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Original Article

Influence of Aggregate Properties on Compressive Strength of Concrete: A Statistical Approach

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Abstract *- This research seeks to show how specific gravity, crushing value, and aggregate shape affect concrete's compressive strength. Concrete samples made with aggregates from seven sources were tested to understand how these aggregates impacted concrete at 7 and 28 days. Relationships between aggregate properties and strength were found by running one-way ANOVA, Pearson correlation and regression analysis. It is seen from the results that as aggregate crushing value goes down, compressive strength rises, and higher specific gravity improves its performance. The accuracy of the regression models for concrete strength prediction using aggregate properties was very high, with R^2 values being over 80%. The residual tests showed that the models can be trusted when developing concrete mixes. According to the results, the type of aggregate significantly used affects concrete strength and can guide decisions about which aggregate to pick for a strong material in construction.*

Keywords *- Aggregate Crushing Value, Specific Gravity, Compressive Strength, Concrete Performance, Regression Analysis, ANOVA, Pearson Correlation.*

1. Introduction

Modern concrete consists of fine and coarse aggregates, cement, water, admixtures and different additives. Strength in concrete depends on the mix proportions, processing methods, aggregates' texture and shape and other traits of the base materials [1].

Stone or rock bits of varying sizes, commonly crushed from granite, basalt, limestone, and gravel, are called aggregates. Also, they may have materials such as recycled concrete or blast furnace slag in their mix. Fine aggregates are particles with diameters up to 4.75 mm, and particles more than 4.75 mm wide are called coarse aggregates [2]. In the past, aggregates had the primary purpose of cost reduction in cement mixtures rather than having any special role. In the past, it was thought that changing the type of aggregate made little impact on concrete [3].

The main constituents of concrete, aggregates, contribute about three-quarters of its overall volume. As a result, the material's performance depends significantly on the quality of aggregates. The durability and solidity of a concrete structure depend a lot on the kind of aggregate contained in the concrete. Earlier, aggregates were seen as simple, inexpensive materials placed into the cement paste to build the concrete volume. Even so, their positioning and properties affect how concrete behaves [4]. Thorough investigations have studied how particles, surface condition, shape and alkali reactivity in aggregate can change the behaviour of concrete. Studies have shown that aggregates play a bigger role in concrete than expected, so further investigation is needed to understand this better [3].

The coarse aggregate added during mixing can strongly influence fresh and hardened concrete. With a large part of concrete being coarse aggregates, their properties can strongly affect the final product's qualities for any mix design. The quality of coarse aggregates is influenced by their beginning, particle dimensions, profile, weight per volume and surface state.

The type of source influences the main features found in building aggregates. Different concrete strength, workability and durability can result from physical or mechanical differences in their chemical composition, leading to reduced overall performance. The source of aggregates plays a crucial role in determining the strength and performance of concrete across various nominal mix designs, both in its fresh and hardened states [5-7]. Different aggregates have a notable impact on the compressive strength of concrete, with higher-strength aggregates contributing to improved overall concrete performance [8-10].

The shape, texture, and grading of aggregates play a vital role in determining the workability, finishability, bleeding, pumpability, and segregation of fresh concrete while also impacting the strength, stiffness, shrinkage, creep, density, permeability, and durability of hardened concrete [11]. Since aggregate properties are influenced by the characteristics of the parent rock-such as chemical and mineral composition, petrographic classification, specific gravity, hardness, strength, stability, and pore structure-these factors significantly affect fresh and hardened concrete [4, 12].

Research on the influence of coarse aggregate content and particle size distribution on concrete compressive strength has shown a strong correlation between these aggregate parameters and the final strength of the concrete mixture [13].

Sahin et al. [14] noted that the aggregate type and the amount of cement used influence the increase in concrete strength corresponding to a rise in cement content. Similarly, Ozturan and Cecen [15] discovered that even when the cement paste properties remain constant, variations in coarse aggregate characteristics-such as shape, texture, mineral composition, and strength-can lead to differences in concrete strength. Ruiz [16] investigated how aggregate content affects concrete performance and found that compressive strength initially improves as the coarse aggregate volume increases, reaching an optimal level before declining. This initial strength gain results from a decrease in void spaces within the mix due to adding aggregate.

Glanville et al. [17] suggested that aggregate properties, including shape, texture, and porosity, significantly impact the workability of concrete. Kaplan [18] analyzed 13 coarse aggregates to assess their influence on high-strength and conventional concrete's flexural and compressive strength. Across all testing periods, basalt-based concrete exhibited greater flexural strength than limestone-based concrete of the same mix proportions. Additionally, basalt aggregates contributed to higher compressive strength compared to limestone aggregates. Contrary to most studies, Kaplan observed that in cases where compressive strengths exceeded 69 MPa (10,000 psi), coarse aggregate played a crucial role in enhancing the final compressive strength of the concrete, surpassing that of the corresponding mortar mix.

Lately, studies have pointed out that the key characteristics of coarse aggregates, such as size, shape and grading, can improve concrete's mechanical characteristics. Experiments have shown that smaller coarse aggregates produce mixes with higher compressive strength than larger ones. For example, compressive strength results indicated that coarse aggregates had an F.M (Fineness Modulus) of 4.81 and performed better at 7, 14 and 28 days than aggregates with an F.M of 6.8 [19]. In addition, investigations revealed that quartzite, granite and river gravel (as coarse aggregates) had different amounts of compressive and split tensile strength, with smaller AGGREGATE SIZE affecting the concrete's technical properties.

This investigation found that both the size of the aggregate and its mineralogy can influence concrete performance, apart from any other changes in the mix [20]. In addition, the compressive strength of HSC (High Strength Concrete) has been shown to rise by up to 141% and the modulus of elasticity by 48% based on the type and flexibility of the coarse aggregate used. Using the Compressive Packing Model (CPM) and data-calibrated equations from ACI 363 shows that the aggregates' structure supports higher concrete performance [21]. These conclusions are compatible with the current study's aim to show, using statistics, that the strength of concrete mixes depends on the aggregate's qualities, proving that careful choice of aggregate is important for making durable and high-quality concrete.

Even so, the statistical modelling of the collective effect of several key properties-specific gravity, ACV and particle shape-on concrete compressive strength is still challenging to address. These parameters are mostly studied independently or independently for different regions, not all within one statistical frame. Progress has not been made in forming applicable predictive models that use several aggregate characteristics to calculate the strength of concrete reliably at any point during curing.

This study fills this gap by evaluating results experimentally and analyzing statistical information, one-way ANOVA, Pearson correlation and regression analysis to measure the effect of aggregate quality on concrete compressive strength. An important feature of this study is that it looks at specific gravity, crushing value and shape indices, all at once, for concrete made from seven different geological sources. The thorough quality of the data and precise regression models (R^2 more than 80%) support a better view of how aggregate quality influences strength growth at the early and final phases.

Unlike most previous similar research, this study provides a proven statistical framework to determine strength based on material properties, making it more usable in standard concrete mixes. In regions with a broad mix of geological structures, such as Karnataka, the work is essential as the quality of aggregates depends on the area from which they are mined.

Using mixes made from seven quarries with a constant Grade M25 ratio lets the study link changes in concrete strength to the particular aggregate used. Using this approach, engineers can find effective aggregate sources and use materials that improve how structures last and perform.

