Environment-friendly sustainable concrete produced from marble waste powder

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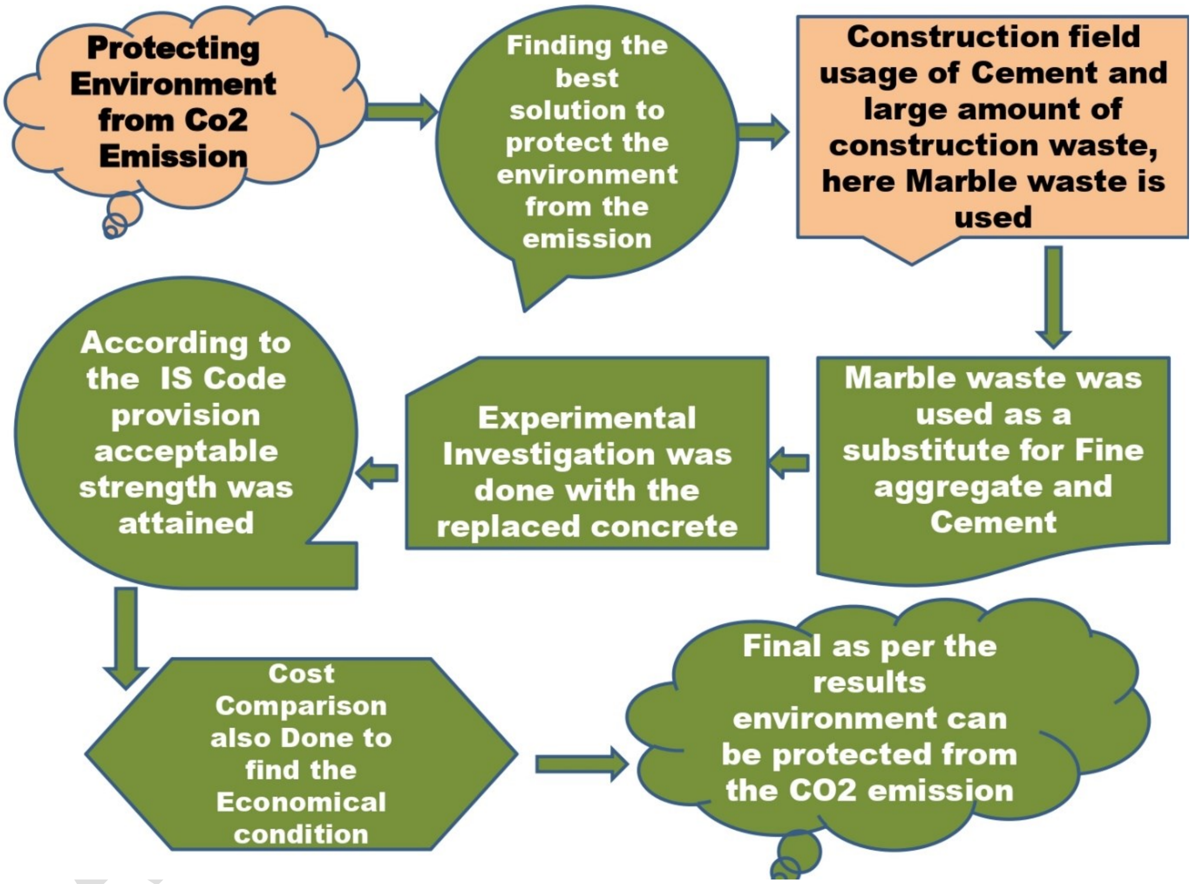
Graphical abstract



Abstract

Concrete is an indispensable construction material renowned for its versatility and durability, yet its traditional components pose significant environmental challenges. The cement industry is a major emitter of CO_2, while the extensive extraction of natural aggregates depletes finite resources. In response, researchers have explored alternative materials like Marble Waste Powder (MWP) as sustainable substitutes in concrete production. This study investigates the feasibility of incorporating MWP as partial replacements for cement and fine aggregate, examining substitution fractions of 25% and 35%. Through experimental analysis, the mechanical properties and cost implications of these modified concrete blends are evaluated. The research findings reveal that integrating MWP into concrete formulations enables the production of high-strength concrete at a reduced cost, offering a promising solution to enhance the sustainability of construction practices. By partially replacing conventional materials with MWP, the environmental impact associated with concrete production can be mitigated, contributing to efforts aimed at reducing carbon emissions and conserving natural resources. Additionally, the study underscores the importance of eco-friendly innovations in construction materials, emphasizing the need for sustainable alternatives to meet the growing demand for infrastructure development while minimizing environmental harm. Overall, this research highlights the novel use of MWP as a sustainable alternative in concrete production, showcasing its potential to address environmental concerns and promote more eco-conscious construction practices. Through the exploration of mechanical performance and economic feasibility, the study provides valuable insights for advancing sustainability in the construction industry and achieving long-term environmental stewardship.

