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Original Article

Correlation of Compressive Strength of Concrete with Aggregate Impact and Crushing Values of Coarse Aggregates

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Abstract - *This paper will explore the influence of the Aggregate Impact Value and Aggregate Crushing Value of coarse aggregates on the compressive strength of concrete, specifically the use of basalt, granite, and marble aggregates. This research would provide insights into the impact of the mechanical properties of different aggregates on concrete. Cement, fine aggregates, and coarse aggregates were analysed in the laboratory by determining specific gravity, water absorption, and crushing strength. Cubes of concrete were cast in mix proportions in accordance with IS 10262 and subjected to a compressive strength test after 3, 7, and 28 days. The outcome revealed that basalt, which has a low crushing and Aggregate Impact, had a better compressive strength than both granite and marble. The results indicate that the materials with low crushing and Aggregate Impact can possess high compressive strengths, and thus this latter characteristic is important in the design of concrete mix. To strengthen these findings, statistical analyses were performed comparing ANOVA, regression analysis, and Pearson correlation. These confirmed that the type of aggregate played a significant role in compressive strength, with there being strong negative correlations (r =-0.93) between the Impact of Crushing of Aggregates and strength, and the regression models gave usable predictive equations of the strength at 7 and 28 days. The study also examines how the specific gravity of aggregates relates to their aggregate crushing value, giving an overall idea of how these attributes impact the performance of concrete. The data of the averaged compressive strength values showed that basalt recorded the highest values, followed by granite and marble, which illustrates the potential benefits associated with using basalt to make concrete. The results identify the necessity to pay attention to the aggregate properties in the course of design mix to increase structural integrity and performance. This study helps to optimize concrete mix designs, providing useful information about the impact of aggregate qualities, and accordingly, directly develops high-quality and strong concrete.*

Keywords - *Compressive Strength, Coarse Aggregates, Basalt, Granite, Marble, Aggregate Impact Values, AggregateCrushing Value, Concrete Mix Design.*

1. Introduction

Among other building materials, concrete is one of the most extensively used because of its versatility, durability, and economical features. Aggregates form up to 60-75% of the total volume of the concrete and, therefore, greatly influence its physical and engineering characteristics. The geometrical characteristics of aggregates, along with their weight per unit volume, water absorption capacity, AIV, and ACV, determine concrete's mechanical characteristics. As coarse aggregates constitute the main load-bearing skeleton in hardened concrete, their strength and resistance to crushing directly influence the structural integrity of concrete members [1].

A number of experiments have been conducted to determine the influence of aggregates on concrete performance. The authors Kozul and Darwin discovered that there was a considerable influence exerted by aggregate types, sizes, and contents on fracture energy and compressive behavior in concrete mixtures [2]. The authors Youseif et al. discovered that there was considerable influence exerted by aggregate sizes on compressive strength, high-strength concretes, and modulus of elasticity in normal [3]. Tumidajski and Gong have shown that the size of the aggregate used coarsely affects the development of workability and strength with respect to water-cement ratio and cement content [4]. On the same note, Jimoh and Awe introduced the fact that smaller-sized granite aggregates had a higher compressive strength than larger aggregates because of better bonding and a decrease in internal microcracking [5]. Woode et al. also affirmed that smaller sizes of aggregate yielded greater compressive strength in concrete that was manufactured with smaller aggregates of crushed gneiss [6].

Besides the size of the aggregate, a number of studies have emphasized the significance of aggregate lithology and mineralogical composition in the control of the concrete behaviour. Teymen documented that aggregate origin, rock texture, and mineral composition have a powerful effect on compressive strength and mechanical behaviour of concrete [1]. The comparative studies done on granite, limestone, quartzite, and marble aggregates have also demonstrated that aggregates with higher crushing resistance tend to produce a concrete with higher compressive strength [7]. Recent studies on basalt aggregates have shown that basalt-based concrete has better mechanical performance and fracture resistance because of the dense and hard mineral structure of basalt rock [8]. Moreover, literature discussing marble waste aggregates has highlighted the emerging interest in sustainable aggregate use and the necessity to assess alternative aggregate sources to use in structural concretes [9]. However, recent advancements in concrete research have been directed towards Non-Destructive Testing (NDT) methods and predictive modelling to estimate the compressive strength of concrete. The popular methods are the in-situ rapid evaluation of concrete quality and structural integrity, often by use of the Rebound Hammer (RH), Ultrasonic Pulse Velocity (UPV), combined SonReb methods, etc. [10, 11]. Arora et al. [10] proved that ensemble learning models that are combined with the data of UPV and rebound hammers can greatly enhance the prediction accuracy of the compressive strength of the concrete. In a similar manner, Angiulli et al. [11] used Gaussian Process Regression to predict concrete strength using SonReb and obtained enhanced reliability in predicting concrete strength with less experimental uncertainty. Shishegaran et al. [12] went further to demonstrate that hybrid predictive models that incorporate the use of UPV and rebound hammer measurements entail greater prediction accuracy than conventional regression methods. These studies indicate the growing importance of predictive statistical and non-destructive evaluation methods in modern concrete technology. Nevertheless, few studies have been conducted to determine statistically validated relationships among aggregate mechanical properties like ACV, AIV, and concrete compressive strength using various mix design aggregate lithologies under controlled mix design conditions. Thus, experimental research that combines aggregate characterization with statistical modelling is all that is needed to have a practical, concrete mix optimization and aggregate selection.

Even though several researchers have investigated the relationship between aggregate size and aggregate type with compressive strength, gaps are still found in existing literature. The majority of previous studies were only concerned about aggregate gradation, maximum aggregate size, or partial replacement studies, while there was not much work established to find out the statistical correlation among ACV, AIV, and compressive strength development. Moreover, few studies have comparatively tested basalt, granite, and marble aggregates under similar mix design conditions with standardized testing protocols. There is also an absence of detailed predictive modelling strategies that incorporate aggregate mechanical properties with compressive strength behaviour. Moreover, there has been little emphasis on practical applications of aggregate selection in sustainable concrete mix design and optimization of structural performance.

The innovation of the present investigation lies in the integrated experimental and statistical analysis of the connection between the mechanical properties of the aggregate and compressive strength of concrete using basalt and granite aggregates, as well as marble aggregates. Unlike other research conducted in the past, where most studies were mainly concerned about the effect of ACV on its own, the current research not only considers the effect of ACV but also takes into consideration the effect of Aggregate Impact Value (AIV) and compressive strength analysis using one-way ANOVA, Pearson correlation analysis, and regression modeling. The comparative evaluation of various aggregate lithologies as a material to use in the construction of durable and high-strength concrete is also provided in the study, and the practical importance of selecting mechanically superior aggregates as materials to be used in the construction of durable and high-strength concrete is also highlighted in the study.

Laboratory experiments were conducted on coarse aggregates of basalt, granite, and marble rocks with the objective of determining the properties of Sp. Gr. water absorption, AIV, and ACV according to the Indian Standards testing method. Concrete specimens were cast with a 30- grade mix ratio with the IS 10262 mix design approach. Compressive strength tests of concrete were shown on concrete cubes after curing periods of 3, 7, and 28 days. Statistical analysis was done by ANOVA, Pearson correlation, and regression techniques. The study findings are likely to help in enhancing the current concrete mix design practices, improving aggregate selection, and building durable and sustainable concrete structures.

2. Experimentation

2.1. Materials

The research materials include cement, fine aggregate, coarse aggregate, granite, basalt, and marble. Cement, a dry material of lime and clay, is used as a binder when combined with water, sand, gravel, or other aggregates. The 53-grade cement is especially employed in Reinforced Cement Concrete (RCC) works needing a high initial strength in 1 to 28 days. Fine aggregate, passing the IS sieve 4.75mm, retained on a 75-micron sieve, consists of sand classified in zone II by degree of fineness in accordance with IS 383 standards. Coarse aggregate, passing only a 4.75mm IS sieve is obtainable in numerous sizes, such as 12.5mm, 16mm, and 20mm, and is essential owing to its great compressive strength. Granite, a long-lasting and beautiful felsic intrusive igneous rock, basalt, a tough and robust fine grained dark coloured intrusive igneous rock composed primarily of plagioclase and pyroxene minerals, and marble, a very pretty metamorphic rock made of recrystallized carbonates such as calcite or dolomite, are Also common in constructive and decor contexts.

