MECHANICAL RESPONSE OF BRICK AGGREGATE CONCRETE USING DIVERSE GRADATIONS AND MIX RATIOS

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ABSTRACT

Brick aggregate concrete (BAC) is commonly utilized in regions where natural stone chips are limited. However, the arrangement of coarse particles and the proportions of the concrete mix significantly influence the mechanical characteristics. This research examines how variations in aggregate gradation and volumetric mix ratios impact essential mechanical properties such as compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio of BAC. Concrete mixes were prepared using three distinct coarse aggregate gradations: well-graded, gap-graded, and uniformly graded, with volumetric mix ratios of 1:1:2, 1:1.5:3, and 1:2:4. The mixtures included standard Portland cement, coarse sand with a fineness modulus of 2.86, and 25-mm crushed brick aggregates, all maintained at a water-to-cement ratio of 0.50. After a curing period of 28 days, 81 cylindrical samples with a diameter of 100 mm and a height of 200 mm were assessed. The concrete using a 1:1:2 mix ratio and well-graded aggregates (WGA) achieved the highest compressive strength of 25.07 MPa, which is 21% greater than that of uniformly graded concrete and 8% greater than gap-graded concrete at the same mix ratio. Meanwhile, uniform-graded brick aggregate concrete (BAC) with a 1:2:4 mix ratio recorded a compressive strength of 18.25 MPa, approximately 27% lower than that of well-graded BAC with a 1:1:2 mix ratio. In the case of the 1:2:4 combination, WGA exhibited a maximum splitting tensile strength of 2.01 MPa, while uniformly graded aggregates (UGA) had a tensile strength of 1.35 MPa. The modulus of elasticity and Poisson's ratio showed similar trends, highlighting the advantages of well-graded aggregates over uniform and gap-graded aggregates. These findings demonstrate that using richer mix proportions and well-graded aggregates significantly improves the mechanical properties of BAC, offering crucial information for optimizing structural applications in resource-constrained locations.

Keywords: *Brick Aggregate Concrete; Mechanical Performance; Aggregate Gradation; Mix Ratio; Water-Cement Ratio*

1. INTRODUCTION

Concrete is a composite construction material made up of cement, water, fine and coarse aggregates, and occasionally admixtures. It is well-known for its exceptional strength, durability, and versatility, making it an essential material in contemporary construction and infrastructure projects. The characteristics of aggregates, such as their type, size, and source, play a crucial role in determining the strength and performance of concrete (Aginam et al., 2013; Hassan, 2011). Since aggregates make up 70-80% of the total volume of concrete, their physical and mechanical properties significantly influence the workability, durability, and strength of both fresh and hardened concrete (Titiksh et al., 2017).

It is essential to optimize aggregate gradation to enhance the rheological behavior, mechanical characteristics, and long-term durability of concrete (Naik et al., 2011). The gradation of aggregates affects the void content of the mixture, which directly influences the quantity of cement paste required to fill those voids and ensure adequate workability (Pawar et al., 2016). Appropriate grading not only results in a mix that is workable and can be easily compacted but also diminishes issues in fresh concrete such as segregation, bleeding, air loss, and plastic shrinkage cracking (Titiksh et al., 2017). A mix made up of uniformly sized particles has a higher void content, but a well-graded mix allows smaller particles to fill the gaps between bigger ones, resulting in a denser structure that requires less fine aggregate and cement (Titiksh et al., 2017). Nonetheless, two major concerns in engineering procedures are high production costs and excessive usage of cement, which necessitates huge amounts of ordinary Portland cement (OPC) (Zhu et al., 2022). The manufacture of OPC produces significant amounts of CO_2, contributing to environmental pollution and climate change.

The design of concrete mixes involves choosing suitable materials and determining their optimal proportions to achieve the necessary strength, workability, and durability in a cost-effective and sustainable way (Banzal, 2007). The amounts of cement, sand, and aggregates used in concrete influence its mechanical characteristics, including compressive and tensile strength, as well as its overall durability. Therefore, modifying the mix ratio is essential for achieving a balance among strength, cost, and long-term stability (Amin et al., 2022). Although there has been significant research on optimizing mixes, a knowledge gap still exists regarding the comprehensive verification of how various mix ratios impact the key mechanical properties of brick aggregate concrete.