Keywords: Marble Waste Powder (MWP), Cement, Cost, Compressive strength, Tensile strength, flexural strength

1. Introduction

Worldwide, many million tonnes of MWP are expected to be created during quarrying. Thus, the practice of marble residue has become a significant alternative material for enhancing the hardening characteristics of concrete[1]. Marble is a sedimentary rock that results from the transformation of pure limestone by metamorphosis. The purity of the marble determines its colour and look; if the limestone is entirely made of calcite, it is white (100 percent $CaCO_3$). Marble is used in building and decorating because it is sturdy and has a noble appearance. As a result, marble is in high demand[2]. MWP is produced in huge quantities during the cutting process [3]. As a result, the amount of marble trash, which accounts for 20% of total marble mined, has risen to millions of tonnes [4]. Directly dumping these waste products into the environment might result in environmental problems [5]. Additionally, because natural aggregate and minerals used to make cement are limited, and it is necessary to reduce energy consumption and carbon dioxide emissions associated with construction processes, a solution to this problem is sought through the practice of MWP as a fractional auxiliary for Portland slag cement[6]. In India, MWP is settled by sedimentation and subsequently disposed of, resulting in environmental degradation, as well as the formation of dust during the summer, posing a hazard to agriculture and public health [7]. Thus, the use of the MWP in a variety of industrial sectors, including building, agriculture, glass, and paper, would contribute to environmental protection. Waste may be recycled to create novel goods or utilized as an intermixture to increase the efficiency of natural resource usage and protect the environment from waste deposits [8].

Alyaseen et al. [9] investigate the impact of design parameters on compressive strength (CS) of high-performance self-compacting concrete (HP-SCC) with recycled concrete aggregate (RCA). Pearson's correlation coefficient analysis and machine learning models (M5P, RF, SVM, LR, ANNs) were employed, with the SVM-PUK-based model showing the highest accuracy, particularly influenced by w/c, w/b, and w/s variables. Alyaseen et al. [10] explore computational techniques like M5P, RF, SVM, and LR to predict concrete splitting strength, addressing its key disadvantage of lower Splitting Tensile Strength (STS). SVM-PUK emerged as the most effective method, emphasizing the significance of curing time (T) among input variables in predicting concrete strength. Alyaseen et al [11] investigate the impact of Bacillus Subtilis bacteria on the strength properties of 100% recycled concrete aggregate (RCA) with silica fume (SF) substitution for cement. Optimal results were observed with 7.5% SF substitution. SEM and EDS analysis confirmed calcite precipitation, densifying the concrete and improving compressive and splitting tensile strength. Sharma et al [12] evaluates concrete flexural strength using waste marble powder and machine learning methods like ANFIS, SVM, and Gaussian processes. With a dataset of 202 observations split into training and testing sets, Gaussian processes outperformed others with a higher correlation coefficient and lower error values, identifying curing days as a significant predictor. Upadhya et al [13] study aims to determine the optimal prediction model for Marshall Stability and Bitumen Content (BC) in carbon fiber reinforced asphalt concrete. Employing machine learning techniques and statistical metrics, Random Forest emerged as the best model, with BC of approximately 5.0% identified as a significant factor influencing Marshall Stability. Sharma et al [14] research aims to predict concrete compressive and flexural strengths using waste marble powder as partial replacements. Support Vector Machines, Gaussian Processes, and other models were applied to experimental data. Gaussian Process and Support Vector Machines Stochastic showed superior performance, offering higher correlations and lower errors, suggesting their suitability for strength prediction. Sharma et al [15] study assesses the impact of waste marble powder on concrete flexural strength using machine learning algorithms. Five models were evaluated, with Gaussian Process performing best, showing a CC of 0.8108 and lower RMSE (2.6025 MPa) and RRSE (59.32%). Sensitivity analysis identified specific concrete mixes as sequentially sensitive due to lower CC values [16]. Due to the lower quality criteria for resources, concrete blocks appear to be the most preferred alternative for using recovered waste materials [17]. This article covers published studies on the use of several types of waste in the manufacturing of concrete blocks, including recycled concrete, crushed brick, soda lime glass, cathode ray tube glass, crumb rubber, and ceramic and tile waste [18-20]. The amount of these elements integrated into concrete blocks can be increased to 100% as a substitute for natural aggregate, or it can be reduced to less than 30% in specific applications to fulfill the standard requirement [21-23]. Researchers identified the most important physicochemical characteristics of conventional cement and marble powder [24]. Marble mud powder can be used to aid in filling voids in concrete construction [25]. This article demonstrates how to utilise marble mud dust as a 100 percent substitute for real sand in concrete [26]. The compression strength and microstructure of mixed cement were investigated in this study [27]. The stronger the marble, the more dust it holds [28]. Sharma et al. employs waste marble powder to predict concrete strength [29]. Gaussian process and SVM techniques exhibit superior performance with high correlation coefficients, lower error values, and reduced experimental time, suggesting their reliability in predicting compressive and flexural strength. Sharma et al. assesses concrete flexural strength using machine learning methods like ANFIS, SVM, and Gaussian processes [30]. Sensitivity analysis identifies influential factors. Gaussian process shows superior performance, with high correlation coefficient (0.7476), lower mean absolute error (1.0884), and root mean square error (1.5621). Curing days are found significant. Alyaseen et al. explores the impact of Bacillus Subtilis bacteria on the strength properties of 100% recycled concrete aggregate incorporating silica fume [31]. Results indicate enhanced compressive and splitting tensile strengths due to calcite precipitation, leading to denser concrete. Economic analysis and regression equations validate the findings, meeting Indian concrete specifications. Upadhya et al. identifed the optimal prediction model for Marshall Stability and Bitumen Content in carbon fiber reinforced asphalt concrete for flexible pavements [32]. Five machine learning techniques were applied, with Random Forest showing the best performance. Sensitivity analysis revealed a significant influence of 5.0% binder content on Marshall Stability. The objective of this research is to investigate the feasibility of using marble debris as a partial substitute for concrete production [33]. Specifically, the study aims to determine the mechanical characteristics and cost implications of incorporating marble debris at two different replacement percentages: 25% and 35%. By doing so, the research seeks to identify the optimal replacement ratio that maximizes concrete performance while minimizing costs. One novelty of this research lies in its focus on exploring marble debris as an alternative material for concrete production. While previous studies [1-52] have examined various supplementary materials for concrete, the use of marble debris in this context is relatively underexplored. Additionally, the research investigates two different replacement percentages, providing insights into the effect of varying substitution levels on concrete properties and cost [34]. The existing literature lacks comprehensive studies on the utilization of marble debris as a partial substitute for concrete, particularly with regards to its mechanical characteristics and cost implications [35]. While some studies have explored the use of alternative materials in concrete production, there is a gap in knowledge regarding the specific effects of marble debris substitution on concrete properties and cost-efficiency [36]. Therefore, this research aims to fill this gap by providing a detailed analysis of the mechanical characteristics and cost considerations associated with incorporating marble debris in concrete mixes at different replacement percentages.