Fig. 1 (a) 53 grade Ramco cement, (b) fine aggregate, (c) granite, (d) basalt, and (e) marble.

2.1.1. Aggregate Selection and Variability Control

The coarse aggregates utilized in the current study were basalt, granite, and marble aggregates with a nominal maximum size of 20 mm. These aggregates were chosen as they are commonly available aggregate lithologies commonly used in the application of structural and decorative concrete in India. The choice of basalt was based on its high density and high mechanical strength, granite on its extensive use in conventional structural concrete, and marble on its architectural importance and relatively lower mechanical resistance.

All aggregate samples were taken from single-source quarry suppliers around and in Bengaluru, Karnataka, India, in order to reduce variability and achieve consistency. The representative aggregate sampling was conducted according to the procedures of IS 2430:1986 in order to minimize the effects of segregation and ensure consistency in the distribution of the particles. Before testing, the aggregates were washed and dried in the air and sieved to get a uniform grading in accordance with 20 mm nominal aggregate size as mandated by IS 383:2016.

All mixes of concrete were made in the laboratory setting by having an equal quantity of cement, water-cement ratio, FA quantity, curing process, and mixing time for all mixes. Proportioning was done by weighing in order to have more accuracy in the proportioning of the materials. For homogenization of the aggregates in the concrete matrix, mechanical mixing was employed in order to have an even dispersion of the aggregates within the concrete matrix. The curing process was carried out in fresh tap water according to IS 516:2018 standards. In order to enhance the reliability of the experiment and reduce any uncertainty, several trials were made for the impact value and crushing value of aggregates. The chosen methodology guaranteed the reproducibility, reduced experimental variability, and allowed for a reliable comparison of the chosen types of aggregate.

2.2. Laboratory Tests

In this study, the laboratory tests performed are fundamental in assessing the cement, fine aggregates, and coarse aggregate properties that have a high impact on the compressive strength and general performance of concrete.

2.2.1. Tests on Cement

Specific Gravity Test: Sp. Gr. The specific gravity of cement is determined with the help of a specific gravity bottle in this test.

Kerosene is used in place of water to prevent any hydration reaction from taking place. This test is based on the standard IS 2720 part 3.

Fineness of Cement: It identifies the fineness of the binder, whose measure is the particle size. The fineness is stated in the units of specific surface area, and in this case, the cement. The fineness of 10% is calculated.

2.2.2. Tests on Fine Aggregates

Specific Gravity of Sand

Sp. Gr. is defined as the ratio between the weight of a certain volume of materials in air and the weight of the same volume of distilled water in air.

Water Absorption Test

The water absorption test is an experiment conducted to estimate the quantity of water that an aggregate is capable of absorbing within the pore spaces of the aggregate, known as water-permeable voids.

2.2.3. Tests on Coarse Aggregates

Sp. Gr. and Water Absorption Tests of Aggregates

The sp gr. Indicates the strength and quality of aggregates. Weak aggregates usually have low specific gravity. The porosity and strength of rocks can be assessed by conducting water absorption tests, whereby higher absorption rates indicate highly porous rocks and therefore weak rocks.

Aggregate Impact value Test on Coarse Aggregates

The test determines the hardness or resistance of the aggregates, such as Basalt, Granite, and Marble, to shock. The Aggregate Impact Value (AIV) is computed according to the formula as AIV = (Weight of fines /Original weight of sample) x100.

Aggregates Crushing Value Test

It is a test that helps determine the crushing strength of aggregates. The load is gradually applied until the aggregates break down into pieces. The ACV is the percentage weight of broken aggregates and the whole weight of the aggregate sample.

Table 1. Results of tests on ingredients of concrete

Constituents	Tests	Results		
53-grade Cement	Sp.gr. (IS 2720 - Part-3)	3.15		
	Fineness	10%		
FA (sand)	Sp. Gr. (IS:2386-PART3-1963)	2.7		
	Water Absorption n (IS:2386- PART3-1963)	1%		
Coarse aggregate		Basalt	Granite	Marble
	Sp.gr. (IS:2386-PART3-1963)	2.83	2.6	2.41
	Water Absorption (IS:2386- PART3-1963)	0.25%	0.46%	0.65%

Table 1 presents the test results for various materials used in the study, including 53-grade cement, FA (sand), and coarse aggregates (basalt, granite, and marble). The specific gravity of 53-grade cement, measured according to IS 2720 Part 3 is 3.15, and its fineness is determined to be 10%. For fine aggregates (sand), the specific gravity is recorded as 2.7, with a water absorption rate of 1%, as per IS:2386-PART3-1963. The specific gravity of the basalt is 2.83, while the water absorption of basalt is 0.25%. The specific gravity of the granite is 2.6, and the water absorption of the granite is 0.46%. The specific gravity of the marble is 2.41, and the water absorption is 0.65%. These findings give a comparative insight into the properties of the materials, which are indispensable in assessing their applicability and performance in concrete manufacturing.

Fig. 2 (a) Wire basket used in specific gravity test, (b) Aggregate Impact value test setup, (c) Aggregate Crushing value setup, and (d) pycnometer.

2.3. Mix Design

In this study, the mix design will be a concrete made with an M30 grade concrete using 53 grade Ordinary Portland Cement (OPC). There were three main kinds of coarse aggregates used, such as basalt, granite, and marble, with a nominal maximum aggregate size of 20mm. There is also a requirement for a mix design to have an attribute of a water-cement ratio of 0.45 and 100mm workability under severe exposure conditions. The minimum content of cement was 320 kg/m3, while the maximum content of OPC was 450 kg/m3. Each aggregate type was checked in terms of specific gravity and water absorption, which are important data concerning the calculation of the mix ratio. Compressive strength was determined to be 35.25 N/mm^2 as the target average with a standard deviation of 5 N/mm^2. Calculations of the mix were done to calculate the weights and volumes of each component, with optimization of proportions with regard to strength and durability. Table 2 below is a summary of the mix design results of both types of coarse aggregate:

Table 2. Mix design results

Material	Basalt	Granite	Marble
Cement (kg/m³)	413	413	413
Water (kg/m³)	186	186	186
FA (kg/m³)	800	800	800
Coarse Aggregates (kg/m³)	1094	1006	929
Water-Cement Ratio	0.45	0.45	0.45
Mix Proportions	1: 1.94: 2.65	1: 1.94: 2.43	1: 1.94: 2.25

Table 2 summarizes the concrete mix designs prepared using 3 various types of coarse aggregates—basalt, granite, and marble. For all three mixes, the cement content was kept constant at 413 kg/m³, and the water content was maintained at 186 kg/m³, giving a uniform water–cement ratio of 0.45. To ensure consistency in the base mix, the fine the aggregate content was also kept the same for all cases at 800 kg/m³. The main variation in the mixes was in the quantity of coarse aggregate used. Basalt required 1094 kg/m³, granite required 1006 kg/m³, and marble required 929 kg/m³. Accordingly, the mix proportions were 1: 1.94: 2.65 for basalt, 1: 1.27: 2.243 for granite, and 1: 1.94: 2.25 for marble. These adjustments were made to account for the differences in the physical properties of the aggregates, such as density and surface characteristics. By keeping the cement, water, and FA constant and varying only the coarse aggregate content, the mixes were optimized to achieve good workability and satisfactory compressive strength for each type of aggregate.

2.4. Casting and Curing

Casting and curing are very important procedures in concrete quality and its strength. In the casting process, the materials used in the process -cement, FA, and coarse aggregate materials are mixed well enough to form a uniform mixture. Such mixing duration is timed properly, until all the materials are in the mixer drum and until the concrete comes out. In this case, nine concrete blocks or cubes were used to test the compressive strength, and three blocks of each condition were made to balance the issue. The curing starts as soon as it is placed and continues after 3 ageing periods of 3, 7, and 28 days, as it is essential in ensuring that it retains proper moisture content. This is done to increase the strength and durability of the concrete by avoiding loss of moisture and improving the properties that it was intended to obtain. Appropriate curing minimizes loss of surface mixing water, hence enhancing the overall concrete performance and life.