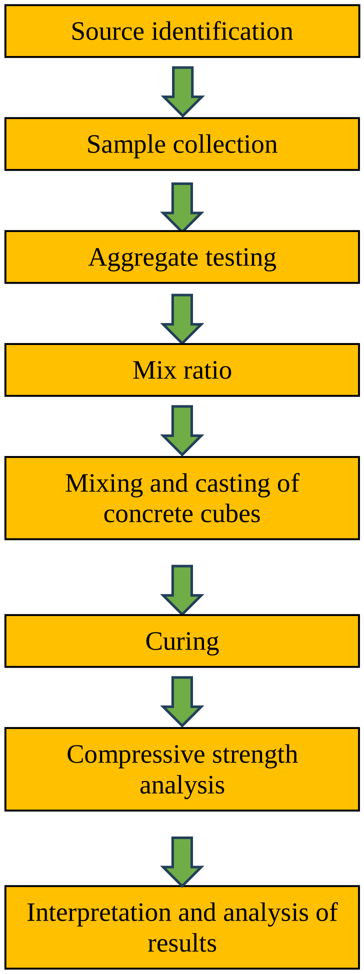

Fig. 1 Methodology flowchart

1.1. Emphasize the Real-World Applications

This study fills a critical research gap in understanding the statistical relationship between aggregate quality and concrete strength and provides practical tools for industry professionals. The predictive regression models and correlation findings can assist civil engineers and construction practitioners in selecting the most suitable aggregates for site-specific conditions, optimising mix design, reducing quality variability, and improving structural performance. These insights benefit regions with diverse geological aggregate sources, helping standardize project quality control practices.

2. Methodology

The study uses experiments to test how coarse aggregate's origin affects concrete's compressive strength. This research focuses on the coarse aggregate by comparing how five different sources affect the final results. The primary dependent variable under study is concrete compressive strength at 7 and 28 days. For consistency, the nominal mix ratio, water-cement (w/c) ratio, cement grade (53), fine aggregates (M-sand), and amount of water remain the same. Before including the coarse aggregates in the M25 design are tested for specific gravity, aggregate crushing value, and shape. After casting the cubes, their compression strength is measured according to standard practices to examine the effects of aggregate properties on concrete performance. The findings are studied to prove connections between the concrete's physical characteristics and its ultimate strength.

2.1. Identification of Source and Collection of Samples

An analysis was performed through field visits, and a questionnaire survey was prepared among construction material providers and local builders. This method achieved a detailed overview of the primary coarse aggregates commonly used in Karnataka's building districts.

Samples of coarse aggregates were purposely obtained from different places within different districts to show a wide range of geological types. The informative spots chosen for the study were Devanahalli in Bengaluru Urban District, Hosur in Krishnagiri District, Chakarasanahalli, Tekal and Kolar District, Bidadi in Ramanagara District, Chikkaballapur in Chikkaballapur District and Kunigal in Tumkur District. Such locations were picked since they provide significant amounts of coarse aggregates to the construction industry, making it easier to see how different aggregate qualities affect the compressive strength of concrete.

2.1.1. Justification of Sample Size and Coarse Selection

The decision to collect aggregates from seven districts in Karnataka was designed to showcase the geology of each region and match the usage of aggregates seen in local construction. Field surveys and consultations with contractors and suppliers revealed these sources to have a high volume and be widely used in many construction projects. The total number of datasets (n = 7) does not seem high, but it shows a fair reflection of what must be tested and verified, given how they must be collected and tested for accuracy. Researchers deeply study only a few samples to ensure accurate analyses with standard IS procedures and strong statistical methods. The fact that the mix design and testing conditions are the same for all sources increases the reliability of the findings.

2.2. Geological Properties of the Coarse Aggregates

The various rock types and mineral mixes in the different sources make the geology of the coarse aggregates very different. Gneisses, dykes, veins of pegmatite and laterites are the main features of Chikkaballapur, and coarse-grained granites mostly occur in its western region. In Yellodu, the outstanding "Queen Rose" granite shows that quartz and feldspar are the main minerals in these igneous rocks. Old Peninsular gneiss is the primary rock found in Achaean-aged granite and gneissic rocks in Tekal. Bare hilltops, many types of slopes and flat valleys make up the area, occasionally punctuated by dykes, pegmatites and quartz veins, all helping to define the region's geology.

Charactered by rock types such as charnockite and granitic gneiss, Hosur is predominantly grey in its metamorphic and sedimentary formations. The region's geology is affected by the rich feldspar, mica, quartz and microcline found in these formations. Most of Devanahalli is formed by metamorphic and igneous rocks, like granites and granitic gneisses, which tend to be light grey. Quartz and feldspar, as the dominant minerals, strongly affect the area's distribution of rock and resources.

Chakarasanalli in Kolar combines sedimentary and igneous rock structures such as laterite, limestone, granites and gneisses. It is essential because of the many minerals found here, such as gold, clay, corundum, feldspar, garnet, kaolin, graphite, tungsten, molybdenum and quartz. The Ramanagara district's Bidadi is part of the Peninsular Gneissic Complex and is mainly built from Archean granites and gneisses. The upper soil layers are lateritic and sedimentary, resting over the original grey to pinkish-grey rock formations. Minerals found underground include feldspar, quartz, mica, clay, and small amounts of iron ore and bauxite because of lateritic weathering.

Archean granites, gneisses, schists, and weathered laterite formations can be found in Kunigal, Tumkur district, and part of the Southern Indian Shield. The rocks are dark grey, and the region is known for plentiful quartz, feldspar, mica, clay, iron ore and manganese. Granitic intrusions and metamorphic changes in this area help Kunigal earn importance among geologists within the Closepet Granite belt and Dharwar Craton. The unique geology and minerals at these locations give the coarse aggregates important properties that affect their suitability for concrete.

2.3. Physical and Mechanical Properties of Coarse Aggregates

Coarse aggregates are suitable for construction use mainly due to their physical properties. Tests check the stone's specific gravity, crushing strength and shape. For bigger aggregates (larger than 10mm), the method requires a balance, an oven, a wire basket, a watertight container, absorbent towels, a shallow tray and an airtight container. Using a 2000 g sample, dust particles are removed by washing and then the sample sits in distilled water for 24 hours at a temperature of 22–32°C while it is lifted and lowered 25 times to remove air bubbles. The basket and sample are weighed in water (Weight A), followed by the empty basket in water (Weight A1). After draining, the aggregate is surface-dried using cloths, exposed to air until completely dry, and then weighed (Weight B). Finally, the sample is oven-dried at 100–110°C for 24 hours, cooled in an airtight container, and weighed (Weight C). These weights are used to determine the specific gravity and water absorption of the aggregate - IS 2386 (Part III): 1963.

The aggregate crushing value test evaluates the resistance of aggregates to crushing under a gradually applied compressive load. This test is crucial in determining aggregate strength and durability, ensuring their suitability for structural applications. The procedure involves selecting aggregate samples retained on a 10 mm sieve and passing through a 12.5 mm sieve. These samples are compacted in a cylindrical mould in three layers, each tamped 25 times. A compression testing machine applies a 40-tonne load over 10 minutes. The crushed material passing through a 2.36 mm IS sieve is weighed and expressed as a percentage of the original sample weight, referred to as the ACV. A lower ACV indicates stronger, more durable aggregates suitable for high-load applications like pavements and runways, while higher values suggest reduced strength and durability.

The shape of coarse aggregates significantly impacts their performance in construction materials. Aggregates may be spherical, cubical, angular, flaky, or elongated. Flaky and elongated aggregates tend to weaken concrete due to poor interlocking and bonding, whereas cubical and angular aggregates enhance strength and durability.

To assess the aggregate shape, two standard tests are conducted as per IS 2386 (Part I): 1963:

- Flakiness Index Test: Determines the percentage of flaky particles by comparing their weight to the total sample weight. Flaky particles are thinner than their mean dimension, leading to weak bonding in concrete.

- Elongation Index Test: Measures the proportion of elongated particles that are excessively long relative to their mean dimension, affecting concrete strength and durability.

The findings of these tests guide the choice of aggregates to provide the best shape, better interlocking, better structure and better overall performance of construction materials. If these physical properties are understood and managed, the results of construction projects can be much better and last longer.

