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DEVELOPMENT AND PERFORMANCE EVALUATION OF SUSTAINABLE CONSTRUCTION MATERIALS FOR GREEN BUILDING APPLICATIONS

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Abstract: The need for sustainability will have to result in the use of eco-efficient materials which can not only provide structural stability but have a non-damaging effect on the environment. This paper reports the development and behavior of sustainable concrete with the use of supplementary cementitious materials (SCM) like fly ash, silica fume and recycled aggregates. Various mix designs were developed to investigate the mechanical and durability properties like compressive, split tensile and flexural strength and water absorption. The laboratory studies also show that the SCMs have a great influence on the strength properties due to the pozzolanic reactions and microstructural development. The optimum mix proportion had attained 46 Mpa of compressive strength after 28 days with good tensile and flexural strength. The water absorption was also reduced by a 30% which is an indicator of strength. The use of recycled aggregates in concrete has only a small effect on the early strength but in combination with SCMs it gives good performance with negligible environmental footprint. The results suggest that sustainable construction materials can be applied to green construction due to its enhanced durability, resource conservation and carbon emission.

Keywords: Sustainable Construction Materials, Green Building, Fly Ash, Silica Fume, Recycled Aggregates, Compressive Strength, Flexural Strength, Tensile Strength, Durability, Eco-Friendly Concrete

I. INTRODUCTION

The construction sector is experiencing rapid expansion, resulting in the over-exploitation of resources and energy consumption, which in turn has considerable environmental impacts. Traditional construction materials, especially Portland cement, are major sources of global carbon dioxide (CO_2) emissions and environmental pollution. Cement manufacturing is estimated to contribute around 7-8% of the world's CO_2 emissions, indicative of the need for a sustainable alternative construction approach.

Recently, green buildings have emerged as a popular approach to achieve environmental sustainability, energy efficiency and conservation of resources. One of the critical components of green building construction is the use of sustainable building materials that minimise environmental footprint while offering equal or improved performance. These materials can contain by-products and recycled materials, thus reducing the wastage of resources and the environmental footprint.

Supplementary cementitious materials (SCMs) such as fly ash and silica fume are among the widely researched and used sustainable materials. Fly ash, a waste product from coal-fired power stations, increases strength and durability over time via pozzolanic activity, whereas the fine silica fume particles increase the density of the microstructure and interfacial bond. Moreover, recycled aggregates from construction and demolition waste offer a way to reduce waste going to landfill and preserve natural resources.

Although sustainable materials have presented positive outcomes, there exist some shortcomings in creating a trade-off between sustainability and mechanical properties. Workability, strength and durability can be affected by the use of recycled aggregates and SCMs. Therefore, thorough research is required to evaluate the characteristics of these materials under different mix designs and conditions.

The study plans to develop and experimentally evaluate sustainable building materials of green building. The key area of interest is the comparison of the mechanical properties (compressive, tensile, flexural strengths) and durability (water absorption, porosity) of these materials. This study contributes to sustainable construction knowledge and enhances the shift towards the sustainable infrastructure through mix design.

II. LITERATURE SURVEY

It is necessary to develop building materials that are eco-friendly due to the environmental impact of the conventional production of concrete. The application of supplementary cementitious materials (SCMs) such as fly ash and silica fume and recycled aggregates has been widely researched to contribute to sustainability and characteristics.

Fly ash is extensively applied SCM since it enhances the long-term strength and durability through pozzolanic reaction. It has been shown that concrete with high levels of fly ash is less permeable and also possesses higher resistance to aggressive environment [1], [2]. Moreover, there is a significant effect of lowering the CO2 emissions of cement manufacture through the use of fly ash [3].

Silica fume is fine in nature and contains a lot of silica content and this has been witnessed to influence the microstructure of concrete. It is capable of enhancing compressive and tensile strength through decreasing pore size, and increasing interfacial transition zone (ITZ) between aggregate and cement paste [4], [5]. However, the incorporation of silica fume may occasionally have an adverse impact on workability that can be countered by incorporation of superplasticizers [6].

Recycled aggregates (RA) are increasingly being considered as an eco-friendly substitute for natural aggregates. Studies have shown recycled aggregate concrete can be satisfactory for structural purposes if the aggregates are well processed and have adequate strength and durability [7], [8]. But, the presence of attached mortar in recycled aggregates can impact strength and water absorption [9].