Fig. 3 Curing of samples

2.5. Compression Test

The compressive strength test was done on the concrete cubes that had ages of 3 days, 7 days, and 28 days of curing period, respectively. It is important for the determination of the strength and durability of concrete to be able to achieve its expected value.

Fig. 4 Compression test setup

3. Results and Discussions

3.1. Aggregate Impact Value Test Results of Coarse Aggregates

Table 3 shows the Aggregate Impact value test results of the coarse aggregates basalt, granite, and marble, which indicate that the aggregates are resistant to sudden shock. Basalt, characterized by the least average value of Aggregate Impact of 10.52%, proves to be the strongest of all materials used and is therefore applicable in situations where a high level of resistance is a key factor of consideration.

Granite has a good balance between toughness and workability, with an average Aggregate Impact value of 17.78% being suitable for a variety of construction jobs. Marble (the highest average Aggregate Impact value of 25.4%) reports the lowest toughness could restrict its application in structural members, but even then, it can be an appealing choice in decorative materials given its visual value.

The findings highlight the need to choose the right type of aggregate depending on the intended use of the construction project, taking into account factors like toughness, workability issues, and aesthetic requirements to improve its performance.

Table 3. AIV test results of coarse aggregates

Sl. N o.	Description	Basalt		Granite		Marble	
		T1	T2	T1	T2	T1	T2
1.	Empty weight of mould (W1)	800	800	800	800	800	800
2.	Weight of mould + Aggregates(W2)	1180	1200	1180	1150	1200	1100
3.	Weight of aggregate (W3)	380	400	380	350	400	300
4.	Passing through 2.36mm sieve (W4)	30	50	70	50	90	85
5.	Aggregate Impact value(W4/ W3) X 100	9.52%	11.52%	18.42%	17.14%	24.8%	26.00%
Average		**10.52%**		**17.78%**		**25.4%**	

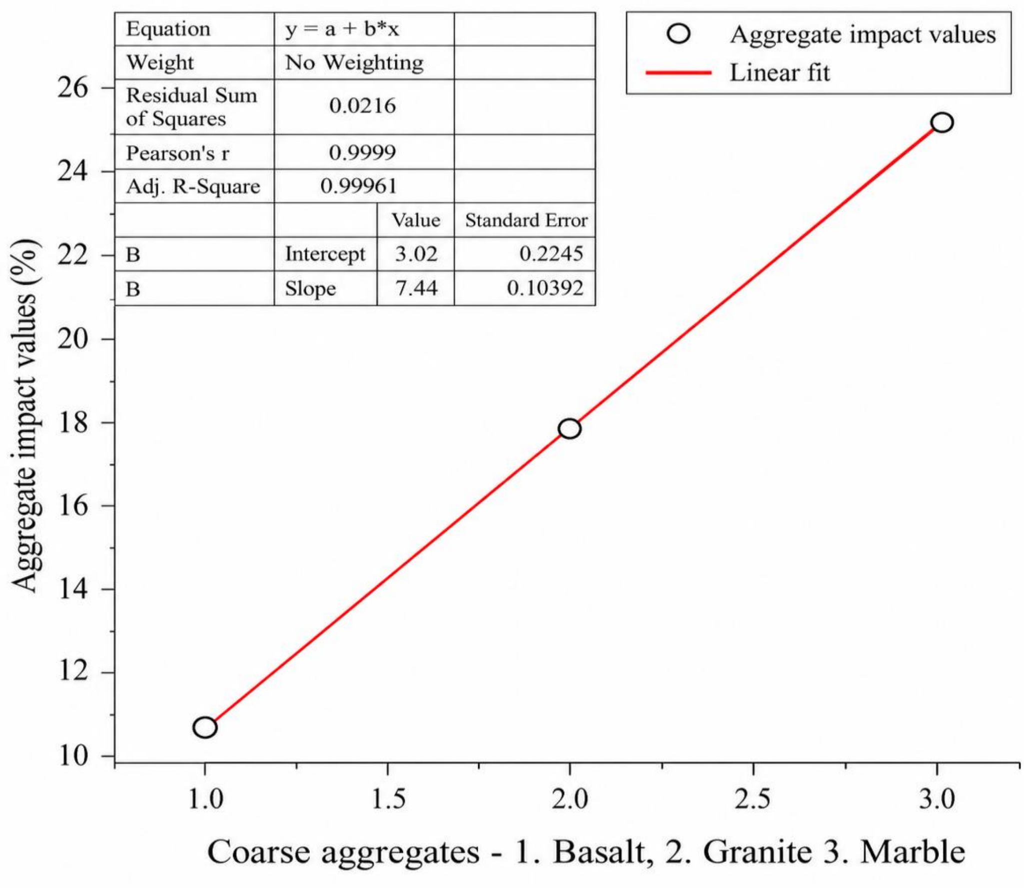


Fig. 5 Aggregate Impact values comparison of different coarse aggregates

3.2. Results of Crushing Values of the Aggregates

The results of the crushing test on coarse aggregates, basalt, granite, and marble, are listed in Table 4 and reflect the mechanical strength of coarse aggregate under compressive loads. Basalt recorded the lowest average Aggregate Crushing value of 19.22 percent, which implied that it is stronger than the other tested materials. Granite came second in average Aggregate Crushing value with 24.87%, and marble with the highest average Aggregate Crushing value of 30.57%, meaning it is the weakest in regard to its compressive strength. When these results were compared to the Aggregate Impact value test results, basalt did not just record the highest toughness but also the strongest compressive strength, making it ideal to be used in applications that demand durability and strength. With moderate Aggregate Impact value and Aggregate Crushing values, granite provides a reasonable overall performance that can be used in a wide variety of construction purposes. Having the largest Aggregate Impact value and the largest Aggregate Crushing value, marble is less tough and has less compressive strength, which restricts its application in structural designs, thus maintaining its status as decorative stone. These results highlight the necessity of choosing the correct aggregate type.

Table 4. Aggregate Crushing value test results of coarse aggregates

Sl. No.	Description	Basalt		Granite		Marble	
		Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
1.	Empty weight of container (W1)	1255	1255	1255	1255	1255	1255
2.	Weight of container + Aggregates (W2)	4300	4400	4050	4010	4100	4260
3.	Weight of aggregate(W3)	590	600	650	680	850	940
4.	Passing through 2.36mm sieve (W4)	3045	3145	2795	2755	2845	3005

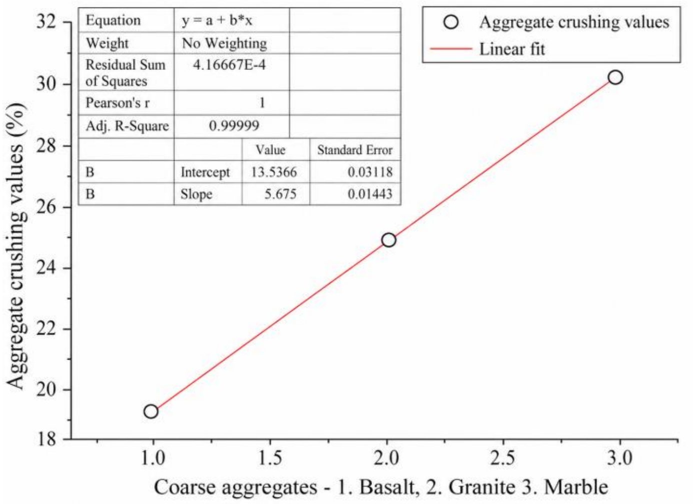


Fig. 6 Aggregate Crushing values comparison

3.3. Compression Test Results

Table 5. Compression test results

Type of Material	Compression strength (N/mm2)		
	3 days	7 days	28 days
Basalt	14.19	21.73	33.93
Granite	13.08	18.47	31.27
Marble	11.71	18.19	30.45