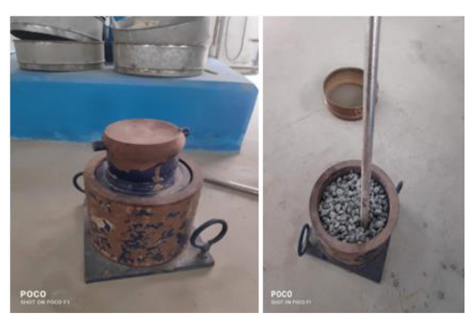

Fig. 2 Crushing test mould, sieves used and crushing test machine

2.4. Materials, Mixing, Casting, Curing and Compression Test

Compressive strength in concrete can be evaluated using sequential phases such as choosing materials, mixing, casting, curing, and placing them in a compression test. This study uses cement, fine aggregates (M-sand), and coarse aggregates, all of which follow standard requirements. The mix has been designed to meet the specifications in IS 10262:2009 and IS 456:2000, so it has excellent strength and durability. The proper tests are reliable because the recommended ratio of 1:2.48:3.31 for cement, sand and aggregate is followed.

The cement in the study is OPC 53 grade (ULTRATECH CEMENT), inspected by hand for colour, lumps, temperature, smoothness of texture, water behaviour and paste stickiness. M-sand is tested using hand, water, salt and inspection methods to prove its quality and suitability for concrete. The compressive strength of coarse aggregates at 7 and 28 days is examined to determine how much they influence the concrete's quality.

Mixing cement, sand, aggregate, and water ensures no differences. Next, the mixed concrete is put into 150mm x 150mm x 150mm cube Moulds to make standardized samples. The material is compacted enough to eliminate gaps and provide greater density.

Fig. 3 Cube casting moulds and standard size of the cube

Following casting, the concrete cubes are preserved in a moist setting for 24 hours before removal. They are placed into clean, fresh water maintained at 27±2°C for 7 or 28 days as required. By curing it, enough moisture is present (hydration) so that the concrete develops the required strength.

Fig. 4 Casting of concrete moulds

Fig. 5 Curing of concrete cubes

All compressive strength tests are performed with the help of a compressive testing machine. Correct placement of the cubes in the test equipment keeps the loads centred to prevent off-axis stress. A gradual rise in the axial force to 140 kg/cm² per minute is maintained until the specimen breaks. Compression strength is determined by dividing the measured load on the cube by the area of the cube's cross-section. The test outcomes confirm that the concrete is strong enough and suitable for building, following structural rules. Paying attention to how products are treated and using proper testing methods are vital for receiving and repeating good results.

Fig. 6 Compression testing machine

All samples were produced in a controlled laboratory setting to maintain consistency in batches. Homogeneity was achieved in mixing by using a pan mixer, and a table vibrator was used during compaction to get rid of trapped air. All mixes were poured into three 150 mm × 150 mm × 150 mm standard cubes, and samples were cured in a water tank at

27 ± 2°C. On days 7 and 28, tests were conducted with a calibrated digital machine that applied force at a constant rate of 140 kg/cm²/min.

In addition, the environment was closely watched, so small changes like temperature and humidity did not influence the results. Cement, M-sand and water were all taken from the same batch to make the results more consistent.

2.5. Limitations and Aggregate Variability

- Even though a rigorous experimental and statistical effort was used, some limitations must be recognized to help explain these findings.
- Although the aggregates were taken from seven quarries, variations within each could still result in different aggregate qualities. Although this study uses representative sampling, the extent to which results can be replicated may depend on the variability found in each quarry.
- The grade of M25 cement was kept constant in all the samples. Even though this step lowers the dependence of the results on mix contents, the findings cannot be applied to mixes that differ from the standard one since the effects might be different with different cement-aggregate interactions.
- With only seven data sources, the regression models cannot always be applied to other settings. Using data with more types of aggregates might increase the strength and practical use of prediction models.
- The way the shapes formed was determined using flakiness and elongation indices. Even so, these measurements can be rough and may not correctly show surface details, which affect how the material connects or holds together.
- Since the study did not account for changes in temperature, humidity or curing conditions, actual real-world effects on compressive strength were not assessed.

3. Results and Discussion

3.1. Physical Properties of Coarse Aggregates

The physical properties of coarse aggregates were examined using gravity testing, crushing value tests and shape analysis.

The specific gravity test helped measure the aggregates' density and quality, and the aggregate crushing value test confirmed their ability to stay strong and durable under pressure.

Moreover, the aggregate shape test gave insight into the shape of the particles, and these shapes guide the amount of cement needed and how well the blocks of concrete fit together. Such tests ensure that aggregates are appropriate for making concrete and follow the set requirements.

Table 1. Specific gravity, aggregate crushing values and aggregate shape test values for aggregates collected from different sources

Source	Sp. Gr.	Crushing value	Flakiness index (%)	Elongation index (%)
Devanahalli	2.7	16	27	33
Hosur	2.68	18	26	34
Chakarasanahalli	2.65	20	25	35
Bidadi	2.64	22	27	34
Tekal	2.65	22	26	34
Chickballapur	2.64	23	28	35
Kunigal	2.62	28	25	35

Various properties of the different coarse aggregates were assessed by looking at their specific gravity, crushing value, flakiness index and elongation index. The specific gravity was between 2.62 (for Kunigal) and 2.7 (for Devanahalli), showing that the aggregates differed slightly in density and composition. However, the values were still inside the range allowed by IS 2386 (part I). Devanahalli aggregates showed less susceptibility to crushing and greater strength, reaching 16% on the aggregate crushing value scale. In contrast, Kunigal aggregates were less resistant, with a crushing resistance of 28%. The number of fine particles was low in Devanahalli (25%) and slightly higher in Kunigal (29%), while the number of elongated particles was higher in Kunigal (35%) and very low in Devanahalli (32%). These characteristics show how the shape of aggregates affects the workability and how the pieces in the concrete are fitted together. The aggregates from Devanahalli had the best properties, suggesting they could be ideal for high-strength concrete.

3.2. Mechanical Properties of Concrete (Compression Strength)

The load-bearing power and strength of concrete are dependent on its compressive strength. Many considerations affect it, including the mix used, the amount of water, curing and the quality of the aggregates. The strength is checked at 7 and 28 days using cubical samples loaded with mechanical force until they break. Selecting the proper ingredients and sticking to careful testing rules guarantee that the concrete meets the expected requirements for use in the building.

Table 2. Compression strength values of cubes at 7 days

Source	Compression strength @ 7 days (N/mm^2)			
	Test 1	Test 2	Test 3	Average
Devanahalli	21.407	21.51	21.49	21.469
Hosur	20.2	21	21.2	20.8
Chakarasanahalli	19.81	21.3	20.9	20.67
Bidadi	20.29	21.1	20.035	20.475
Tekal	20.2	19.8	19.67	19.89
Kunigal	18.9	19.34	18.31	18.85

Chickballapur	18.41	19.25	18.5	18.72

Table 3. Compression strength values of cubes at 28 days

Source	Compression strength @ 7 days (N/mm^2)			
	Test 1	Test 2	Test 3	Average
Devanahalli	32.9	33.09	33.1	33.03
Hosur	32.5	33	32.6	32.7
Chakarasanahalli	31.40	32.1	31.9	31.8
Bidadi	30.80	32	31.70	31.5
Tekal	30.4	31.3	30.1	30.6
Kunigal	29.80	28.9	28.30	29
Chickballapur	28.1	29.4	28.9	28.8

At 7 and 28 days, the results for compressive strength were not the same, depending on the source of coarse aggregates. The average strength at 7 days in Devanahalli was the highest at 21.47 N/mm², followed by Hosur at 20.8 N/mm² and Chakarasanahalli at 20.67 N/mm². Chickballapur and Kunigal had the lowest strength values, at 18.72 N/mm² and 18.85 N/mm², respectively. A similar trend is observed at 28 days, where Devanahalli aggregates achieved the highest strength of 33.03 N/mm², while Chickballapur (28.8 N/mm²) and Kunigal (29 N/mm²) recorded the lowest values. The results suggest that aggregate properties, such as specific gravity and crushing value, significantly influence concrete strength, with higher specific gravity aggregates generally leading to improved compressive strength.