2. MATERIALS AND METHODOLOGY

2.1 Materials

To start the experiment, 25 mm downgraded crushed brick was used as the coarse aggregate and locally available coarse sand as the fine aggregate. For this study, Ordinary Portland Cement (OPC) was used as the binding material. For both mixing and curing, pure drinking water was used.

2.1.1 Cement

In this study, Ordinary Portland Cement (CEM 1) served as the main binding agent in the production of concrete. A series of laboratory tests were performed to verify its suitability. The normal consistency of the cement paste, as well as the initial and final setting times, were assessed using ASTM C187. In addition, the compressive strength of cement mortar was measured according to ASTM C109. The properties of the cement obtained are summarized in the Table 1.

Table 1: Properties of Ordinary Portland Cement

Engineering properties	Unit	Test standard	Present study	ASTM C150 (2022)
Residue (45µm)	%	-	5	-
Specific gravity	-	BS 1377(1990)	3.08	-

Unit weight		kg/m^3	ASTM C188 (2017)	1445	1440
Consistency		%	ASTM C187(2016)	28.75	28-32
Setting time	Initial	min	ASTM C191(2021)	85	≥ 45
	Final	min	ASTM C191(2021)	215	≤ 375
Compressive strength	3days	MPa	ASTM C109(2016)	19	12
	7 days	MPa	ASTM C109(2016)	25.5	19
	28 days	MPa	ASTM C109(2016)	31.5	28

2.1.2 Fine Aggregate

Locally collected Sylhet sand was incorporated in the concrete as the fine aggregate having maximum particle size of 4.75 mm. To ensure its appropriateness for the study, the FA was introduced to a series of laboratory tests, including gradation, specific gravity, unit wight and water absorption according to the associated standards. The obtained properties are outlined in Table 2

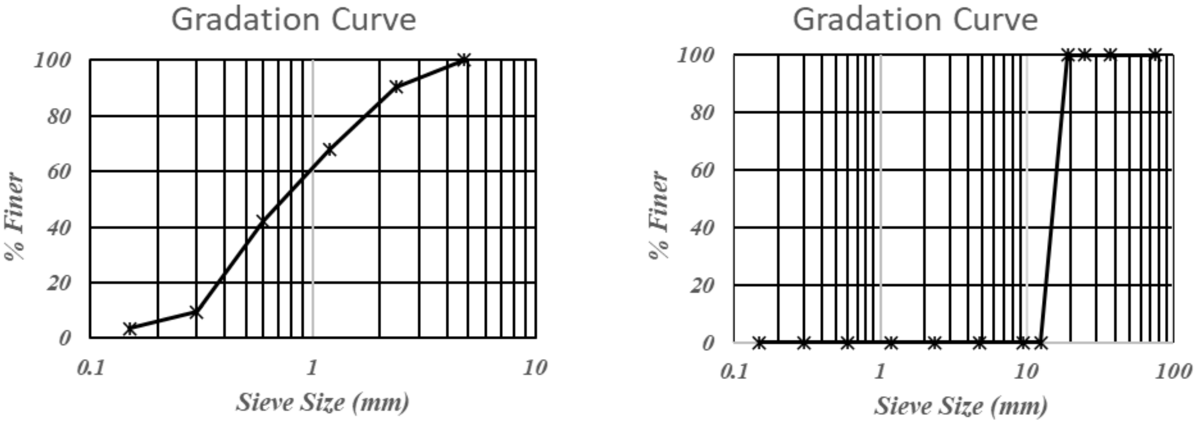
Table 2. Physical properties of aggregates