In recent years, the use of SCMs and recycled aggregates in combination has been explored. The combined use of fly ash and silica fume has been found to enhance strength and durability [10], [11]. Also, the use of SCMs mitigates the strength loss associated with the use of recycled aggregates [12].

Another important aspect of sustainable building materials is durability. Several studies have shown that the incorporation of SCMs helps minimise water absorption, permeability and chloride ingress, thus enhancing the durability of concrete [13]. Sustainable concrete is also more resistant to environmental attacks than traditional concrete [14].

However, this improvement can still be achieved through the development of sustainable concrete with desired mix proportions and optimum properties. Previous research has mostly investigated individual materials, with little research on the effect of fly ash, silica fume, and recycled aggregates in different proportions [15]. Thus, this study seeks to bridge this knowledge gap by creating and testing of sustainable construction materials for green building.

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III. METHODOLOGY

In this research, the approach followed for producing, preparing and testing eco-friendly construction materials using supplementary cementitious materials (SCMs) and recycled aggregates as shown in figure 1. The aim is to evaluate the strength and durability of sustainable concrete mixes in the controlled environment of the laboratory.

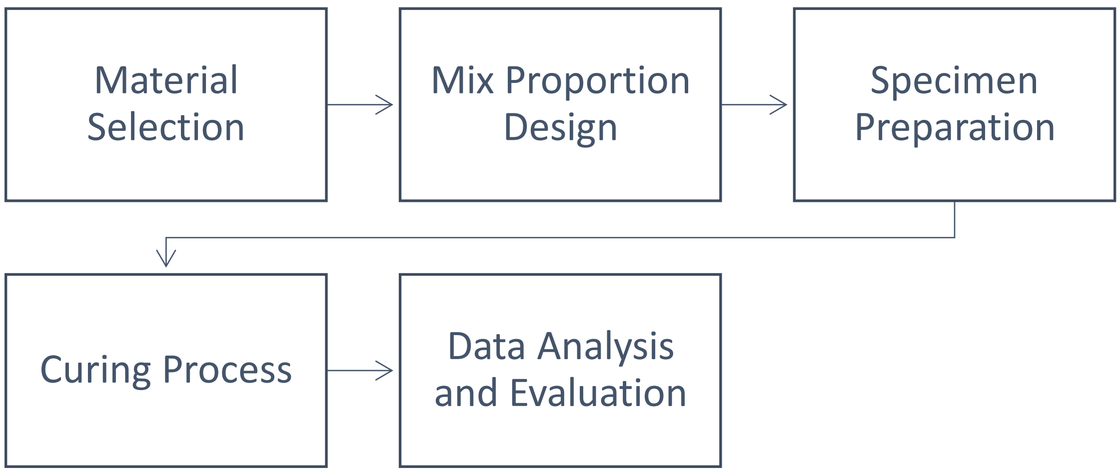

Figure 1: Flow of Work

A. Material Selection

The design of sustainable composites that are to be used in construction takes into consideration material choice that influences structural behaviour, durability and environmental sustainability of the composite. The use of sustainable materials like supplementary cementitious materials (SCMs) and recycled aggregates in the present study was done to achieve the balance between environmental and performance goals where the traditional materials were used.

Ordinary Portland Cement (OPC 53 Grade) was selected as the main binder due to its quality and strength. To reduce the environmental effects of the cement production, however, a portion of the cement was replaced with fly ash and silica fume. The binder may be described as:

$$B = C + FA + SF\text{-----}1$$

B = the binder content of total amount in the cement, C = the cement content, FA = the fly ash content, SF = the silica fume content. Fly ash that is a by-product of thermal power stations was selected due to its pozzolanic characteristics that aid in the formation of delayed strength. The reaction between the pozzolana and hydrated silicate may be expressed as:

$$Ca(OH)_2 + SiO_2 \rightarrow C\text{-}S\text{-}H\text{----}2$$

This process enhances the creation of calcium silicate hydrate (C-S-H) which results in the creation of better strength and reduced permeability.

Silica fume containing a large amount of silica and fine particle size was introduced to enhance the structures of the pores and interfacial transition zone (ITZ) between the aggregates and the cement paste. The increased packing density using silica fume can be visualised as:

$$\rho_{composite} = \frac{M_{total}}{V_{solid}+V_{void}}\text{----}3$$

whereby the increment of solids because of the smaller particles reduces the voids and raises the density and strength. Fine aggregates were made out of river sand which was of good grade to give good workability and mixing. Construction and demolition waste (CDW) was also recycled into aggregates that were used to replace part of coarse aggregates. The ratio of recycled aggregates that are replaced can be determined as:

$$R_{RA} = \frac{W_{RA}}{W_{RA}+W_{NA}} \times 100\text{----}4$$

and WRA, WNA are the weight of recycled aggregates and natural aggregates, respectively. To maintain sustainability, recycling aggregates aids in avoiding landfill and conserves the natural resources. However, the bonded mortar of recycled aggregates causes them to be more water-absorbing to influence the quantity of water required in the mixture.