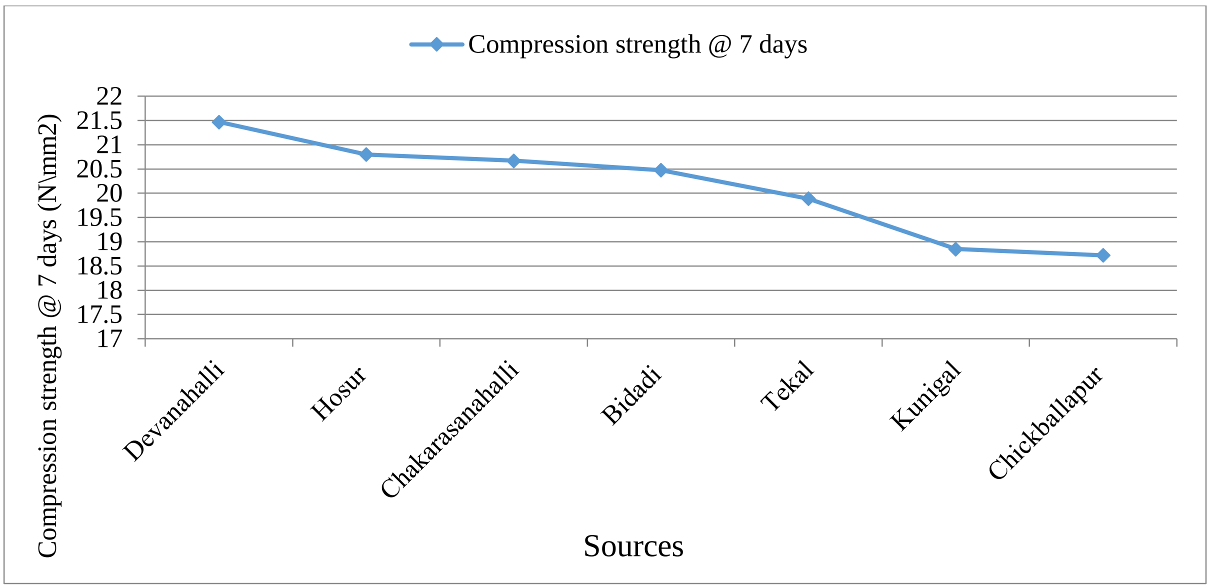

Fig. 7 Compression strength @ 7 days of cubes from different sources

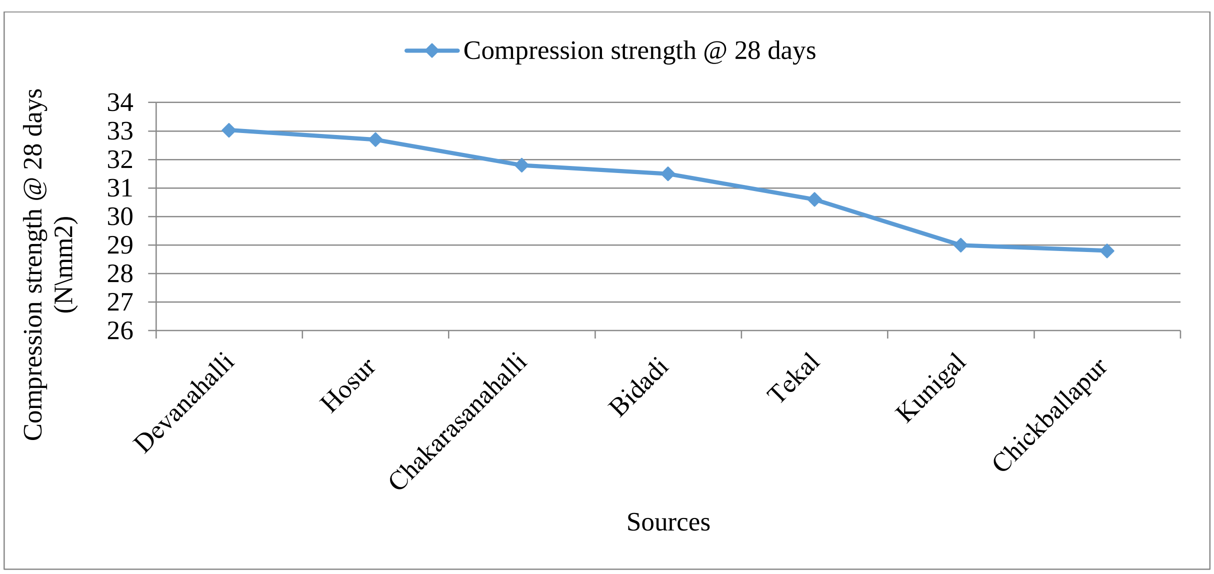

Fig. 8 Compression strength @ 28 days of cubes from different sources

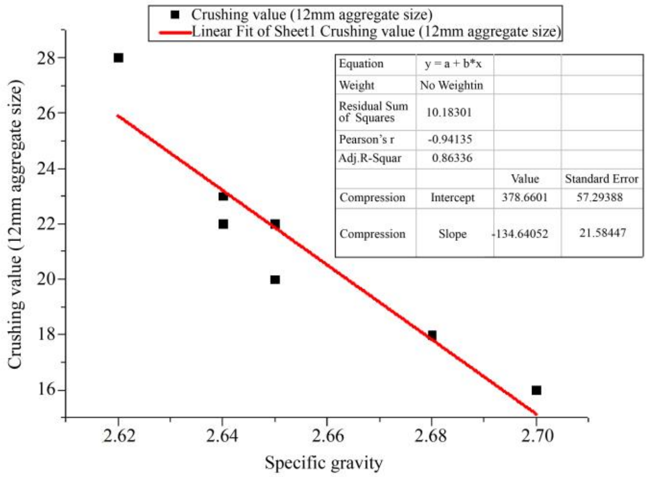

Fig. 9 Specific gravity v/s aggregate crushing strength

3.3. Influence of Specific Gravity on Aggregate Crushing Strength

The relationship between specific gravity and aggregate crushing value indicates an inverse correlation, as shown by the negative slope (-134.64). Aggregates with higher specific gravity tend to have greater density and lower porosity, making them stronger and more resistant to crushing forces. This is evident from the trend in the graph, where an increase in specific gravity results in a decrease in crushing value. A lower crushing value signifies better durability and load-bearing capacity, making such aggregates suitable for high-strength construction applications. The Pearson correlation coefficient (r = −0.941) further confirms the strong negative correlation, highlighting specific gravity as a key factor in determining aggregate strength. Aggregates with lower specific gravity, being more porous and weaker, are more prone to crushing, which could compromise the durability and stability of concrete structures.

3.4. Source Effect Analysis on Compression Strength of Concrete @ 7 days and 28 days

The bar chart illustrates the variation in compression strength (N/mm²) of concrete cubes sourced from different locations at 7 days (black bars) and 28 days (red bars). The data reveals a significant increase in strength from 7 to 28 days across all sources, indicating proper hydration and curing of concrete. Among the sources, Devanahalli, Hosur, and Chakarasanahalli exhibit the highest 28-day compressive strength, exceeding 32 N/mm², while Chickballapur and Kunigal show comparatively lower values, around 29 N/mm². The 7-day strength follows a similar trend, with Devanahalli and Hosur showing higher early-age strength (~21.5 N/mm²), whereas Kunigal and Chickballapur have the lowest (~18.7 N/mm²). This variation suggests that aggregate quality and material properties from different sources significantly influence concrete strength. A higher-strength mix at an early stage usually leads to a stronger final product, though the rate of strength increase can differ according to the type of materials, water content and the mix used. Differences in strength over seven and 28 days are a key measure of long-term concrete performance, proving why choosing the best aggregates is essential for reliable structures.