This study addresses the scarcity of research comparing the impact of marble waste powder (MWP) substitution for fine aggregate versus cement in M40 grade concrete. It aims to assess mechanical properties such as flexural-tensile strength (FTS) and elasticity, often overlooked in previous studies focused solely on compressive strength. Moreover, the research provides a vital cost estimate for market viability, enhancing understanding of MWP utilization in concrete. By emphasizing these aspects, the study seeks to contribute valuable insights into optimizing MWP incorporation in concrete mixtures, thereby advancing sustainable construction practices and resource management in the industry.

2. Materials and Methodology

The goal of this study was to conduct an experiment to see if 25% and 35% MWP could be applied as a partial supplement for PC and fine aggregate in construction mixes [37-39]. Because the existing literature has indicated that these percentages may be used without substantial reduction, the high percentages of 25% and 35% were chosen [40-44]. In order to assess the economic viability of this substitution, the physical behaviour of the new concrete was compared to the cost [45]. As shown in Figure 1, all of the ingredients utilised in the mixes are as follows:

Table 1: Characteristics of replacing materials in concrete mix

Figure 1: Materials used in current study A) NFA B) Cement C) 20mm NWA D)10mm NWA E) MWP F) MFA

The Portland Cement that was utilised in this experiment was manufactured by UltraTech Cement in India [46]. In this experimental investigation, mixtures of 10 and 20mm Normal Weight Aggregates (NWA's) are employed [47]. ASTM C33 standards were used to conduct several tests (Table 1 summarises the results of these testing) [39]. Additionally, the ratio of coarse aggregates (1 -20 cm) employed to present investigation is one part to 4 parts [48]. In

Characteristics	**Normal Weight Coarse Aggregate (NWA) (5mm-20mm)**	**Normal Fine Aggregate (NFA) (less than 4.75mm)**	**MWP**
Specific gravity	2.8	2.7	2.7
Fineness	6.7	2.5	3
Abrasion %	42	-	-
Moisture Content %	0.9	1.3	0.12
Water absorption %	0.6	0.98	4.9
Bulk density (t/m^3)	1.9	1.6	1.4

this research, river sand fine aggregate is utilised to create the mixtures. ASTM-compliant tests (Table 1) were revealed [49]. The marble scraps utilised in this project are from Indian industrial trash. This waste was collected and crushed into particles (size ~4 mm) for use in substitution of fine aggregate [50]. Marbles are crystalline rocks that are mostly made of calcite, dolomite, or serpentine minerals. The remaining mineral components differ according to their origin. Magnesia, phosphate, lead, zinc, alkalis, and sulphides are the major contaminants in fresh CaO (to cement) that might alter the characteristics of final cement. The characteristics of Marble Fine Aggregate are illustrated in Table 1. The specific gravity of MFA is lesser than Normal Fine Aggregate (NFA). Additionally, it is more refined because to the significantly lower fineness modulus (3.0). In comparison to the NFA, the MFA has a significantly higher water absorption capacity and a higher moisture content. Apart from MFA, Marble Waste Powder (MWP) from the marble polishing process was utilised in place of cement in some instances [51]. The naphthalene sulphonated superplasticizer (NSSP) was added to make concrete more workable [52]. For all mixes, the content of NSSP was 1.25 % of the weight of cement.