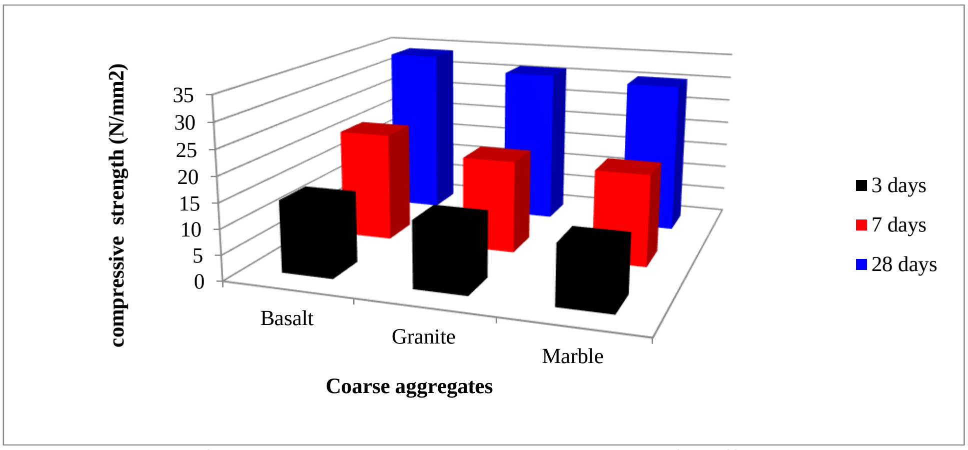


Fig. 7 Comparison of 3 days, 7 days, and 28 days compression strengths for different coarse aggregates

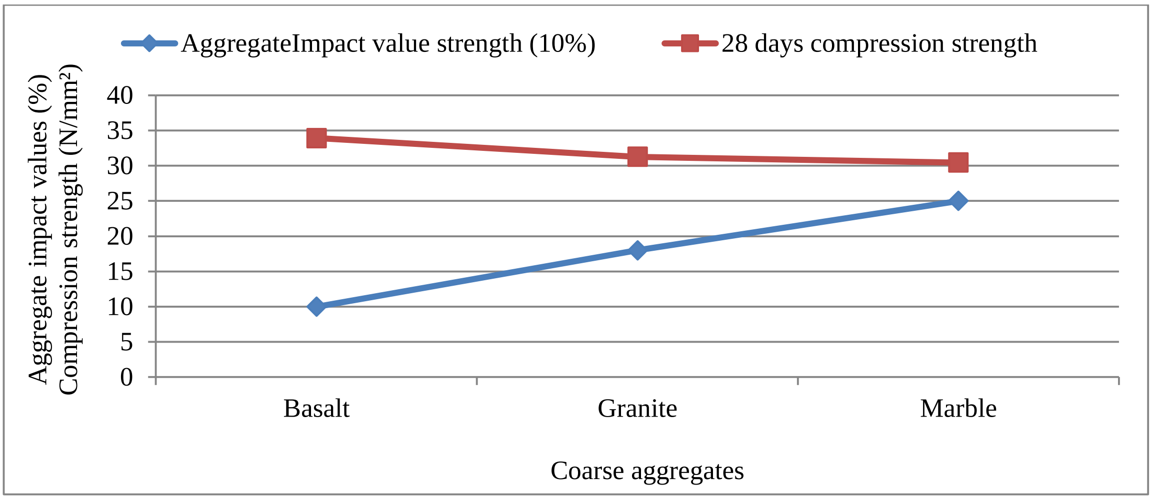
Table 5 shows the findings of the compressive strength in square concrete blocks, produced with three coarse aggregates (basalt, granite, and marble) and cured at three periods (3, 7, and 28 days). These findings illustrate how compressive strength increases or decreases with time, which is a vital insight into how the concrete would perform at any given point during the curing process.

The compression strength of the basalt at 3 days stands at 14.19 N/mm^2, with the granite standing at 13.08 N/mm^2, as the marble is 11.71 N/mm^2. This early development of strength shows that basalt has a quicker initial development of strength than granite and marble. After 7 days, the strengths have improved significantly, with the leading being basalt at 21.73 N/mm^2, granite at 18.47 N/mm^{2,} and marble at 18.19 N/mm^2. This is an indication that basalt still outshines the other aggregates in early strength development. After 28 days of standard curing as per IS Codes, all three blocks of concrete have a strength greater than 30 N/mm², which is the minimum strength required for M30 grade of concrete. Basalt is found to have the highest strength of 33.93 N/mm², whereas granite and marble concretes have compressive strengths of 31.27 N/mm² and 30.45 N/mm², respectively. These results confirm that all.

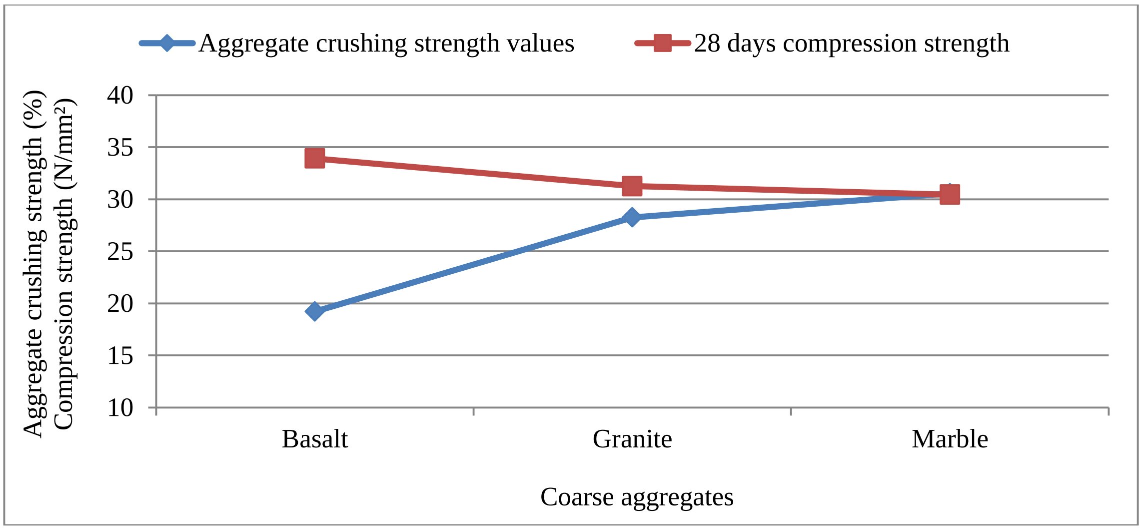
Three aggregates are suitable for producing M30 grade concrete; however, basalt offers the most substantial improvement in compressive strength.

Table 6. Comparison of ACV and AIV strength of aggregates and the compression strength of the concrete at 28 days of curing

Coarse Aggregates	Aggregate Crushing Value (%)	Aggregate Impact value Strength (10%)	Compression Strength (N/mm2)
Basalt	19.22	10	33.93
Granite	28.27	18	31.27
Marble	30.57	25	30.45



(a)



(b)

Fig. 8 Comparison of Aggregate Crushing value and aggregate Impact value strength with 28 days compression strength of the concrete

Table 6 and the related diagram are comparisons of the crushing, Aggregate Impact value strength, and the compression strength of the concrete produced using the basalt, granite, and marble aggregates after 28 days of curing. The data shows that basalt, with an aggregate crushing value of 19.22% and an Aggregate Impact value of 10%, achieves the highest compression strength at 33.93 N/mm². It means that the low crushing strength and the Aggregate Impact value strength of basalt helps to enhance its compressive capabilities. Granite, on the other hand, has a higher Aggregate Crushing value of 28.27% and an Aggregate Impact value strength of 18 %, but the compression strength is slightly lower (31.27 N/mm2). Marble has the highest Aggregate Crushing value of 30.57 and the highest Aggregate impact value strength of 25%, and thus the lowest compression strength among the three of them, 30.45N/mm2.