The mixing and curing water was drinkable and clean to provide hydration of cementious materials. Water to cementitious ratio (w/cm) is a critical element of influence on the strength and durability of concrete, and is computed as:

$$w/cm = \frac{W}{C+FA+SF}\text{-----}5$$

The ratio of w/cm of 0.30 leads to high strength and low porosity, whereas the water content may lead to the weakening of the matrix. The workability was also augmented using a superplasticizer, and no extra water was applied. This assists in spreading of materials and enhancing the consistency of the mix.

B. Mix Proportion Design

The mix proportion design of sustainable construction materials was to create a balance between the strength and durability and to be eco-friendly. The mix design idea was to substitute some of the cement with additional cementitious materials (SCMs) such as fly ash and silica fume, and the utilization of recycled aggregates to save on the natural resources.

The mix binder content will be cement, fly ash and silica fume that can be expressed as:

$$B = C + FA + SF\text{----}6$$

with B being the total binder, C the cement content, FA the fly ash content and SF the silica fume content. The water-to-cementitious ratio (w/cm) is an important factor affecting the strength and durability, calculated as:

$$w/cm = \frac{W}{C+FA+SF}\text{-----}7$$

and W is the weight of water. The smaller the w/cm ratio, the greater the compressive strength and the less the porosity. Aggregates = natural aggregates (NA) + recycled aggregates (RA):

$$A_{total} = NA + RA\text{----}8$$

The percentage replacement of recycled aggregates is calculated as:

$$R_{RA} = \frac{W_{RA}}{W_{RA}+W_{NA}} \times 100\text{-----}9$$

where WRA and WNA are the weights of recycled and natural aggregates, respectively.

Table 1:Three different mixes were designed to evaluate performance:

Mix ID	Cement (%)	Fly Ash (%)	Silica Fume (%)	Recycled Aggregate (%)	w/cm
M1	100	0	0	0	0.45
M2	70	25	5	20	0.40
M3	60	30	10	30	0.38

To maintain workability while keeping a low water content, a superplasticizer was used. The dosage of superplasticizer is generally expressed as:

$$SP(\%) = \frac{W_{sp}}{B} \times 100\text{----}10$$

where Wsp is the weight of superplasticizer and B is the binder content.

The density of the concrete mix is given by:

$$\rho = \frac{M_{total}}{V_{total}}\text{----}11$$

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Porosity, which affects durability, can be expressed as:

$$n = \frac{V_{void}}{V_{total}} \times 100----12$$

Lower porosity leads to improved strength and durability.

C. Specimen Preparation

To obtain uniformity, repeatability and accuracy in determining the mechanical and durability characteristics of sustainable building materials, the preparation of a specimen is a crucial step. In the current study sample, the preparation of specimens was done according to conventional practice, IS 516 and ASTM requirements.

Initially, all the dry materials including cement, fly ash, silica fume, fine and coarse/recycled aggregate were mixed in a mechanical mixer until a uniform mix was achieved. Afterwards, water with the required amount of superplasticizer was poured. The mixture was mixed until a consistent workable mixture was obtained. The mixing proportion can be represented as:

$$M_{total} = C + FA + SF + NA + RA + W + SP----13$$

where C, FA, SF, NA, RA, W and SP are cement, fly ash, silica fume, natural aggregate, recycled aggregate, water and superplasticizer, respectively.

The volume of the specimens is:

- Cube:

$$V = a^3----14$$

- Cylinder:

$$V = \pi r^2 h----15$$

- Beam:

$$V = l \times b \times h----16$$

Proper compaction was ensured using mechanical vibration to remove air voids and achieve maximum density. The degree of compaction directly affects strength and durability and can be related as:

$$\rho = \frac{M}{V}----17$$

where ρ is density, M is mass, and V is volume.

After compaction, the top surface of the specimens was finished smoothly using a trowel to ensure uniformity and proper surface texture.

D. Curing Process

The process of curing is a significant aspect of the sustainable building material preparation since it influences the hydration, microstructure and mechanical properties of the composite. Proper curing will ensure a long-term supply of water, whereby the cementitious materials will be fully hydrated and enhance strength and durability in the long-term.