Table 2: Description concrete mix proportions

Mix ID	f_{cu} (MPa)	f_c (MPa)	f_{ct} (MPa)	E(GPa)
A0	53	46	41	4.3
Acc25	56	52	57	3.6
Acc35	61	51	54	3.5
Acfa25	65	59	51	3.8
Acfa35	63	54	59	3.7

2.6. Mix Proportioning and Specimen Preparation

The concrete mix design was performed in accordance with ASTM standards in order to meet the A40 concrete grade requirement [45]. The objective of the grade A40 is to reach a typical fcc (Cylindrical compression strength ~ forty MPa) and fc (mean Cylindrical compression strength ~ fifty MPa). Table 2 shows the mix proportions.

2.7. Test Methods

Water-cured specimens corresponding to each concrete mix outlined in Table 2 were fabricated and kept in storage until the testing phase. As depicted in Figure 2, the specimens include cubes with dimensions of 15 x 15 x 15 cm, cylinders with a diameter of 15 cm, and a height of 30 cm. These specimens were utilized to determine the compressive strength and elasticity. Moreover, beam samples measuring 10 x 10 cm in cross-section and 50 cm in length were prepared for a four-point flexural tensile test [47]. The tests were conducted on the 56th day to ensure minimal strength reduction due to hydration. Figure 2 provides an illustration of the testing apparatus utilized in the experiments.

Table 3: Test abstract concrete mix (56 days)

3. Results

The findings of the experiments that were carried out on concrete cubes on day 56 are summarised in Table 3, where f_{cu} (Cube compression strength), f_c (Cylindrical compression strength), E (elasticity) and f_{ct} (flexural-tensile strength) respectively.

ID	Materials (kg/m^3)							
	Cement	MWP	NWA 20 mm	NWA 10 mm	NFA	MFA	Water	NSSP
A0	420		720	270	820		183	5.25
Acc25	315	75	720	270	820		183	5.25
Acc35	273	147	720	270	820		183	5.25
Acfa25	420		720	270	615	205	183	5.25
Acfa35	420		720	270	533	287	183	5.25

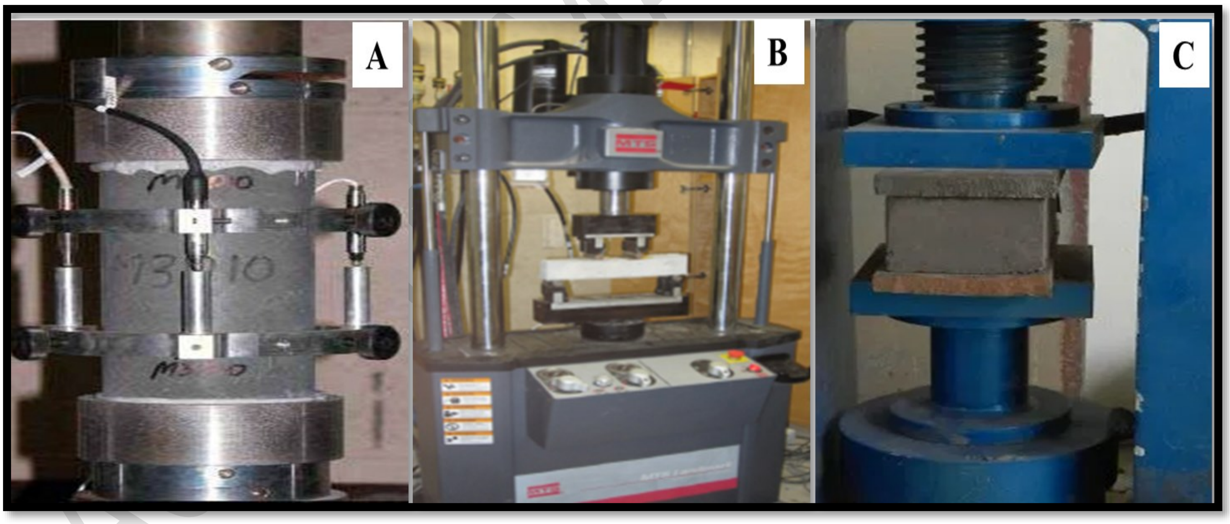


Figure 2: Machines used for test study A) Elasticity B) Flexural-tensile strength C) Compressive strength

4. Discussion

The MWP is a significant waste product generated in the stone industry during the cutting, shaping, and polishing of marbles. Around 20%–25% of the marble used in this procedure is converted to powder. India is the globally third largest exporter of marble (~10%), and each year, millions of tonnes of marble debris from processing facilities are dumped. This project was planned and preceded due to the availability of a huge quantity of trash generated by the marble industry. The chemical characteristics of MWP are summarised in Table 4. To determine the findings, the MWP content of Calcium Oxide (CaO) was 55.6 percent for the marble, which is in compliance with the criteria for natural cement, which is 65.9 percent. However, additional components like as SiO_2, Al_2O_3, Fe_2O_3, and MgO do not fit within the parameters of ordinary natural cement. This means that MWP is classified as natural cement but does not operate entirely like natural cement (Table 5).