The findings report the negative correlation between the mechanical properties of the aggregates and the compressive strength of the concrete. The higher compressive strengths of the concretes using the more appropriate basalt aggregates can be attributed to lower crushing and Aggregate Impact value intensities of the basalt aggregates. Granite, although still offering excellent compressive strength, is ranked between basalt and marble in comparison of crushing and Aggregate Impact value strengths. Though marble is aesthetically attractive, it is not quite as good a structural material because it has a high crushing and Aggregate Impact value strength, and this results in decreased compressive strength of the concrete.

This discovery highlights the use of suitable aggregates that are picked according to their mechanical characteristics in order to maximize compressive strength and overall performance of concrete. The comparison highlights the beneficial aspects of basalt in those applications that demand a high level of durability and toughness, and granite takes a symmetric position in this matter, whereas marble, albeit weaker, could be applied where its aesthetic properties are valued.

Table 7. Comparative analysis with previous studies

Study	Aggregate Type	Concrete Grade	Major Observation	Comparison with Present Study
Kozul and Darwin [2]	Basalt and limestone	Normal & high strength concrete	Aggregate type influences fracture and strength behaviour	Present study confirms superior performance of basalt aggregates
Jimoh and Awe [5]	Granite	Normal concrete	Smaller aggregates improved compressive strength	Present study similarly shows stronger aggregates improve strength
Woode et al. [6]	Crushed gneiss	Conventional concrete	Smaller aggregate size increased compressive strength	Similar strength enhancement observed with basalt aggregates
Beshr et al. [7]	High- quality crushed aggregates	High- strength concrete	Strong aggregates improved compressive strength	Basalt with lower ACV produced highest strength
Aliabdo et al. [9]	Marble waste aggregates	Conventional concrete	Marble aggregates resulted in lower compressive strength	Present study shows marble produced lowest strength among tested aggregates
Present Study	Basalt, granite, marble	M30 concrete	Lower AIV and ACV produced higher compressive strength	Statistical validation through ANOVA and regression modelling

3.4. Statistical Approach

A statistical approach was used in determining the correlation between aggregate properties and compressive strength of concrete. ACV was analyzed as an independent variable, and compressive strength at 7 and 28 days as dependent variables.

To establish whether the differentiation of aggregate type made a significant effect on the compressive strength, one-way ANOVA was applied, whereas Pearson correlation analysis was used to determine the direction and strength of linear relationships between ACV and compressive strength.

The regression analysis was also conducted in order to build the predictive models and measure the change in aggregate properties that influence the concrete strength. This mixed method provided a thorough insight into the statistical significance and predictive performance of aggregate characteristics in determining concrete performance.

3.4.1. One-Way ANOVA

Tables 8 and 9 show the results of the one-way ANOVA, which indicates that the type of aggregate significantly affects the compressive strength of concrete at 7 days and 28 days. At 7 days, the model describes a total of 99.26 percent variation in compressive strength, and the contribution of the aggregate factor is 99.26 percent (23.2267/23.4000 x 100); the error is a mere 0.74 percent. Due to a very high F-value of 402.00 and the pointer to a p-value of 0.000, it is highly conclusive that this effect is significant. At 28 days, the type of aggregate contributes 99.10 percent of the total variance in compressive strength, and the error consists of 0.90 percent. The F-value of 329.48 and a p-value = 0.000 once again show that aggregate properties have a great effect on the long-term strength development. The above results strongly confirm that the mechanical properties of aggregates, especially their impact and crushing resistance features, are the controlling processes determining the compressive strength. Basalt has the highest strength of any of the aggregates tested because its Aggregate Impact and Crushing values are lower than those of granite and marble. This has verified the fact that the right choice of aggregates can contribute to over 99 percent of the reaction variations of strength, which points out its importance in concrete mix design to generate durable and high-performance concrete.

Table 8. One-way ANOVA for Compressive Strength of Concrete at 7 Days

Source	DF	Adj SS	Adj MS	F -Value	P -Value
Aggregate	2	23.2267	11.6133	402.00	0.000
Error	6	0.1733	0.0289		
Total	8	23.4000			

Table 9. One-way ANOVA for Compressive Strength of Concrete at 28 Days

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Aggregate	2	19.7689	9.88444	329.48	0.000
Error	6	0.1800	0.03000		
Total	8	19.9489			

3.4.2. Pearson Correlation

Table 10. Pairwise Pearson Correlations @ 7 days

S1	S2	N	Correlation	95% CI for ρ	P-Value
Strength_7days (N/mm2)	Aggregate Crushing Value (%)	9	-0.926	(-0.985, -0.680)	0.000

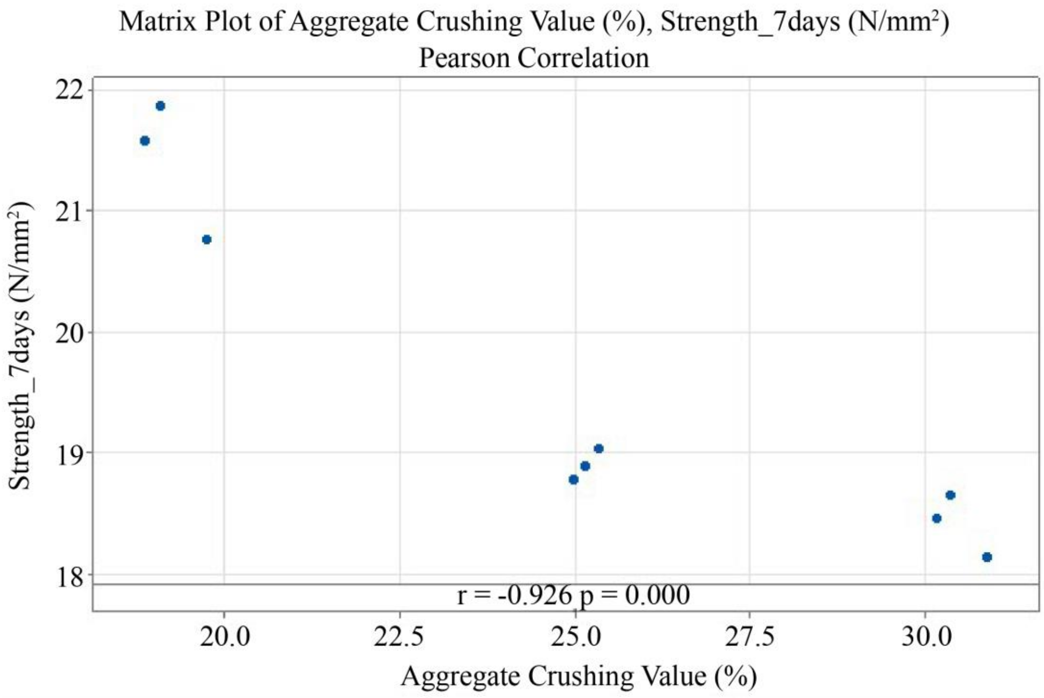


Fig. 9 Pearson Corelation @ 7 days

Table 11. Pairwise Pearson Correlations @ 28 days

S1	S2	N	Correlation	95% CI for ρ	P-Value
Strength_28days (N/mm2)	Aggregate Crushing Value (%)	9	-0.937	(-0.987, -0.721)	0.000