Properties of materials	**Unit**	**Test Standard**	**Coarse aggregates**				**Fine Aggregate**	
			Well Graded	**Gap Graded**	**Uniform Graded**	**Naoman et al., 2018**	**Present Study**	**Naoman et al., 2018**
Fineness modulus	-	ASTM C136(2019)	7.45	7.30	7.80	7	2.86	3.11
Unit weight	kg/m^3	ASTM C29(2017)	1059	1043	983	925	1692	1504
Absorption capacity	%	ASTM C127(2007)	16.5	16.3	17.2	16.38	4.2	1.01
Specific Gravity (OD)	-	ASTM C127(2007)	1.89	1.86	1.83	2.56	2.51	-
SSD specific gravity	-	ASTM C128(2015)	2.20	2.16	2.13	-	2.62	2.65

2.1.3 Coarse Aggregate

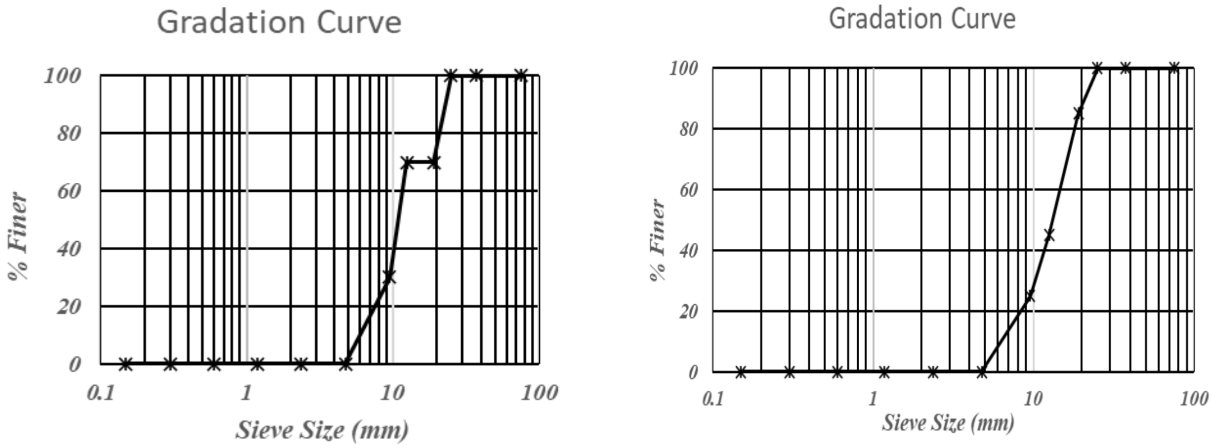
Figure 1: Coarse Aggregate

Well-burnt clay bricks were crushed to produce brick aggregates (BA), which served as the coarse aggregate (shown in figure 1) in this study. Three gradation types, well-graded, uniformly graded, and gap-graded were prepared to evaluate their suitability for concrete production. The particle size distribution of BA was determined through sieve analysis following ASTM C33, and the corresponding gradation curves are presented in Figure 2. The physical properties of the coarse aggregates, along with relevant test standards, are summarized in Table 2.



a) Gradation Curve of Fine Aggregate

b) Gradation Curve of Uniform-Graded CA



c) Gradation Curve of Gap-Graded CA

d) Gradation Curve of Well-Graded CA

Figure 2: Gradation Curve of Aggregates

2.2 Preparation of Specimens

Concrete samples were produced in accordance with the relevant testing standards in order to maintain homogeneity and reproducibility. A drum mixer was used to blend the ingredients for each specified mix. Firstly, cement, sand, and coarse aggregate had been mixed in dry condition for two minutes. Then water was introduced in line with the prescribed water-cement ratio (w/c) of 0.50, depending on the mix. The mixer drum was then rotated at a speed of approximately 20 to 25 rpm, and the concrete mixer was blended for an additional three to four minutes. Before casting the concrete, cylindrical molds with a diameter of 150 mm and a height of 300 mm were thoroughly cleaned, oiled, and lubricated. Subsequently, the freshly mixed concrete was placed into molds and compacted to eliminate trapped air and obtain a dense mass. After compaction, the surface was leveled with a trowel to maintain flat and parallel top and bottom surfaces. Once the surface was compacted, a trowel was grabbed and smoothed everything out, making sure the top and bottom were flat and lined up. After 24 hours, the specimens were demolded and labeled them, just to keep things straight during testing. Then, the specimens were kept into water and soaked for 28 days. This step lets the cement fully hydrate and helps the concrete reach the desired strength. The mix proportion of preparing brick aggregate concrete are shown in Table 3.