Table 4: Chemical composition of cement and marble powder

Elements	Cement	Marble Powder
Calcium oxide	66	56
Silica oxide	30	1
Aluminium oxide	5	0.5
Iron oxide	3	0.3
Magnesium oxide	2	0.2
Potassium oxide	0.48	-
Sulphur trioxide	0.5	-
Calcium carbonate	-	0.9
Chloride	0.1	0.1
LOI	1	42.9
Specific density	3	2.69
Blaine Surface (cm^2/g)	2792	2126

4.1. Density

Figure 3 depicts the relationship between each concrete mix and its corresponding densities. The findings revealed a decrease in the densities of all three types of concrete, attributed to the lower specific gravity of Marble Waste Powder (MWP) and Marble Fine Aggregate (MFA) compared to Natural Washed Aggregate (NWA). When considering only the oven dry density (ODD) of concrete, it ranged from 2361 kg/m^3 to 1944 kg/m^3. Furthermore, the density of demolded concrete varied between 3316 kg/m^3 and 2981 kg/m^3. This alteration in density affects the strength characteristics of the concrete [10].

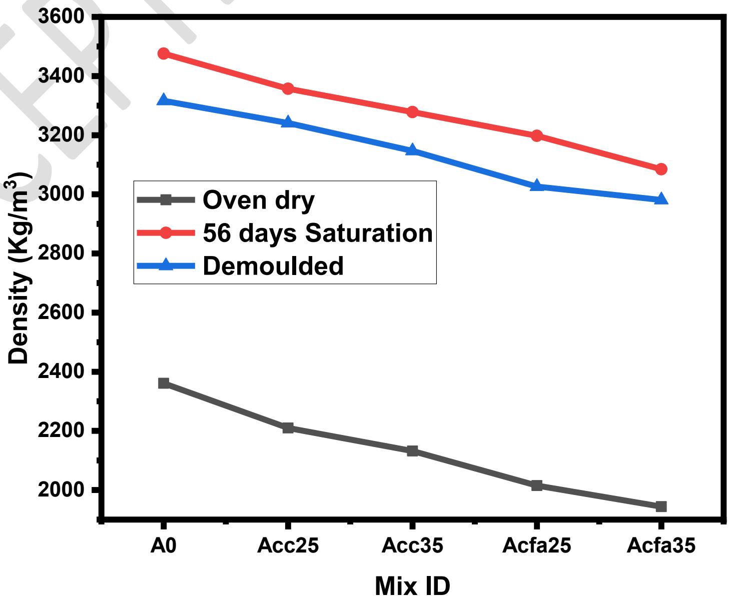


Figure 3: Density of each mix

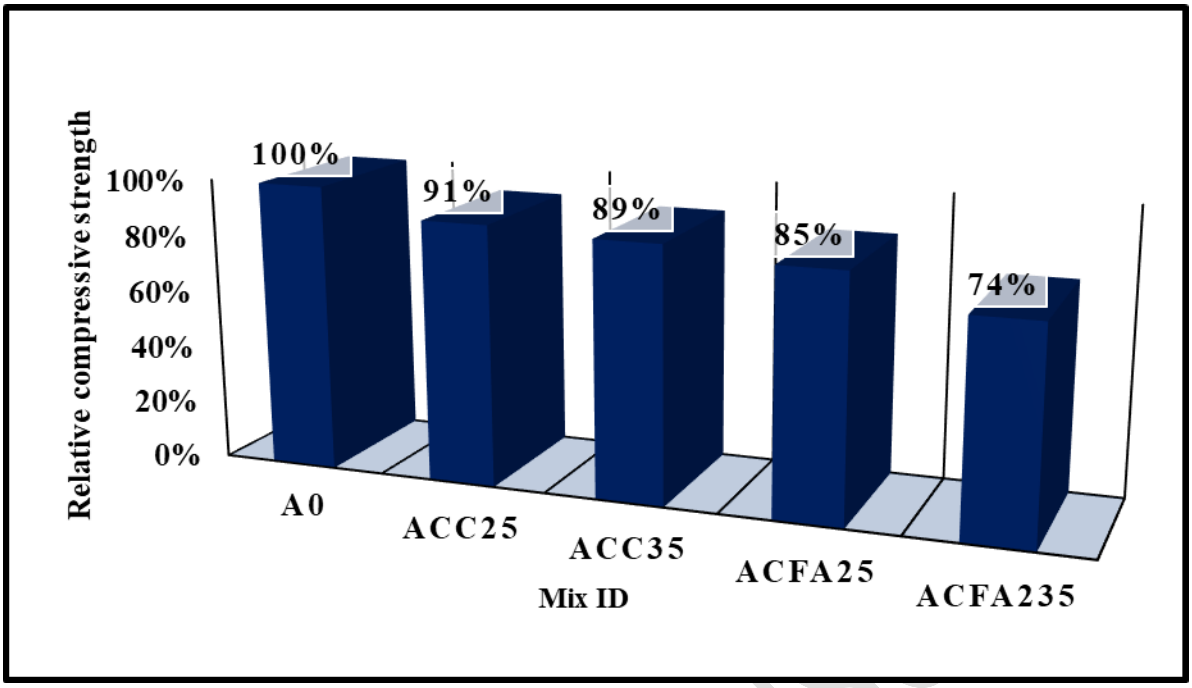


Figure 4: Relative compressive strength percentages between each mix with control

4.2. Compressive strength

The Cylindrical compression strength (ƒc) values in Table 4 may be examined in detail by referring to Fig. 4, which depicts the comparative ratios of the standard mix and the other mixes. According to Fig. 4, a compressive strength decreases of between 9 and 26% was found. The compressive strength is lowest when 35% of the cement is substituted by marble (Acc35), while the compressive strength is greatest when 25% of the cement is replaced by marble (Acc25). Additionally, it can be demonstrated that using more MFA rather than NFA results in increased strength (Acfa35). Table 4 cylindrical compression strength may be described using Fig.4 displays the relative ratios(percentages) of the standard mix (MO) vs the individual mixes. According to Fig.4. A decrease in compressive strength was reported in a range of 9-26 percent. The lowest compressive strength was recorded when marble replaced 35 percent of the cement (Acc35), while the highest compressive strength was recorded when marble replaced 25 percent of the cement (Acc25) [11]. Furthermore, it has been demonstrated that using more MFA rather than NFA results in greater strength (Acfa35).

4.3. Elasticity

Figure 5 depicts a comparison of the elasticity of the material mixes in concrete (Table 3) in terms of comparative percentages, where Ao represents the standard mix and is assumed to be 100%. As was the case with compressive strength, Acc25 recorded the lowest elasticity once again. 25% cement substitution results in a 3% increase in elasticity over Acc35. A low elasticity might cause structural components to deflect more. It is worth noting, that a lower cement concentration lowers concrete's long-term impacts, such as shrinkage and creep. This contributes to the reduction of bend and moderates the result of the reported decrease in the E (elasticity). Fig. 4 indicates that substituting 25% NFA for MFA (Acfa25) reduces the elasticity by just 12% compared to the standard mix [10]. Increased NFA replacement results in a decrease in elasticity (Acfa35).