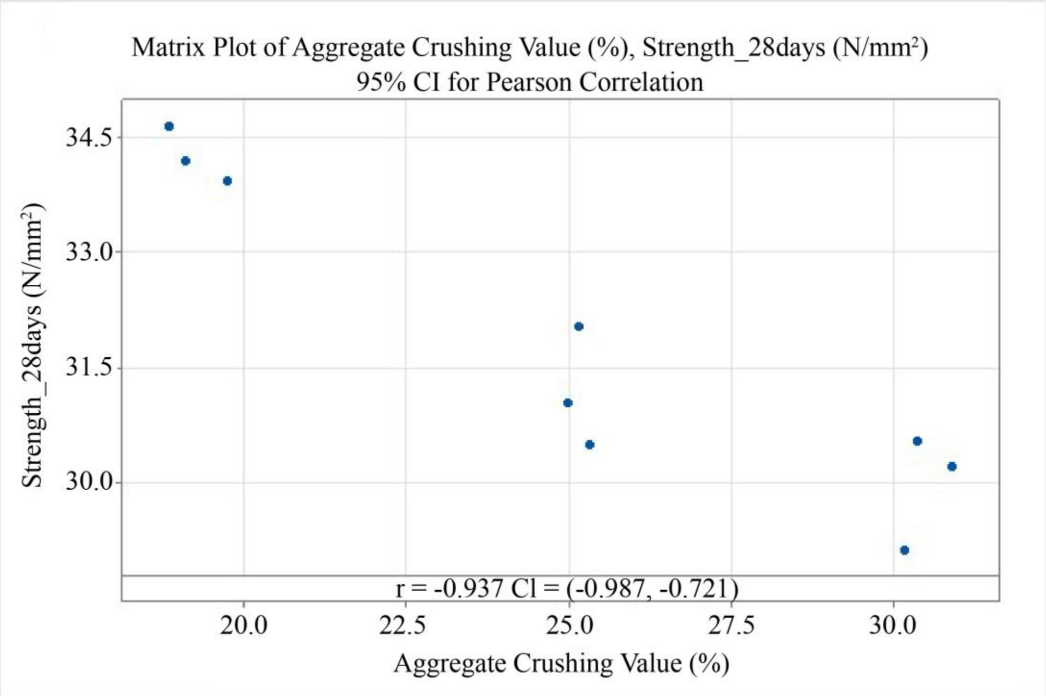


Fig. 10 Pearson Corelation @ 28 days

The Pearson correlation analysis has indicated a strong and statistically significant negative correlation between the Aggregate Crushing Value (ACV) and compressive strength at 7 and 28 days, clearly. At 7 days (Table 10), the correlation coefficient was -0.926 with 95% confidence interval (-0.985, -0.680) and p-value was 0.000, implying that crushing values and early-age strength are strongly related, where higher crushing values yielded lower early-age strength. Likewise, at 28 days (Table 11), the correlation coefficient continued to be even stronger, retaining a value of -0.937 with a confidence range of (–0.987, –0.721) and the same highly significant lower value of p=0.000. These findings reflect the fact that low-crush aggregates like basalt make concrete with a high compressive strength, and high-crush aggregates like marble make concrete with a low compressive strength. This decreasing trend is further exhibited in the scatter plots, where it can be observed that as the ACV increases, there is a progressive decrease in compressive strength. In general, the results indicate that aggregate crushing resistance is a decisive factor that influences early and long-term concrete strength.

3.4.3. Regression Analysis

Table 12. Analysis of Variance @ 7days

Source	DF	Adj SS.	Adj MS.	F-Value	P-Value
Regression,	1	14.003	14.0028	42.15	0.000
Aggregate Crushing Value (%)	1	14.003	14.0028	42.15	0.000
Error	7	2.326	0.3322		
Total	8	16.328			

Regression Equation

Strength_7days = 26.32 – 0.2704 Aggregate Crushing Value (%)

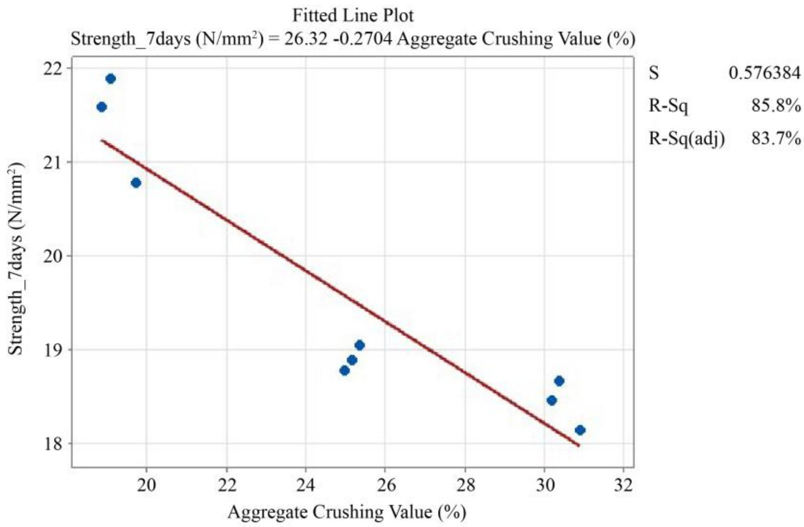


Fig. 11 Fitted line plot @ 7 days

At 7 days of the regression analysis, Aggregate Crushing Value (ACV) exhibits a strong negative impact on compressive strength. The resulting model Strength 7 days = 26.32 - 0.2704 x ACV shows that each 1 percent increment in ACV implies a reduction of about 0.27 MPa compressive strength. This relationship is also supported by the ANOVA results, where the F-value is very high (42.15), and the p-value is very small (0.000), indicating a strong statistical significance. The coefficient of determination (R2 = 85.8%) indicates that the variation in 7-day compressive strength is explained by ACV, with only a small proportion of around 14 % being attributed to other sources of variation. This downward trend is particularly evident in the fitted line plot, which indicates that concrete manufactured with aggregates with lower ACVs, like basalt, has substantially greater early-age strength than those with higher ACVs, like marble. This highlights the importance of aggregate crushing resistance in the early compressive strength of concrete.

Table 13. Analysis of Variance @ 28 days

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	1	28.057	28.0572	49.95	0.000
Aggregate Crushing Value (%)	1	28.057	28.0572	49.95	0.000
Error	7	3.932	0.5617		
Total	8	31.989			

Regression Equation

Strength_28days = 41.36 – 0.3827 Aggregate Crushing Value (%)

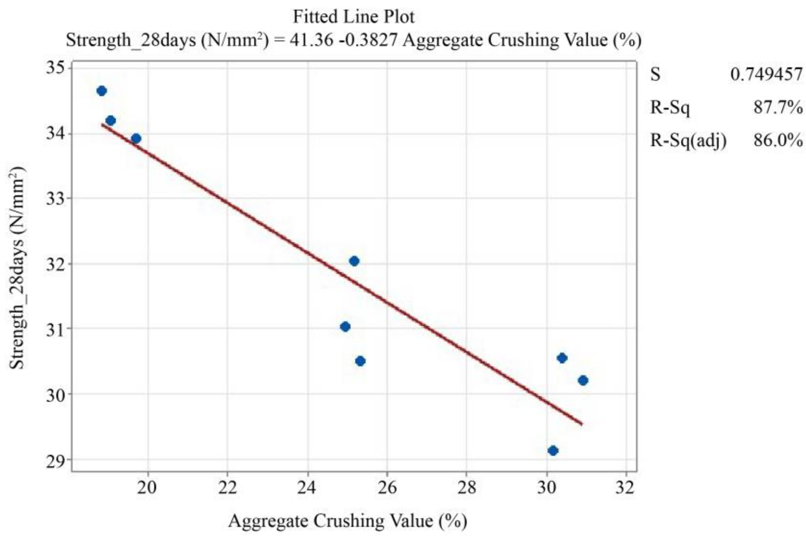


Fig. 12 Fitted line plot @ 28 days

At 28 days, regression analysis indicates that there is a high negative relationship between (ACV) and compressive strength of concrete. Using the equation of the regression, Strength 28days = 41.36 + 0.3827 x ACV, the 28-day compressive strength will decrease by approximately 0.38 MPa with each 1 percent rise in ACV, a more rapid decline as compared to the 7-day trend. The ANOVA table shows that the regression model is so strong with F-value = 49.95 and p-value = 0.000, showing high significance that ACV is the biggest predictor factor of concrete strength. The model shows that 87.7 percent of the variation in the strength at 28-day (R 2) is explained by the model, and the adjusted R 2 (86.0) further demonstrates its strength. The plot of the fitted line reveals a descending trend, suggesting that higher crushing value aggregates significantly reduce long-term strength. This implies that the aggregate quality and strength are even more essential in dictating the durability and final concrete resistance at later curing stages.