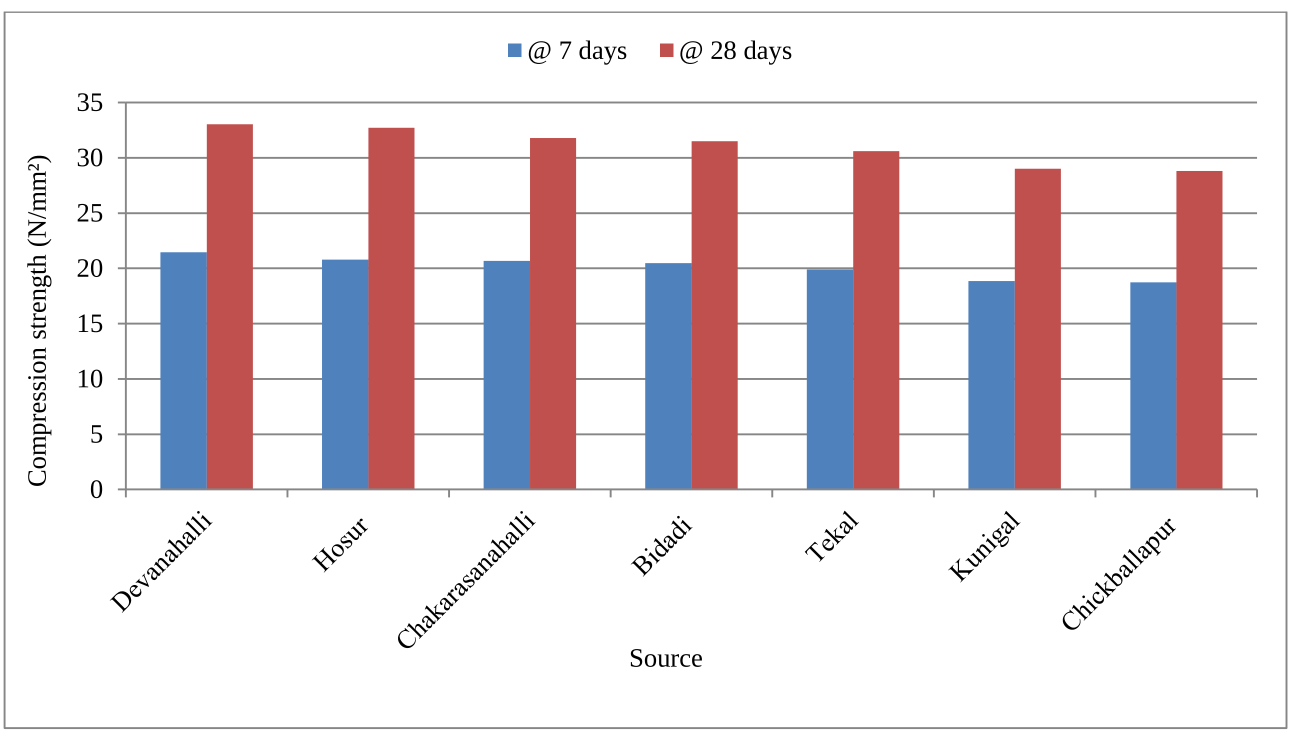

Fig. 10 Source of aggregates v/s compression strength @ 7 and 28 days

3.5. Effect of Aggregate Crushing Value on Concrete Performance

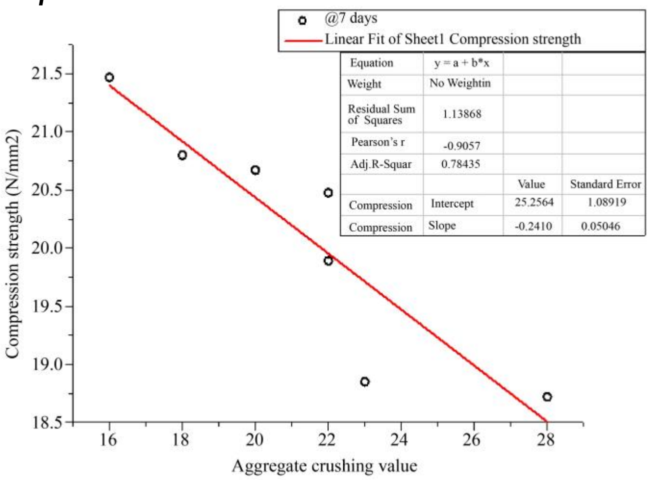

Fig. 11 Aggregate crushing value v/s compression strength @ 7 days

The compression strength of concrete is strongly affected by its aggregate crushing strength. Aggregates with an enormous crushing value tend to break apart under pressure, weakening the concrete mix. At the same time, crushing resistance is lower in aggregates that are stronger and make concrete more durable. Because aggregates comprise most of the concrete mixture, their strength determines how well the concrete will perform and last. When the aggregate crushing value increases, the cement can also weaken because crushed or weak aggregates affect the concrete's ability to resist crushing forces. This trend is significant in high-performance and structural concrete, where strong aggregates contribute to long-term stability and durability. A strong negative correlation is observed between aggregate crushing value and compressive strength at 7 days when correlating this general behaviour with the fitted graph. The regression analysis confirms that the compressive strength decreases as the aggregate crushing value increases, reinforcing the fundamental understanding that weaker aggregates negatively impact concrete performance. This highlights the need to select aggregates with a lower crushing value to achieve better strength and durability in concrete applications.

The aggregate crushing strength plays a critical role in determining the compressive strength of concrete. Aggregates with a higher crushing value are structurally weaker, leading to poor interlocking and reduced overall concrete strength. On the other hand, aggregates with lower crushing values provide better mechanical interlocking, higher load-bearing capacity, and improved durability. Since concrete relies on the strength of aggregates to resist compressive forces, weaker aggregates contribute to a significant decline in overall performance. As a general trend, an increase in aggregate crushing value reduces compressive strength, meaning that aggregates' quality directly influences the concrete's structural integrity. This trend is especially significant at 28 days, as concrete gains most of its strength during this curing period. Poor-quality aggregates with higher crushing values result in lower long-term strength, which can compromise the durability and load-bearing capability of the concrete structure. When correlating this general observation with the fitted graph, a strong negative correlation is observed between aggregate crushing value and compressive strength at 28 days. The regression analysis further confirms that as the aggregate crushing value increases, the compressive strength decreases, reinforcing the importance of using high-quality, low-crushing-value aggregates for better concrete strength and durability.