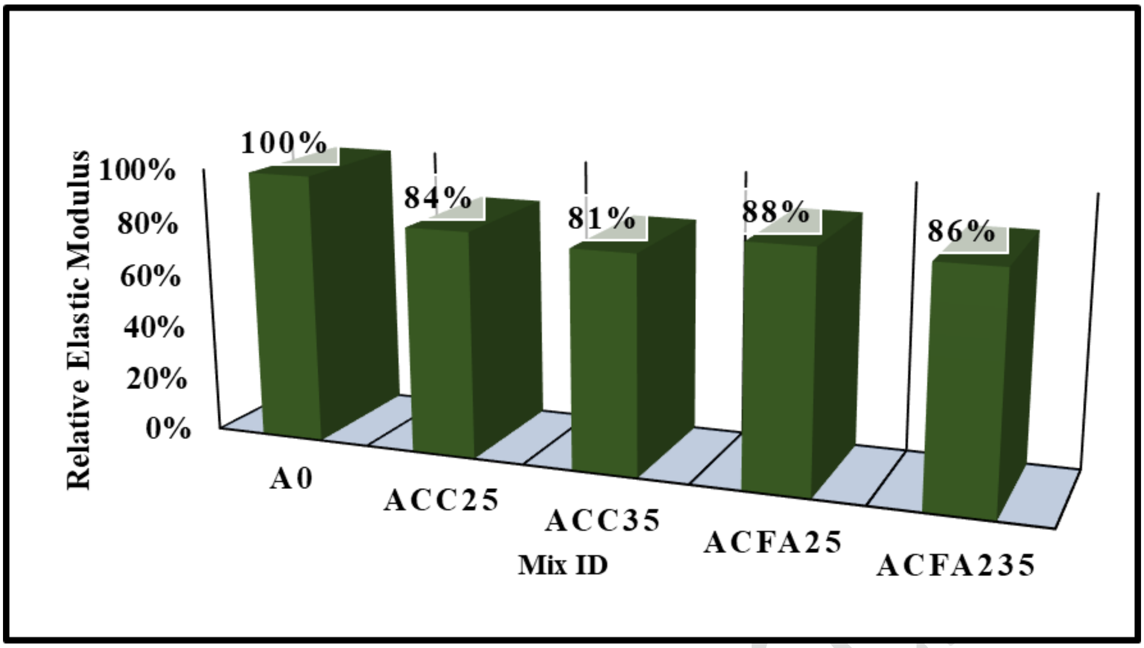


Figure 5: Relative elasticity percentages between each mix with control

4.4. Flexural Strength

The relative differences between the control mix and other concrete mixes were analyzed based on the flexural test results presented in Table 3 and illustrated in Figure 6. The investigation revealed a discernible impact of cement substitution on the tensile strength of the concrete specimens. Specifically, there was a notable decrease in tensile strength, with a 10% reduction observed when 25% of the cement was replaced (Acc25), and a more significant 17% reduction observed with a 35% cement replacement (Acc35). Notably, the smallest decline of 24% was observed when 25% of the Natural Fine Aggregate (NFA) was substituted with Marble Fine Aggregate (MFA) (Acfa25) [12]. However, as the substitution of NFA was increased further, the decline in tensile strength became more pronounced, particularly evident in the case of Acfa35. These findings underscore the influence of cement and aggregate substitutions on the mechanical properties of the concrete, highlighting the importance of optimizing mix proportions to achieve desired strength characteristics while incorporating alternative materials.

Material	Cement/Kg	MWP/Kg	NWA/Kg (20mm)	NWA/Kg (10mm)	NFA/Kg	NSSP/Kg
Cost in Rs.	6.8	0.88	0.440	0.655	0.94	40