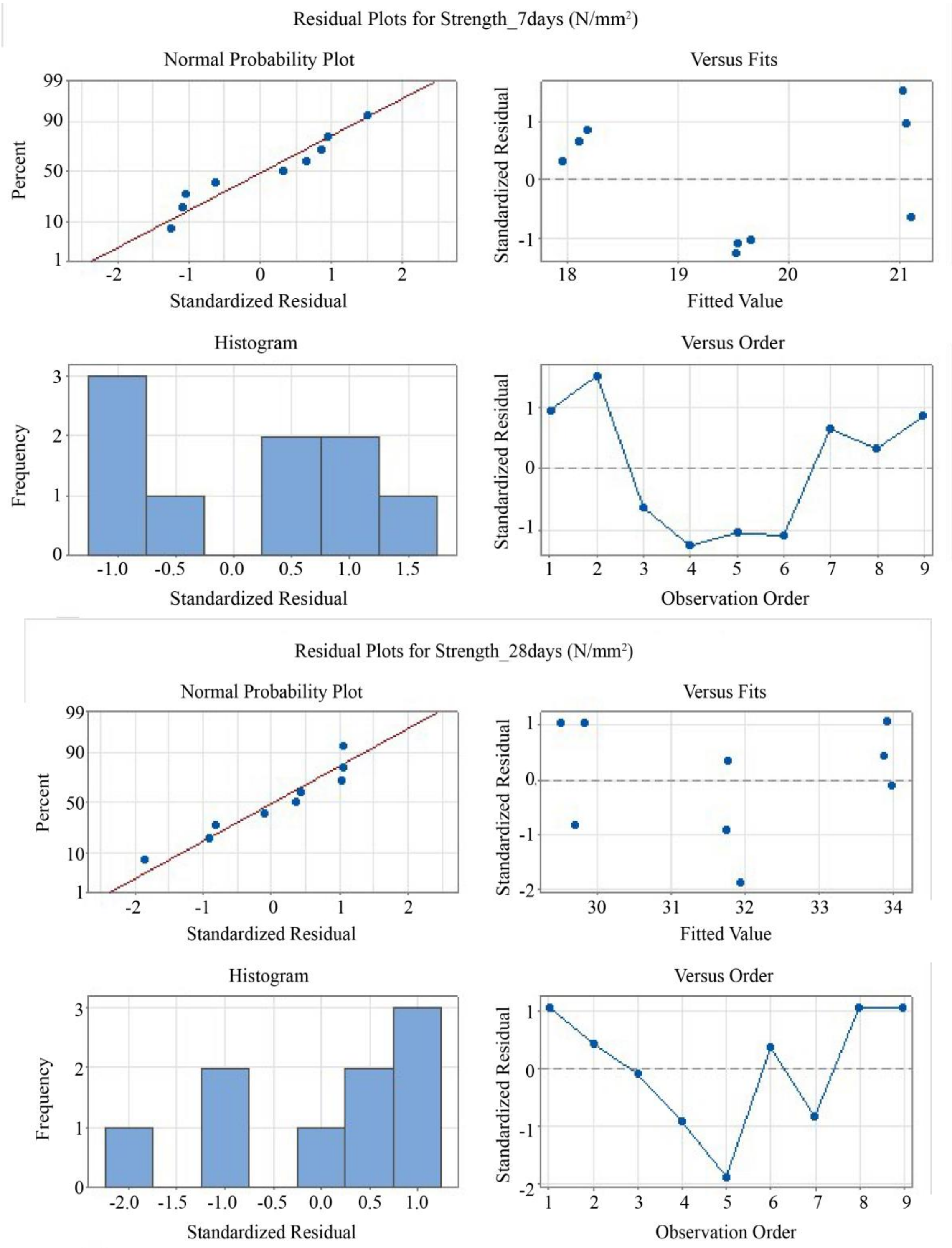


Fig. 13 Residual plots for compression strength @ 7 and 28 days

Both 28-day and 7-day compressive strength residual plots verify the statistical validity of the regression models and satisfy major assumptions. The normal probability plots indicate that the residuals display an approximate straight-line direction, which implies normality. Their histograms are mostly symmetrical with no severe skew, and the versus fits plots do not show any pattern, indicating that the homoscedasticity hypothesis was met. Lastly, the versus order plots portray no systematic patterns, which means that the residuals are independent and do not exhibit autocorrelation. In sum, these residual diagnostics affirm the sufficiency of the regression models and consequently certify Aggregate Impact Value as a dependable predictor of compressive strength at early and more mature curing ages.

3.4.4. Predictive Performance and Error Analysis

Statistical indicators like coefficient of determination (R^2), adjusted R^2, and residual analysis were used to test the predictive capability of the developed regression models. The 7-day compressive strength model had R^2 = 85.8%, and the 28-day compressive strength model had R^2 = 87.7%, which showed a strong relationship between (ACV) and compressive strength. The regression models showed statistically significant behaviour with large F-values and p- values lower than 0.05. The plots of the residuals were randomly distributed, and no significant patterns were observed, indicating that the regression models were adequate and the assumptions of linear regression were met. The resulting equations can be employed to preliminarily predict concrete compressive strength based on aggregate crushing behavior, thus supporting aggregate selection and optimization of concrete mix design.

Table 14. Predictive Performance of Regression Models

Parameter	7-Day Model	28-Day model
Regression Equation	Strength = 26.32 − 0.2704(ACV)	Strength = 41.36 − 0.3827(ACV)
R^2 (%)	85	87
Adjusted R^2	83.7	86
F-value	42.	49.
P-value	0	0
Model	Significant	Significant

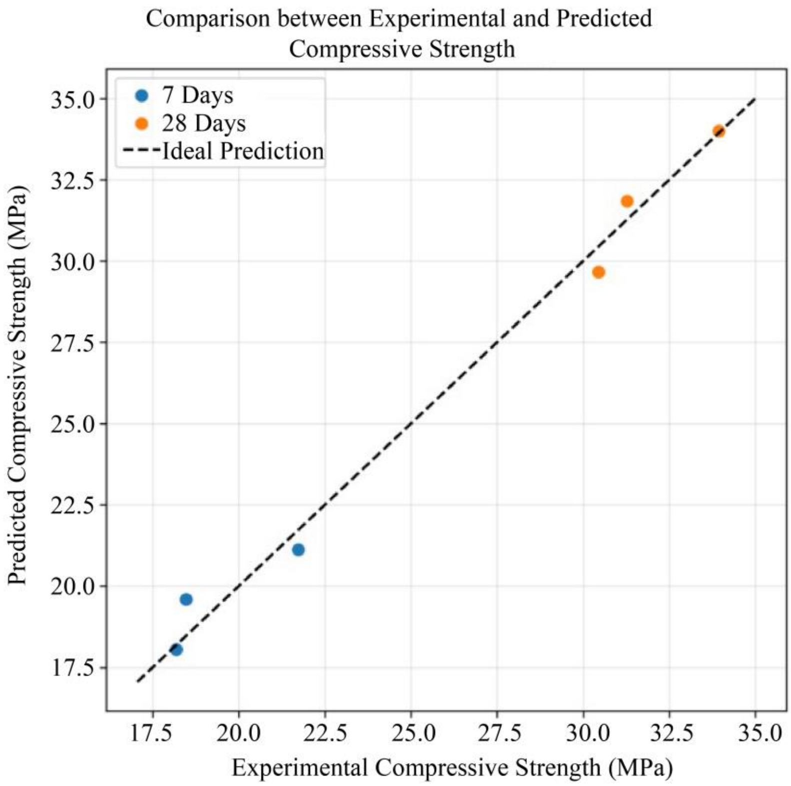


Fig.14 Comparison between experimental and predicted compressive strength

Figure 14 compares the experimentally measured compressive strengths at 7 and 28 days and the regression-predicted compressive strengths at 7 and 28 days. The strong correlation between the predicted and the experimental values is an indication that the regression models developed are sufficient and reliable enough to be used to predict the experimental values.

3.4.5. Statistical Consistency and Data Reliability

To guarantee the reliability and consistency of experimental results, three trials were carried out to measure AIV and ACI and compressive strength. Three concrete specimens were tested at each curing age and type of aggregate, and the average compressive strength was given.