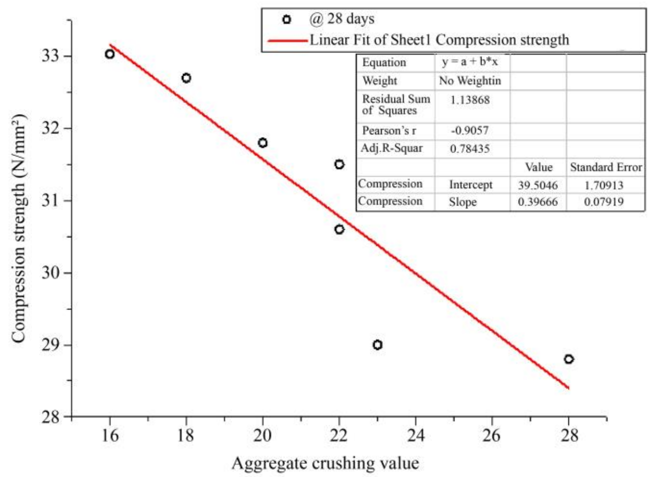

Fig. 12 Aggregate crushing value v/s compression strength @ 28 days

3.6. Failure Mechanism in the Concrete Cubes @ 7 and 28 Days

The failure mechanism of concrete cubes varies between 7-day and 28-day curing periods due to differences in hydration, bond strength, and aggregate properties. At 7 days, concrete is still in the early stages of strength development, and the failure is primarily brittle. The incomplete hydration results in weaker interfacial bonding between the aggregate and the cement paste, leading to crack initiation at the paste-aggregate interface. When weaker aggregates with higher crushing values are used, stress concentration points develop, causing early crack propagation through the cement matrix rather than the aggregates. In contrast, when stronger aggregates are present, failure may occur progressively, with initial cracks forming in the cement paste before extending to the aggregates. By 28 days, hydration is significantly more advanced, and concrete achieves a higher compressive strength. The bond between the cement matrix and the aggregates improves, altering the failure mechanism. At this point, the failure mode becomes more likely to be that of aggregate failure, especially when stronger aggregates are involved. Weak aggregates begin to fracture internally under load, while stronger aggregates distribute stress more effectively, delaying failure. The failure surface at 28 days is generally rougher and more irregular than the 7-day stage, indicating better stress absorption and uniform load distribution. The influence of aggregate quality is more pronounced at 28 days, as weaker aggregates significantly reduce concrete's overall strength.

Comparing both curing stages, the failure mechanism transitions from a paste-dominated failure at 7 days to an aggregate-dominated failure at 28 days. The cement pastes control failure early, while the aggregate quality becomes a significant factor later. Concrete with higher aggregate crushing values consistently exhibits lower compressive strength, reinforcing the importance of using high-quality aggregates. This trend highlights the role of aggregate selection in achieving durable and high-performance concrete structures.

3.7. Statistical Analysis for Aggregate Crushing Value and Compression Strength @ 7 and 28 days

3.7.1. One-Way ANOVA

By analyzing the statistical significance of the parameters using ANOVA in Minitab, it can be determined whether variations in aggregate properties and source locations significantly affect concrete strength, aiding in material selection and mix optimization for improved structural performance.

Table 4. ANOVA for Aggregate Crushing Value and Compression Strength @ 7 days

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Aggregate crushing value	5	6.1652	97.30%	6.1652	1.2330	7.21	0.0275
Error	1	0.1711	2.70%	0.1711	0.1711		
Total	6	6.3364	100.00%				

Table 5. ANOVA for Aggregate Crushing Value and Compression Strength @ 28 days

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Aggregate crushing value	5	16.4695	97.60%	16.4695	3.2939	8.13	0.0260
Error	1	0.4050	2.40%	0.4050	0.4050		
Total	6	16.8745	100.00%				

The ANOVA results for the 7-day compressive strength analysis indicate that the aggregate crushing value significantly impacts concrete strength development. With a contribution of 97.30%, the aggregate crushing value accounts for nearly all the variation in compressive strength, leaving only 2.70% unexplained error. The F-value of 7.21 suggests a strong influence, and the P-value of 0.0275, being less than 0.05, confirms that this effect is statistically significant at a 95% confidence level. The adjusted mean square value for aggregate crushing strength is 1.2330, while the error term is 0.1711, indicating minimal variability from other factors. These findings highlight that the crushing resistance of aggregates plays a crucial role in early-age strength development. Poor-quality aggregates with higher crushing values tend to result in lower compressive strength at 7 days, emphasizing the need for high-quality aggregates in concrete production for improved early-age performance.

The ANOVA results for the 28-day compressive strength analysis reveal that the aggregate crushing value remains a dominant factor influencing concrete strength. A 97.60% contribution accounts for almost all the variation in compressive strength, leaving only 2.40% as an unexplained error. The F-value of 8.13 further supports the strong relationship between aggregate crushing and compressive strength. The P-value of 0.0260, below 0.05, confirms statistical significance at a 95% confidence level, indicating that the effect of aggregate quality on long-term strength is substantial. The adjusted mean square value for aggregate crushing strength (3.2939) is significantly higher than the error term (0.4050), reinforcing the reliability of the observed relationship. These results emphasize that aggregates with lower crushing values contribute to enhanced long-term concrete strength, highlighting the importance of selecting durable aggregates to ensure structural integrity and performance over time.

3.7.2. Pearson Correlation

Table 6. Pairwise pearson correlations

Sample 1	Sample 2	Correlation	95% CI for ρ	P-Value
Compression strength at 7 days	Aggregate crushing value	-0.906	(-0.986, -0.480)	0.005

Pearson correlation analysis reveals that aggregate crushing value and compressive strength at 7 days have a powerful negative relation (r = -0.906), which means that higher aggregate crushing causes concrete to have lesser compressive strength. The 95% Confidence Interval (CI) indicates the statistically significant and dependable correlation range from -0.986 to -0.480. This relationship is unlikely to result from accidental factors, as the p-value of 0.005. Finer aggregates, which give a high aggregate crushing value, make concrete less strong and able to bear weight. This trend aligns with general expectations that weaker aggregates lead to lower compressive strength due to reduced bonding efficiency and higher internal micro-cracking.

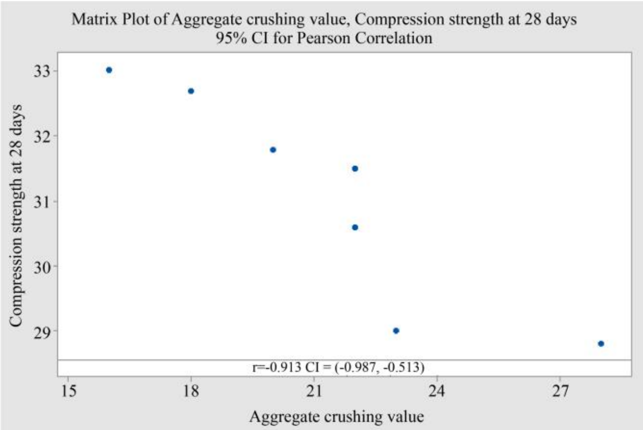

Fig. 13 Pearson correlation for aggregate crushing value and compression strength @ 7 days

Table 7. Pairwise pearson correlations

Sample 1	Sample 2	Correlation	95% CI for ρ	P-Value
Compression strength at 28 days	Aggregate crushing value	-0.913	(-0.987, -0.513)	0.004

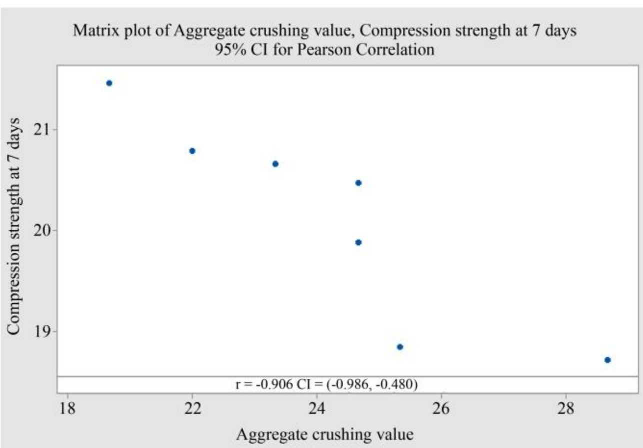

Fig. 14 Pearson correlation for aggregate crushing value and compression strength @ 28 days

The Pearson correlation analysis between aggregate crushing value and compressive strength at 28 days reveals a strong negative correlation (r = -0.913). This signifies that an increase in aggregate crushing value leads to a considerable reduction in compressive strength. The 95% confidence interval (CI) ranging from -0.987 to -0.513 indicates that the correlation is statistically significant and reliable. Moreover, the p-value of 0.004 further confirms the significance of this relationship, suggesting that the observed correlation is unlikely to be due to chance. This trend aligns with expectations, as aggregates with higher crushing values are weaker, leading to reduced interfacial bonding and increased micro-cracking in the concrete matrix, ultimately lowering its compressive strength.

