines for these replacement levels would help the Philippine construction industry adopt eco-friendly alternatives to traditional cement with more confidence.

To bridge the gap between these numerical findings and industry acceptance, future studies should pursue laboratory validation and physical testing of these optimized mixes under actual cyclic and dynamic earthquake loading. A formally designed sensitivity or parametric study — varying modulus of elasticity, density, and compressive strength independently rather than through four fixed material cases. Hybrid sustainable mixes, combining two or more of FA, GGBS, and RCA, are also worth exploring, to see whether they can capture both the environmental benefits and the mechanical efficiency of single-material replacements at once. Finally, extending this comparison to include embodied carbon reduction, life-cycle assessment, and a detailed cost analysis would strengthen the case for GGBS and FA adoption beyond structural performance alone.

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