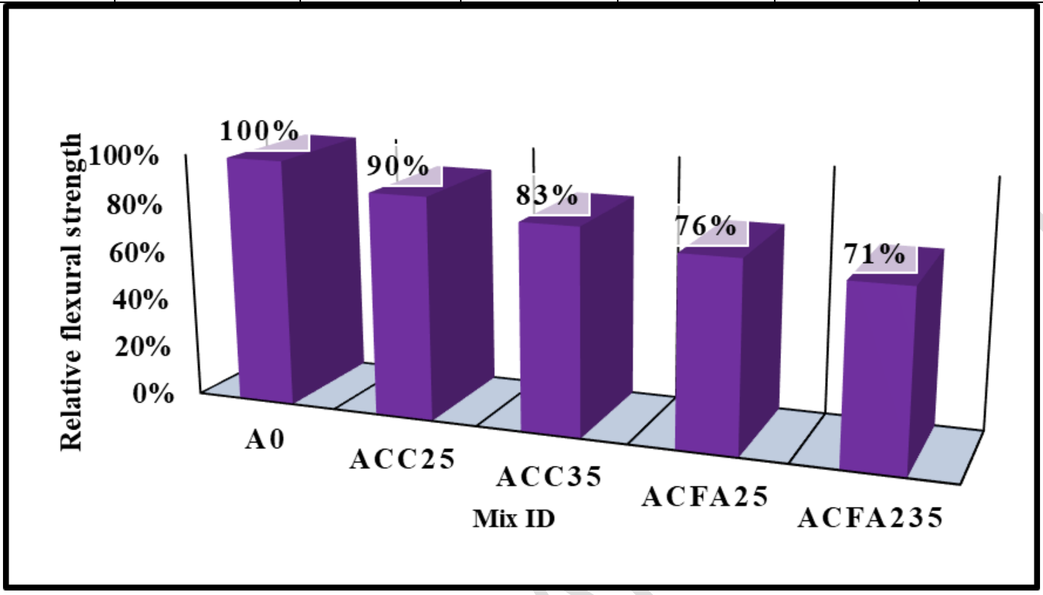


Figure 6: Relative elasticity percentages between each mix with control

Table 5: Cost of each concrete mix as per Indian standards

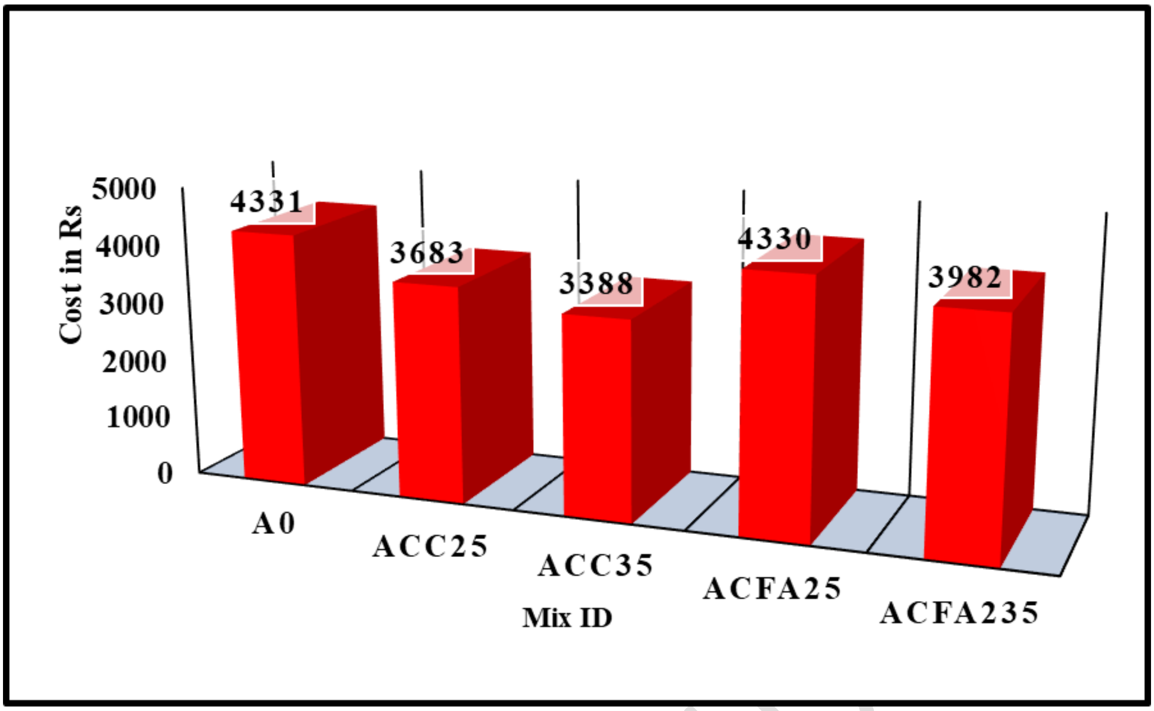


Figure 7: Cost of Mix

4.5. Cost

A comprehensive cost analysis was conducted to evaluate the economic feasibility of producing different material combinations presented in Table 2. Market prices of individual constituents used in concrete production were determined based on prevailing rates in India in 2021, as outlined in Table 5. The total cost of each combination was examined, revealing a significant impact of cement substitution on reducing overall costs. Notably, the price of Acc25 decreases by 15% with a 25% cement replacement, while Acc35 experiences a more substantial 22% decrease with a 35% cement replacement. Conversely, substituting Natural Fine Aggregate (NFA) with Acfa25 and Acfa35 yields no significant cost reduction. Marble Waste Powder (MWP) emerges as the most economically viable substitute for cement. However, substituting MWP for Fine Aggregate (F.A) does not yield economic benefits. To assess the cost-effectiveness of each combination, the compressive strength of each blend was compared to its cost, with compressive strength chosen as it best reflects concrete material properties. For instance, steel reinforcement can enhance concrete's tensile strength. In Figure 8, the cylindrical compression strength is juxtaposed with the cost of each combination. Notably, Acc25 emerges as a blend with both high compressive strength and low cost, demonstrating that replacing 25% of cement with MWP results in superior compressive strength at a lower cost.