The -0.906 correlation coefficient shows a strong linear negative relationship between aggregate crushing value and compressive strength at day 7. Likewise, on day 28, the correlation coefficient stood at r = –0.913, which means the compressive strength significantly declined as the crushing value grew. It has been confirmed that strong aggregate strength plays a vital role in concrete quality and that quality control of these aggregates is necessary.

3.7.3. Regression Analysis

Table 8. Analysis of Variance (7 days)

Source	DF	SS	MS	F	P
Regression	1	5.19768	5.19768	22.82	0.005
Error	5	1.13868	0.22774		
Total	6	6.33636			

Regression Equation

Compression strength at 7 days = 25.26 - 0.2411 Aggregate crushing value

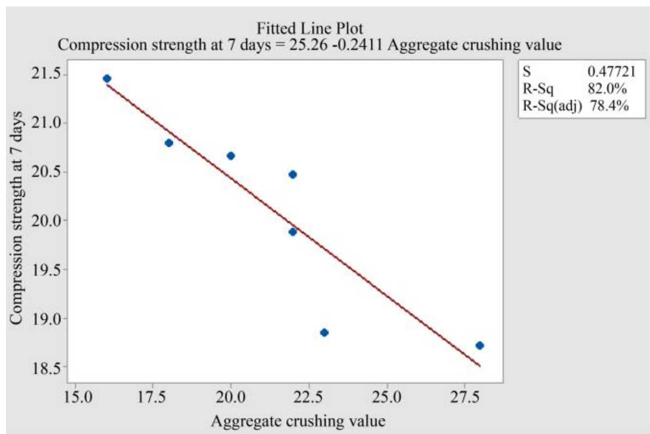

Fig. 15 Fitted line plot (7 days)

The regression analysis establishes a significant inverse relationship between aggregate crushing value and compressive strength at 7 days, as represented by the equation Compressive Strength at 7 days = 25.26 - 0.2411 × Aggregate Crushing Value. The negative slope (-0.2411) indicates that for every unit increase in aggregate crushing value, compressive strength decreases by 0.2411 MPa. The model's R^2 value of 82.0% signifies that 82% of the variation in compressive strength is explained by the aggregate crushing value, with an adjusted R^2 of 78.4%, further confirming the model’s robustness. The F-value of 22.82 highlights the statistical strength of this relationship, and the p-value of 0.005 confirms its significance, indicating that aggregate crushing value substantially impacts compressive strength. Furthermore, the standard error (S = 0.477217) indicates that the model can successfully predict the variations in compressive strength. The model demonstrates that greater aggregate crushing value usually results in weaker compressive strength at 7 days, so it can help forecast compressive strength from aggregate properties.

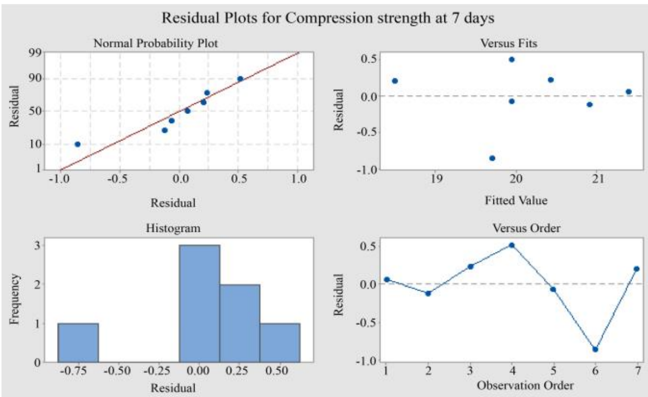

Fig. 16 Residual plots for compression strength @ 7 days

Plots of the residuals for compressive strength at 7 days confirm whether the regression model assumptions are correct and if the values are similar. The Normal Probability Plot (top-left) demonstrates that the data is roughly linear, so the normality assumption seems correct. The graph at the top-right in the Versus Fits Plot spreads the residuals across zero, suggesting that no clear pattern is present and supporting that the variance stays constant. The Histogram on the bottom-left shows that almost all the residuals are evenly distributed, suggesting normality. Additionally, the Versus Order plot (at the bottom right) suggests no clear pattern in residuals, showing no autocorrelation. All in all, these plots indicate that the regression model is valid and can be used to predict compressive strength after 7 days.

Table 9. Analysis of Variance (28 days)

Source	DF	SS	MS	F	P
Regression	1	14.0707	14.0707	25.09	0.004
Error	5	2.8038	0.5608		
Total	6	16.8745			

Regression Equation

Compression strength at 28 days = 39.50 - 0.3967 Aggregate crushing value.

The regression analysis of compression strength at 28 days reveals a strong relationship between these parameters (aggregate crushing value and compression strength). The regression equation implies that compressive strength at 28 days will decrease when the aggregate crushing value increases. A low p-value of 0.004 and an F-value of 25.09 confirm that the model is statistically significant, so the aggregate crushing value affects the compressive strength. With a low Mean Square Error of 0.5608, the proposed model fits well for estimating 28-day compressive strength.

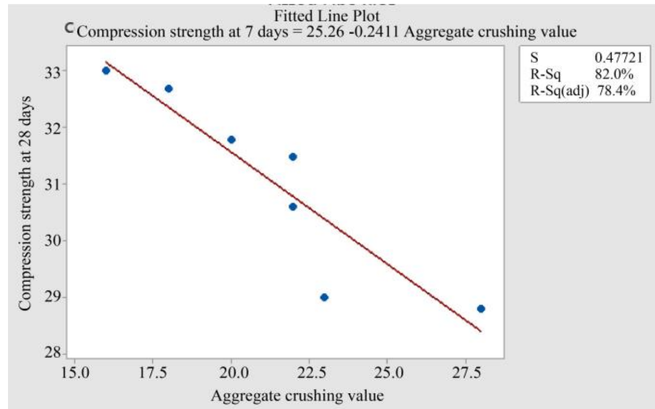

Fig. 17 Fitted line plot (28 days)

The relationship shown by the fitted line plot for 28-day compression strength is negative and linear. As the aggregate crushing value rises, the compressive strength lowers. The regression equation shows 28-day compressive strength = 39.50 - 0.3967 (aggregate crushing value). A strong correlation is shown by the fact that the aggregate crushing value explains 83.4% of the variability in compressive strength. The adjusted R^2 value of 80.1% supports the model's reliability. Since the standard error of regression shows S = 0.748836, approximately half of the data points lie within one standard error of the fitted regression line. Overall, the model estimates how strong the concrete will be by considering the aggregate crushing value, proving that quality in aggregates is significant for successful concrete results.

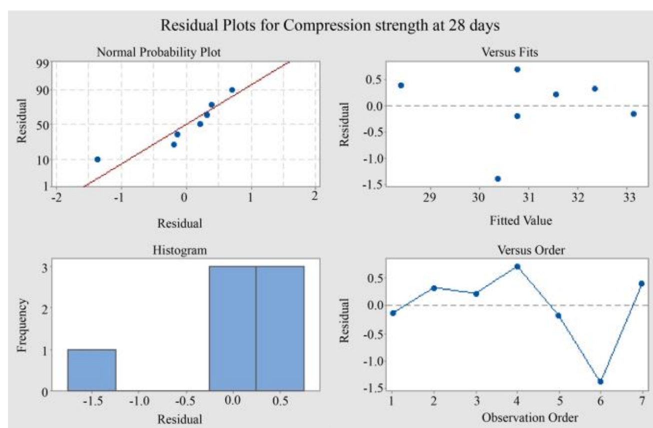

Fig. 18 Residual plots for compression strength @ 28 days

Plots of residuals for compression strength at 28 days evaluate the performance of the regression model. The residuals on the standard probability plot form a straight line, suggesting that the data is usually distributed. Residuals within the versus fits plot appear in no evident pattern, implying the data is homoscedastic. The roughly symmetric form of the Histogram of residuals gives further evidence of normality. The plot with the versus order does not show any pattern or autocorrelation. The results of the plots indicate that the regression model is correct and suitable for forecasting 28-day compression strength.