Initial setting after casting was left in laboratory conditions in 24 ± 2 hours. The specimens were then carefully demoulded, without causing damage to the surface and/or micro-cracking. These were then dried in water.

The cement hydration contributes to the strength increase of concrete and it can be expressed as:

$$\text{Cement} + H_2O \rightarrow C\text{-}S\text{-}H + Ca(OH)_2 + \text{Heat}---18$$

The formation of calcium silicate hydrate (C–S–H) gel is primarily responsible for the strength and durability of the material.

The variation of compressive strength with curing time can be approximated using:

$$f_t = f_{28}\left(\frac{t}{28}\right)^n----19$$

where:
ft = strength at time t days

f28 = 28-day strength

n = empirical constant

E. Mechanical and Durability Testing

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The developed sustainable construction materials were subjected to a series of mechanical and durability tests. These tests were performed as per the IS and ASTM standards to achieve consistent and reliable results. The aim was to evaluate the strength and durability performance of the concrete mixes with supplementary cementitious materials (SCMs) and recycled aggregates.

The compressive strength was measured on cube specimens with dimensions 150 x 150 x 150 mm following the IS 516 standards. The cubes were centrally placed in a compression testing machine and the load was applied until failure. The compressive strength was calculated as:

$$f_c = \frac{P}{A} \text{----}20$$

where P is the ultimate load and A is the cross-sectional area.

Water absorption was measured to evaluate the permeability and porosity of the concrete. Specimens were dried in an oven and then immersed in water. The percentage water absorption was calculated as:

$$WA = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100\text{----}21$$

where Wwet and Wdry are the saturated and dry weights, respectively.

Porosity is an important indicator of durability and was determined using:

$$n = \frac{V_{void}}{V_{total}} \times 100\text{----}22$$

Lower porosity values indicate better durability and resistance to environmental degradation.

The load–deformation response of the specimens was recorded during testing to evaluate ductility and stiffness. The modulus of elasticity was estimated using:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}\text{----}23$$

where $\Delta\sigma$ is the stress change and $\Delta\varepsilon$ is the corresponding strain.

Material performance is tested by conducting mechanical and durability tests. Strength performance is measured by mechanical tests and environmental performance is measured by endurance tests. It is possible that the use of SCMs and recycled aggregates in concrete will enhance strength and durability by enhancing microstructure and reducing the number of voids.

F. Data Analysis and Evaluation

The mechanical and durability tests were thoroughly analysed to determine the behaviour of sustainable concrete materials with supplementary cementitious materials (SCMs) and recycled aggregates. This included testing the trends in the strength gain, durability improvement and material use efficiency at different mix proportions.

Each test was tested on three specimens and the average value was calculated to give statistical significance. The mean of the measured parameter was calculated as:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i\text{----}24$$

where xi represents the individual observations and n is the number of specimens. The variability in the results was assessed using standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}}\text{----}25$$

Larger values of σ are more uniform specimen preparation and testing. The various mixes were analyzed and assessed in compressive, tensile and flexural strengths. The improvement in strength was measured in percentage improvement over the control mix:

$$\%\ \text{Increase} = \frac{f_{mix} - f_{control}}{f_{control}} \times 100\%\text{-----}26$$

where fmix is the strength of the modified mix and fcontrol is the strength of the reference mix. To evaluate the overall efficiency of material utilization, a performance index was defined as:

$$PI = \frac{f_c}{B}\text{----}27$$

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in which fc is the compressive strength and B is the binder content. The higher the value of the performance index, the better the cementitious materials are being used. The durability was evaluated according to water absorption and porosity. Durability and porosity can be related as:

Mix ID	Water Absorption (%)
M1	5.2
M2	4.3
M3	3.6

$$D \propto \frac{1}{n} \text{----}28$$

where D represents durability and n is porosity. Lower porosity leads to higher resistance against moisture ingress and environmental degradation.

The reduction in water absorption due to SCMs was calculated as:

$$\%\,\text{Reduction} = \frac{WA_{control} - WA_{mix}}{WA_{control}} \times 100\text{----}29$$

WAcontrol and WAmix: where WAcontrol and WAmix are the water absorption values of control and modified mixes, respectively. The analysis revealed that the strength and durability are positively influenced by the addition of fly ash and silica fume. The decreased porosity and water uptake imply microstructural integrity enhancements. Although the use of recycled aggregates influences, slightly the early age strength, SCMs counteract the effect.