The difference between repeated measurements was found to lie within reasonable experimental boundaries, indicating good repeatability of the testing procedure. In statistical analysis, experimental datasets were analyzed against abnormal deviations and observation inconsistencies. No major outliers were found in the measured data, and thus all experimental observations have been retained to be evaluated statistically.

The sufficiency and consistency of the datasets were further ensured by the residual analysis that was conducted during the regression modelling. The residual plots were random, and no systematic tendencies were observed, which meant that the experimental behaviour was stable and that the model reliability was acceptable. The near coincidence between experimental and predicted compressive strengths also confirmed the strength of the developed regression equations.

The combination of the controlled laboratory conditions, constant mix proportions, uniform curing procedures, and calibrated testing equipment contributed collectively to minimizing experimental uncertainty and enhancing the reproducibility of the results.

3.4.6. Mechanism of Aggregate Influence on Compressive Strength

The disparity noted between the compressive strength of basalt, granite, and marble aggregate can be explained by their differences in mineralogy, density, porosity, and their respective resistances to crushing and impact forces. Aggregate materials that exhibit greater mechanical strength and lesser porosity provide better load distribution and improved bonding capabilities within the cement matrix.

Basalt aggregates had the highest compressive strength because it had a dense microstructure, reduced water absorption, and was more resistant to crushing and impact forces. The lower (ACV) and (AIV) of basalt presuppose more powerful aggregate particles, which could resist internal fracture under compressive loading. Moreover, the geometric surface roughness of basalt can play a role in enhanced mechanical interlocking and enhanced aggregate-paste bond formation.

Aggregates of granite exhibited moderate compressive strength. Strength behaviour because their mechanical properties were relatively well balanced, and their crushing resistance was moderate. Whereas granite structural stability is good, its relatively high ACV and water uptake compared with basalt may result in a slight decrease in the efficiency of stress transfer in the concrete matrix.

The marble aggregates had a relatively lower compressive strength due to their greater crushing value, greater water absorption, and lesser resistance to impact loading. Marble is mostly constituted by recrystallized carbonate minerals, which are generally softer and more prone to fracture under compressive stress than the silicate-based basalt aggregates.

The smoother surface texture and increased porosity of marble can also undermine the Interfacial Transition Zone (ITZ) between aggregate and cement paste, and initiate and propagate cracks earlier.

The negative correlation between ACV/AIV and compressive strength observed thus indicates that aggregates with greater mechanical resistance help to make concrete stronger and more durable by improving the distribution of internal stresses and reducing the fracture of aggregates during loading.

3.5. Practical Implications and Sustainability Considerations

The practical implications of the current study are significant in terms of concrete mix design and the selection of aggregates in structural applications. The findings clearly suggest that aggregates with lower (ACV) and (AIV) yield high compressive strength concrete. Thus, aggregate mechanical properties must be given thoughtful consideration in mix proportioning to obtain enhanced structural performance and service life. Basalt was found to be an excellent performer in terms of mechanical performance among the aggregates investigated because it had lower crushing and impact values than other aggregates and could be used in high-strength and heavy-duty concrete applications. Granite is moderate and can be effectively utilized in conventional structural concrete, which is not critical, and in structural architectural work, which is not critical.

In terms of sustainability, the proper selection of aggregates can lead to the reduction of excessive cement consumption by enhancing the efficiency of strength through the optimization of aggregate performance. Application of durable aggregates can also improve service life and minimize maintenance needs of concrete structures. Moreover, the analysis of other aggregates like marble also adds to the sustainable use of materials and effective management of natural resources. The resulting statistical relationships can also help the engineers in the preliminary aggregate screening and mix design optimization, thus saving the experimental trials, wastage of materials, and construction expenses.

3.6. Limitations and Future Scope

The main focus of the present investigation was to identify the relationship between aggregate mechanical properties and compressive strength behavior of grade M30 concrete.

Despite the fact that the compressive strength is an essential factor for assessing the quality of concrete, other factors like flexural strength, tensile strength, elastic modulus, abrasion resistance, and durability were not studied in this particular investigation. Past research has indicated that aggregate properties play a significant role in determining durability- related properties such as permeability, shrinkage, abrasion resistance, and cracking resistance. Consequently, it is possible that future studies can include more mechanical and durability tests to create a more detailed picture regarding the impact of aggregate lithology on concrete performance.

Further studies on the subject of recycled aggregates, additional cementitious materials, and concrete mix design of high-grade concrete can better advance the practical applicability and sustainability of concrete mix design.

3.7. Comparison with Codal Provisions and Standards

The obtained results of the aggregate properties and compressive strength in the present investigation were compared with the corresponding Indian Standard and international codal recommendations to determine their applicability in structural concrete applications.

IS 383:2016 and IS 2386 (Part IV) specify that aggregates to be used as structural concrete should have sufficient crushing and impact loading resistance to achieve satisfactory durability and strength performance. Aggregates used in concrete to wear surfaces have their Aggregate Crushing Value (ACV) generally recommended to be less than 30, but values below 45 are considered acceptable in other concrete works. Correspondingly, smaller Aggregate Impact Values (AIV) represent enhanced toughness and resistance to abrupt loading situations.

In the current research, basalt aggregates recorded the lowest ACV (19.22%) and AIV (10.52%), which reflect the high aggregate quality and excellent applicability in structural concrete applications.

Granite aggregates also complied with codal requirements at moderate ACV and AIV values, but still remained within acceptable limits of normal concrete applications.

All concrete mixtures surpassed the typical compressive strength requirement of 30 MPa at 28 days of curing. The highest compressive strength of basalt aggregate concrete was 33.93 MPa, followed by granite (31.27 MPa) and marble (30.45 MPa), which conformed to codal strength requirements.

ACI 318 and EN 12620 provisions have reported similar observations, where aggregate strength and durability are regarded as important parameters in influencing the long- term performance of concrete.

The current results thus justify the significance of using mechanically superior aggregates to enhance structural reliability, durability, and service life of concrete structures.

Table 15. Comparison with codal recommendations

Parameter	Present Study Results	Codal Recommendation	Complianc e
Aggregate Crushing Value (Basalt)	19.22%	< 30% preferred	Satisfied
Aggregate Crushing Value (Granite)	24.87%	< 30% preferred	Satisfied
Aggregate Crushing Value (Marble)	30.57%	≤ 45% acceptable	Satisfied
Aggregate Impact Value (Basalt)	10.52%	Lower value preferred	Excellent
Aggregate Impact Value (Granite)	17.78%	Lower value preferred	Good
Aggregate Impact Value (Marble)	25.40%	Moderate acceptable range	Acceptable
28-Day Compressive Strength	30.45–33.93 MPa	≥ 30 MPa for M30 concrete	Satisfied

4. Conclusion

This work examined how Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV) of basalt, granite, and marble aggregates affect compressive strength behaviour of M30 grade concrete. The experimental results revealed that basalt aggregates, which have the lowest ACV (19.22%) and AIV (10.52%), produced the highest compressive strength at 28 days, which is 33.93 MPa, whereas marble aggregates with higher crushing and impact values yielded relatively lower compressive strength.

Statistical data analyses, such as ANOVA, Pearson correlation, and regression modelling tests, validated the hypothesis that aggregate mechanical properties had a significant impact on compressive strength development. There were strong negative relationships between ACV and compressive strength at 7 days and 28 days (r ≈ = -0.93). The regression models developed showed good predictive ability with an R^2 of more than 85, indicating that aggregate crushing resistance could be effectively used as a predictor of concrete strength performance.

The current study is contrasted with previous studies in that it incorporates experimental characterization of various aggregate lithologies with statistical modelling and predictive analysis under the same mix design conditions. The results create quantitative correlations between aggregate mechanical properties and compressive strength Behaviour and enhance the perception of aggregate selection in concrete mix design.

The research also shows the practical importance of using mechanically superior aggregates like basalt to enhance concrete strength, potential durability, and structural integrity. The relationships that have been developed can help engineers in preliminary aggregate screening, mix optimization, and sustainable material selection to be used in structural concrete applications.

Future investigations may include additional durability properties, non-destructive testing methods, recycled aggregates, and advanced predictive modelling approaches to further enhance concrete performance evaluation.

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