3.7.4. Statistical Assumptions and Model Validity

Standard parametric assumptions were evaluated and identified as valid for all three statistical analyses-ANOVA, Pearson correlation and linear regression-used in this study.

Residual Normality: The assumption that residuals are normally distributed was checked using standard probability plots, and both 7-day and 28-day models seem to comply (see Figures 15 and 18). The residuals were nearly straight in trend, proving that normality was fulfilled.

Constant Variance (Homoscedasticity): The plots showed that the residuals were randomly dispersed around the zero line for all fits, so the assumption of constant variance for ANOVA and regression was met.

Error Independence: The residual plots showed no organized patterns, confirming that the experimental results were unrelated and the data was truly independent through time.

Linearity: The fitted lines for aggregate crushing value and compressive strength indicate a strong linear connection, which is required for regression analysis.

Independence of Observations: Since new batches were mixed for every aggregate source and the samples remained independent, the measurements used remain untainted by repetition.

Considering these confirmations, all the statistical analyses and conclusions presented in this study are deemed valid and reliable when only tested within the outlined experiment.

Outlier Detection and Influence

During the analysis, residual, normal probability and versus fits plots were used to see if any data points were outliers. No points were observed that greatly challenged the model's assumptions or made the trendlines look very different. Each variable stayed within acceptable ranges; neither Cook's distance nor the standardized residuals exceeded ±2. As a result, all observations were included, and the models were thought to reflect real-world situations accurately without being skewed by unusual data.

3.8. Comparative Discussion with Existing Literature

Stronger predictive accuracy in the regression models, as shown by R^2 scores of 82.0% at 7 days and 83.4% at 28 days, is due to various methodological and analytical advantages over previous research.

In contrast to most advanced studies that consider aggregate features by themselves, this work uses several integrated parameters in statistics. By using several influencing factors, this method gives a clearer picture of how all aggregate properties impact the strength of concrete.

Additionally, selecting samples from seven various quarries contributed to the diversity and reliability of the overall set of samples. On the other hand, previous research usually studies few sources or similar regions, which reduces the potential for their conclusions to be applied more widely. In comparison, Sahin et al. [14] and Kaplan [18] covered only some aggregate types or a select group of geological regions, whereas this study covers many types of minerals and enhances the model's strength.

Furthermore, detailed statistical methods such as one-way ANOVA, Pearson correlation, and regression analysis made the results more reliable. While former researchers such as Ozturan and Cecen [15] and Ruiz [16] built their work on observations and simple regression, this study ensures the model by checking the residuals, a standard statistical practice. Having residual diagnostics and confidence intervals makes the analysis better and more credible than what was done before.

Additionally, assessing both short-term (7-day) and long-term (28-day) strength adds another important feature to the study. Much of what is written on concrete strength highlights the 28-day phase and may not stress the initial moisture content influencing construction and scheduling.

Unlike previous research that usually concluded with qualitative patterns or insights for one place, this study also provides applicable predictive models in situations. Engineers can make better material and mixture choices across all construction zones by relying on these derived equations.

The improved approaches and detailed analysis explain the impressive outcomes and point out how this study brings fresh insights and helpful facts to the study of concrete materials.

4. Conclusion

This research thoroughly studied how concrete properties are influenced by the aggregate by focusing on its crushing value, gravity and shape. Statistical analyses such as regression, ANOVA and correlation were performed to estimate these effects. The main points discovered are the following:

- Aggregates found in Devanahalli had the highest specific gravity (2.7) and lowest crushing value (16%), making them resistant and strong. Alternatively, the crushing value of Kunigal aggregates was most significant (28%), and their specific gravity was lowest (2.62), which gave the concrete the poorest performance. Lower crushing value was linked to higher compressive strength, probably because concrete depends directly on aggregate strength.
- The compressive strength of samples from Devanahalli was highest (16.96 kg/mm²) at 7 days, compared to the

lowest from Chickballapur (14.2kg/mm²). At the end of 28 days, the sample from Devanahalli was strongest (33.03 N/mm²), compared to the lowest strength shown by Chickballapur (28.8 N/mm²). The importance of aggregate source and quality becomes clear from these strength variations.

- Aggregate crushing value was related to weaker compressive strength at 7 and 28 days. It proves that better quality aggregates are vital to ensure superior structure and strength of concrete.
- The results from statistical analysis confirmed these findings. Compressive strength changed significantly when measured for different aggregate sources at a p-value of 0.05. An analysis of the Pearson correlation showed a clear negative relationship ($r \approx -0.91$) between aggregate crushing value and compressive strength. The results from regression analysis allowed for predicting strength using equations strength = 25.26 - 0.2411 (Crushing Value) at 7 days and strength = 39.50 - 0.3967 (Crushing Value) at 28 days.
- Tests on residuals helped confirm the quality of the statistical models used. Standard probability plots showed that the residuals were normally distributed, proving that the model worked. The residual scatter in the versus fits and histograms confirmed homoscedasticity. Results from the versus order plot did not reflect any pattern, supporting the stable regression models.

Better concrete strength comes from high specific gravity and low crushing values in aggregate, so choosing the right materials is very important. Weaker concrete can make buildings less durable and less able to last shortly. Using regression models, engineers can get strength predictions that help make informed decisions about selecting materials. The research emphasizes how important good-quality aggregates are in creating concrete and offers strong statistics for predicting strength with the Aggregate Crushing Value method.

4.1. Practical Implications

- This research allows engineers and material specifiers to focus on aggregate sources that ensure sturdy and long-lasting concrete structures.
- With the regression models found in the study, concrete strength can be estimated efficiently with available aggregate data, which is crucial when adjusting a mixture in different settings.
- The information gleaned can help construction agencies improve the consistency of concrete use by setting standards for aggregate sourcing and managing risks related to poor aggregates over the years.
- An adaptive approach is practical for areas with various soil types, such as Karnataka. It allows the development of location-specific concrete standards that benefit the environment and economy.

By matching theoretical information with performance results from research, this study promotes a logical, effective way of making concrete mixes, contributing to better and safer construction.

4.2. Future Research

Although the findings here clearly describe the general effect of aggregate properties on compressive strength, additional research may make them more useful.

4.2.1. Dataset Expansion

In the future, studies might cover more aggregate sources coming from several geological regions here in India or from all over the world to check the applicability and effectiveness of the models under various mineral conditions.

4.2.2. Aggregate Parameters Inclusion

If water absorption, abrasion resistance, surface texture and mineralogy are considered, simulation models can predict behaviour more accurately and provide further insight into the relationships between aggregates and concrete.

4.2.3. Different Mix-Designs

Evaluating concrete grades (e.g., M15, M40, M60) and checking their mix with similar aggregates would allow assessment of if the behaviours are the same and set unique performance requirements for top and bottom grades.

4.2.4. Non-Destructive Testing

Real real-world use would benefit by adding non-destructive and compressive strength tests and checking results on-site.

4.2.5. Predictive Methods

Going forward, researchers could apply advanced machine learning models such as Artificial Neural Networks (ANN), Support Vector Machines (SVM) or random forest models to predict outcomes based on several variables.

4.2.6. Long-Term Performance

Research into the long-term durability of concrete structures (such as freeze-thaw survival, effect of sulphates and ingress of chloride ions) relating this to aggregates would be very useful for civil engineering.

This way, future studies can use the information to choose suitable materials for making strong concrete structures.

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