Table 3: Required Materials for Making 1 m^3 Brick Aggregate Concrete

Mix ratio	CA Gradation	Cement (kg)	Sand(kg)	BA(kg)	Water(kg)
1:1:2	Well-Graded	542	634.5	794	271
	Gap-Graded	542	634.5	782	271
	Uniform-Graded	542	634.5	737	271
1:1.5:3	Well-Graded	394	692	866	197
	Gap-Graded	394	692	853	197
	Uniform-Graded	394	692	804	197
1:2:4	Well-Graded	310	725	907	155
	Gap-Graded	310	725	894	155
	Uniform-Graded	310	725	842	155

2.3 Tests on Specimens

After a curing period of 28 days, all concrete samples underwent testing to evaluate their mechanical properties following ASTM standards. Compressive strength was determined using cylindrical samples in line with ASTM C39, while breaking tensile strength was assessed according to ASTM C496 guidelines. The modulus of elasticity was measured in accordance with ASTM C469 to quantitatively express the concrete's stiffness and deformation behavior. The tests were conducted in a controlled laboratory environment to ensure accurate alignment, loading, and minimal experimental error. Multiple specimens from each mix were tested to guarantee statistical reliability and reproducibility. These measurements facilitated a comprehensive assessment of the concrete's structural performance, allowing for a comparison of different mix designs and water-to-cement ratios.

3. RESULTS AND DISCUSSIONS

This section discusses the experimental findings related to the mechanical behavior of concrete, focusing on key parameters including compressive strength, splitting tensile strength, Poisson’s ratio, and modulus of elasticity. The influence of different coarse aggregate gradations and mix proportions on these properties has been systematically evaluated. By analyzing the variation in mechanical performance across a range of concrete mixes, this study aims to highlight how aggregate grading and mix design collectively affect the strength, ductility, and elastic characteristics of concrete. The following discussion provides a detailed interpretation of the observed trends, correlating the experimental results with established theoretical insights and previous literature.

3.1 Compressive Strength

Figure 3 illustrates the effect of coarse aggregate (CA) gradation on the compressive strength of concrete for three mix ratios of 1:2:4, 1:1.5:3, and 1:1:2 respectively. The results indicate that aggregate gradations and mix ratios have a significant influence on compressive strength.

Well-graded aggregates consistently produced the highest strength across all mix proportions, followed by uniformly graded and gap-graded mixes. In the 1:1:2 mix, the compressive strength of well-graded concrete reached 25.07 MPa, which is approximately 21% higher than that of uniformly graded aggregates and 8% greater than that of gap-graded aggregates in the same mix. Similarly, well-graded concrete achieved a compressive strength of 23.38 MPa in the 1:1.5:3 mix, while uniformly graded concrete reached 21.87 MPa, signifying an improvement of about 25% over gap-graded concrete. For the 1:2:4 mix, well-graded aggregates demonstrated approximately 20% greater strength in comparison to the uniformly graded mix.

Moreover, when transitioning from the 1:2:4 mix to the 1:1:2 mix, the compressive strength of gap-graded aggregates increased by roughly 15.34%, illustrating the positive influence of richer mix proportions even within the same grading. The inconsistent strength behavior of concrete is evident in the standard deviation values, which range from 0.25 to 0.90 and indicate relatively minor variation in compressive strength among the mixes.

3.2 Splitting Tensile Strength

The bar chart in Figure 4 illustrates how the gradation of coarse aggregate (CA) influences the splitting tensile strength of concrete across three mix ratios: 1:2:4, 1:1.5:3, and 1:1:2. The results clearly indicate that both the mix proportions and the gradation of aggregates significantly affect the tensile characteristics of concrete.