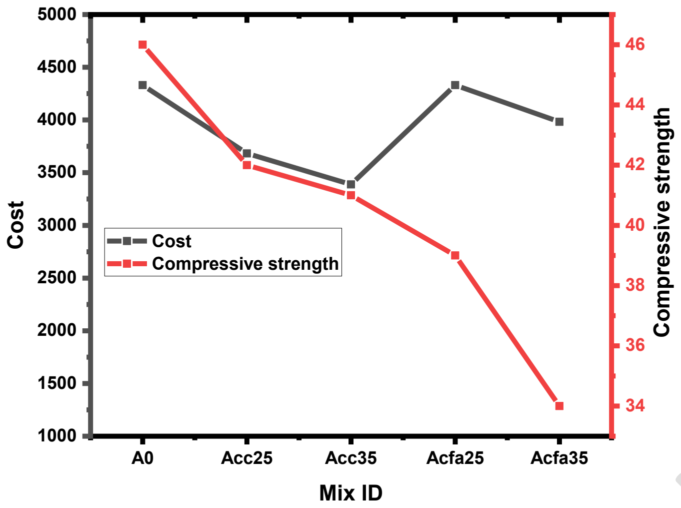


Figure 8: Comparison of cost with compressive strength of each Mix

5. Conclusion

This study aimed to investigate the viability of utilizing marble debris as a substitute material in concrete production, focusing on two replacement percentages: 25% and 35%. Mechanical properties and cost analyses were conducted for each combination to assess their suitability for practical application. It was observed that a maximum cement replacement of 25% yielded satisfactory mechanical characteristics, beyond which further substitution led to diminished mechanical performance. Additionally, the replacement of natural fine aggregate had negligible effects on pricing. However, increased substitution of marble debris adversely impacted elasticity and tensile strength. Notably, a minimal increase in compressive strength was observed with 35% marble fine aggregate (MFA) substitution. Cost analysis revealed that substituting cement resulted in a reduction in material costs. Overall, the findings suggest that a 25% replacement of cement with marble debris is the optimal choice for achieving a high-quality concrete mix at a reasonable cost. This study underscores the importance of balancing material substitution with mechanical requirements and cost considerations in concrete production, providing valuable insights for sustainable construction practices.

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