The optimal blend was discovered to be the most proficient in terms of strength, endurance and environmental efficiency. The results indicate that the construction materials that are eco-friendly can work as effectively as, or even better than, conventional concrete and reduce their environmental impact.

IV. RESULTS AND DISCUSSION

The performance of the sustainable building materials including fly ash, silica fume and recycled aggregates were evaluated using the test results of mechanical and durability tests. We record the results as compressive strength, tensile strength, flexural strength and water absorption.

Table 1: Compressive Strength Results

Mix ID	28-Day Strength (MPa)
M1	42
M2	44
M3	46

The compressive strength increases with M1 to M3. The optimum mix (M3) gives the maximum strength of 46 MPa, suggesting that the addition of fly ash and silica fume results in a denser matrix through pozzolanic reactions. This increases load-bearing capacity.

Table 2: Tensile Strength Results

Mix ID	Tensile Strength (MPa)
M1	3.2
M2	3.8
M3	4.3

The tensile strength is significantly increased by the sustainable materials. The strength of Mix M3 is approximately 34 percent higher than the strength of M1. This is due to enhanced bonding and micro-cracking.

Table 3: Flexural Strength Results

Mix ID	Flexural Strength (MPa)
M1	5.5
M2	6.1
M3	6.8

The flexural strength increased gradually with SCM content. The performance of bending is better because of the optimal distribution of stress and refinement of microstructure.

Table 4: Water Absorption Results

Water absorption is significantly lower between M1 and M3, which means that the porosity is decreased and the durability is increased. Silica fume and fly ash additive improve pore structure and reduce permeability.

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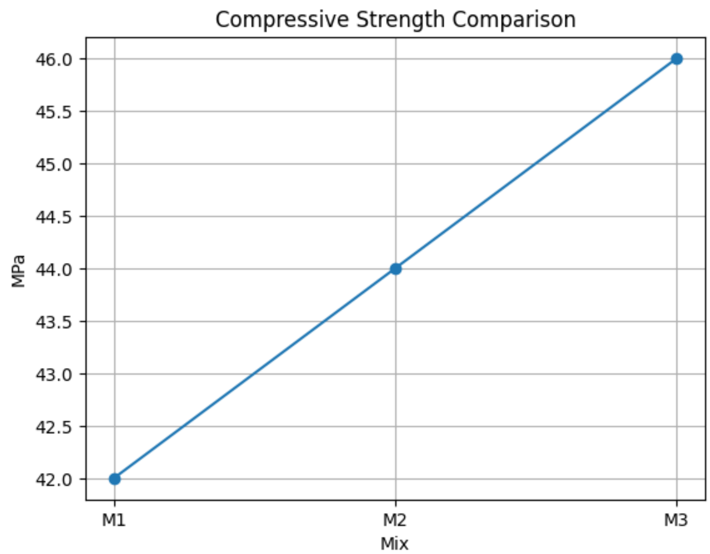

Figure 2: Compressive Strength Comparison

Figure 2 indicates that the compressive strength of the three mixes (M1, M2 and M3) at 28 days differs. It is observed that compressive strength is rising slowly with the addition of supplementary cementitious materials (SCMs). The weakest control mix is the control mix (M1) and the strongest with the value of 46 Mpa is the optimized mix (M3).

The pozzolanic reaction of the fly ash can be attributed to this increase and the micro-filling effect of the silica fume which is raising the density of the cement matrix. The reduction in the voids and strengthening of the contact between the particles results in an increase in the load bearing capacity. The figure is a bright example that compressive strength can be effectively enhanced with the help of sustainable materials that do not lead to the decline in structural performance.

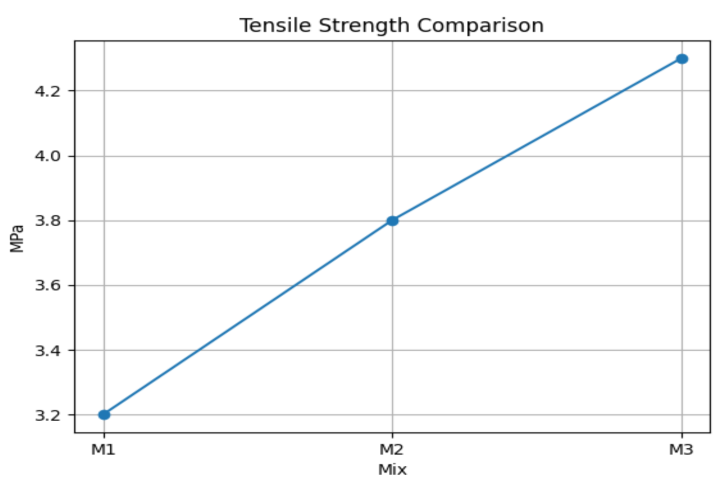

Figure 3: Tensile Strength Comparison

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Figure 3 indicates the tensile strength change of all mixes. There is an apparent improvement of tensile strength between M1 and M3 with the highest tensile strength of 4.3 MPa in M3.