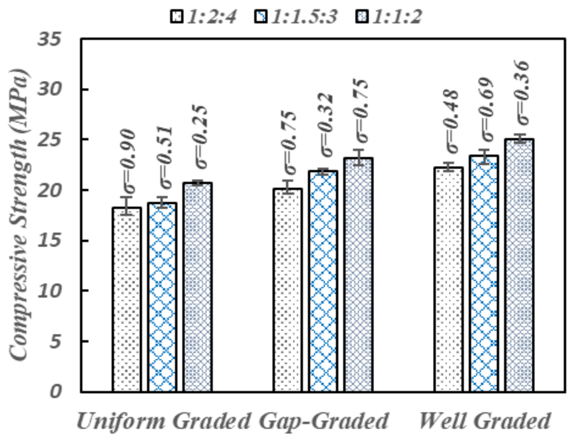


Figure 3: Compressive Strength vs Gradation of CA for Different Mix Ratios

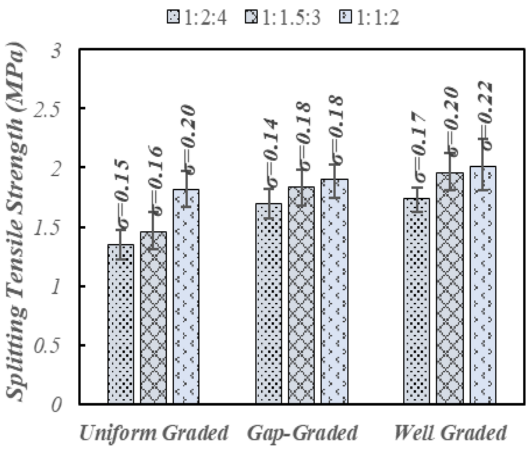


Figure 4: Splitting Tensile Strength vs Gradation of CA for Different Mix ratios

In all mix ratios, the well-graded aggregates consistently displayed the highest splitting tensile strength compared to the three gradations. For the 1:1:2 mix, the well-graded concrete achieved a tensile strength of 2.01 MPa, which is approximately 11% greater than the uniform graded concrete and 6% higher than the gap-graded concrete. Similarly, the well-graded concrete's tensile strength for the 1:1.5:3 mix showed an improvement of about 34% over the uniform graded mix and 6% over the gap-graded mix. The well-graded concrete in the 1:2:4 mix attained nearly 2.3 MPa, indicating a strength that was about 29% higher than that of the uniformly graded mix. Overall, the findings suggest that, depending on the mix ratio, the use of well-graded aggregates enhances the splitting tensile strength by roughly 10-35%. This improvement is primarily attributed to better particle packing, lower void content, and enhanced aggregate–paste bonding, which together contribute to a more efficient transfer of stresses within the concrete matrix (Cheng et al., 2021) .

Moreover, the chart indicates that for well-graded aggregates, the 1:1:2 mixture exhibited a splitting tensile strength approximately 15% greater than the 1:2:4 mixture and 2.55% higher than the 1:1.5:3 mixture, all within the same aggregate gradation. In contrast, uniformly graded aggregates demonstrated a more significant difference, with a compressive strength increase of nearly 30% compared to the 1:2:4 mix and about 24% compared to the 1:1.5:3 mix. This trend implies that mix proportions have a more pronounced effect on uniformly graded concrete, where strength is more dependent on cement content due to inadequate particle interlocking.

3.3 Modulus of Elasticity

The modulus of elasticity of concrete was determined experimentally through a uniaxial compression test in accordance with ASTM C469. Axial stress–strain data were recorded during loading, and the modulus of elasticity was calculated from the slope of the stress–strain curve within the specified linear elastic range. Figure 5 depicts the variation in the Modulus of Elasticity (GPa) of concrete with respect to the gradation of coarse aggregates (CA) for three distinct mix ratios: 1:2:4, 1:1.5:3, and 1:1:2. The results demonstrate a clear and consistent influence of aggregate gradation and mix ratios on the elastic behavior of concrete.

Well-graded aggregates exhibit the highest modulus of elasticity across all mix ratios compared to uniformly-graded and gap-graded aggregates. This suggests that concrete with a wider variety of aggregate sizes offers better stiffness and more resistance to deformation when loads are applied. For example, the well-graded mixes recorded modulus values ranges 10 GPa to 15.63 GPa, while the uniform-graded mixes showed much lower values between 7 to 10.50 GPa. This trend indicates that the proportions of the mix significantly influence evenly graded concrete, as its strength is more dependent on the amount of cement because of insufficient particle interlock.

The superior performance of well-graded aggregates can be attributed to enhanced particle packing, lower void ratios, and more effective stress transfer between the aggregate skeleton and the cementitious matrix (Cheng et al., 2021; Subash et al., 2025). A denser microstructure experiences less strain under a specific tension, thereby enhancing the modulus of elasticity (Chen et al., 2015). Conversely, uniform-graded mixes typically demonstrate poorer interlocking, higher void content, and less effective load distribution, resulting in decreased stiffness (Subash et al., 2025). Additionally, it is clear how the proportions in the mix influence these characteristics. As the cement ratio rises from the 1:2:4 to the 1:1:2 mix, all gradations consistently show an increase in modulus of elasticity.

In summary, both aggregate gradation and mix proportion play crucial roles in determining the elastic modulus of concrete. The results affirm that optimizing aggregate gradation can significantly improve the mechanical efficiency and structural performance of concrete, even at constant cement content**.**

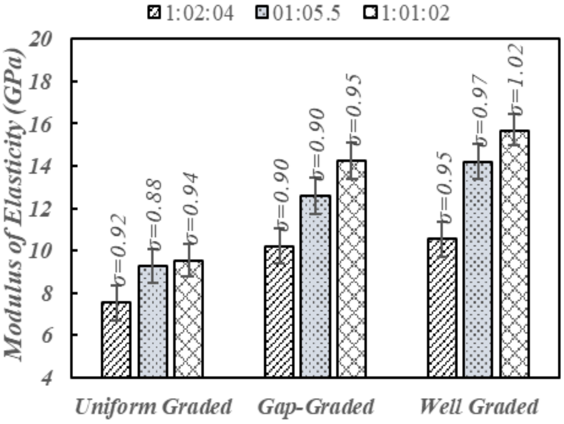


Figure 5: Modulus of Elasticity vs Gradation of CA for different Mix ratios

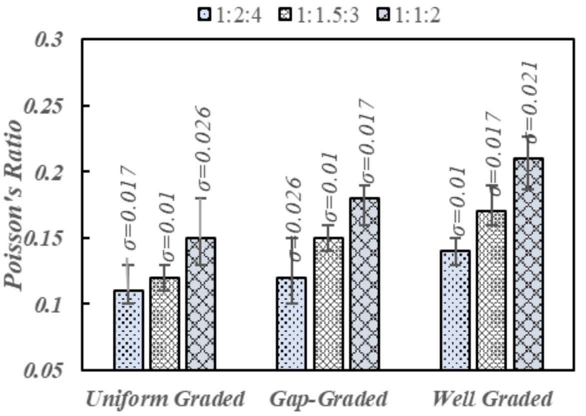


Figure 6: Poisson's Ratio vs Gradation of CA for different Mix ratios

3.4 Poisson's Ratio

Poisson's ratio of concrete was determined experimentally following ASTM C469, based on simultaneous measurements of axial and lateral strains during uniaxial compression, and calculated as the ratio of change in lateral strain to corresponding change in axial strain within the elastic range. Figure 6 depicts the variation of Poisson's Ratio for concrete with three different mix designs (1:2:4, 1:1.5:3, and 1:1:2) that include evenly graded, gap-graded, and well-graded coarse aggregates (CA). The findings suggest that both aggregate gradation and mix proportions significantly influence the elastic properties of concrete. Poisson's Ratio tends to increase with larger mix ratios in all types of gradation, indicating that a higher cement content enhances the material's capacity to undergo lateral displacement when subjected to compressive stress (Chang, 2002). This effect arises from the creation of a denser and more cohesive matrix, which strengthens the bond between the aggregate and paste and facilitates a more uniform strain distribution throughout the composite material (Fan et al., 2023). Uniform-graded and gap-graded mixes typically exhibit lower Poisson's Ratio values, often between 0.14 and 0.17 for the same mix ratio. In contrast, well-graded mixes consistently show the highest Poisson's Ratio values, achieving around 0.21 for the 1:1:2 mix. Improved particle interlocking, lower void ratios, and more effective load transfer mechanisms within the concrete matrix result in a superior elastic response (Klein et al., 2020) and increased Poisson's ratio. On the other hand, The mix ratio of 1:2:4 with various aggregate gradations resulted in Poisson's ratios ranging from 0.10 to 0.14. While the 1:2:4 mix using uniformly graded aggregates exhibited some increased variability, the standard deviations (σ) noted across all testing conditions remained fairly low, demonstrating a strong consistency in the experiments. In summary, the findings indicate that utilizing well-graded coarse aggregates along with richer cement mixes significantly enhances Poisson's Ratio, which signifies improved microstructural integrity, greater ductility, and better elastic deformation properties in concrete.