The tensile strength is enhanced mainly by the strengthening of the interfacial bonding and reduction in the growth of micro-cracks. Silica fume also increases the interfacial transition zone (ITZ) and fly ash increases the formation of long-term strength. The figure highlights the increased crack propagation and crack initiation resistance of sustainable concrete mixes.

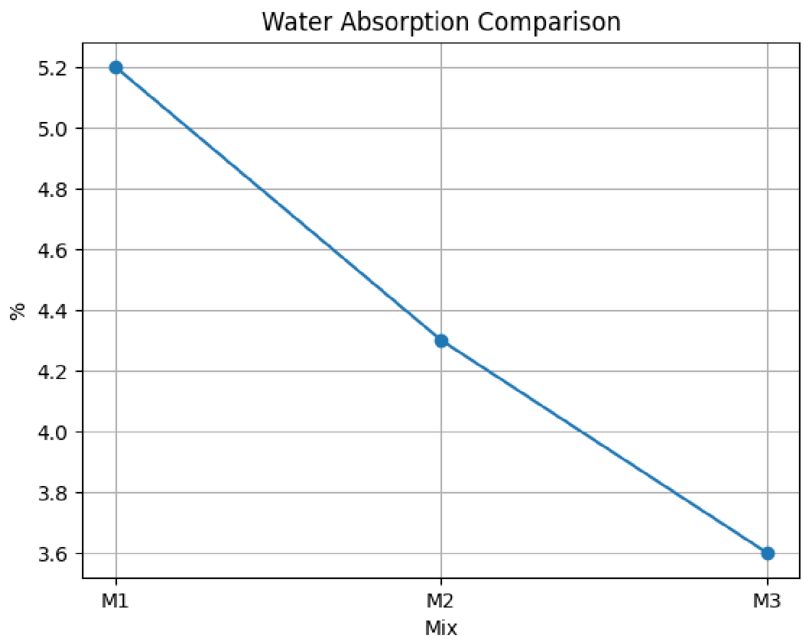

Figure 4: Flexural Strength Comparison

Figure 4 shows the flexural strength performance of the mixes subjected to bending loads. Between M1 and M3, there is a continuous increase in flexural strength with M3 of 6.8 Mpa.

This has been improved by the increase in stress distribution in the matrix and the cohesion among the constituents. The fine microstructure due to the SCMs leads to an enhanced resistance to the bending stresses. The figure illustrates that sustainable materials contribute hugely to flexural and toughness of concrete.

V. CONCLUSION

The paper has discussed the manufacturing and performance of sustainable building materials utilizing the addition of supplementary cementitious materials (SCMs) such as fly ash and silica fume, and recycled aggregates that will be employed in green buildings. Based on the experiment and analysis the following conclusions can be drawn. Incorporation of SCM produced significant influence on the mechanical properties of concrete. The optimized mix (M3) was the highest compressive strength of 46Mpa and the tensile and flexural strengths were significantly increased. The described enhancements can be mostly attributed to the pozzolanic activity of fly ash and micro-filling effect of silica fume that assists in raising the densification of the matrix and the strength of the interfacial bond. The performance of critical durability was also recorded with significant improvement recorded using sustainable materials. The lower water absorption of approximately 30% of M3 mixes implies that porosity is decreased and moisture ingress resistance increased. This confirms that when the SCMs are incorporated the pore structure becomes developed and durable. Although the use of recycled aggregates causes minor variations in the initial strength, it has benefits on the environment and can be used alongside the SCMs therefore becomes an alternative to natural aggregates. The use of aggregates is sustainable and structural performance balanced; this is due to the recycled aggregates and use of SCMs. Overall, the results show that environmentally-friendly construction materials may perform as well as or even better than regular concrete. The optimized mix is an excellent solution in terms of reduction of carbon emissions, saving natural resources and durability and this is the reason why it is highly applicable in green building.

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