3.5 Different Correlations between Mechanical Properties of Concrete

Assessing the overall structural behavior of concrete necessitates a comprehension of the interrelationships among its mechanical characteristics. By formulating empirical relationships between key factors such as modulus of elasticity, compressive strength, tensile strength, and Poisson's ratio, engineers and researchers can effectively estimate one property based on another, thus reducing the necessity for extensive testing. These correlations are vital for material characterization, quality control, and the development of design equations that accurately depict material performance under load.

3.5.1 Relation between Splitting Tensile Strength and Compressive Strength

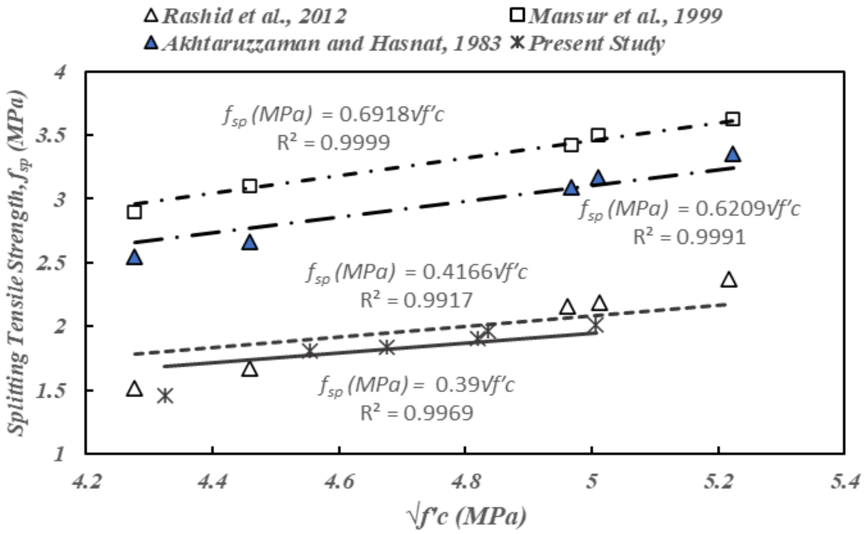


Figure 7: Splitting Tensile Strength vs Compressive Strength

Figure 7 illustrates the linear correlation between the splitting tensile strength (f_{sp}) and the compressive strength (f_c') of concrete, expressed through the empirical relation $f_{sp} = k\sqrt{f_c'}$. The figure compares the outcomes of the present study with previously established relationships reported by Akhtaruzzaman and Hasnat (1983), Mansur et al. (1999), and Rashid et al. (2012). For the respective studies, the relationships were obtained as:

Rashid et al. (2012) : $f_{sp}(MPa) = 0.6918\sqrt{f_c'}$, R^2=0.9999 (1)

Mansur et al. (1999) : $f_{sp}(MPa) = 0.6209\sqrt{f_c'}$, R^2=0.9991 (2)

Akhtaruzzaman and Hasnat (1983) : $f_{sp}(MPa) = 0.4166\sqrt{f_c'}$, R^2=0.9917 (3)

Present Study : $f_{sp}(MPa) = 0.39\sqrt{f_c'}$, R^2=0.9969 (4)

For the equations 1 to 4, the specified compressive strength of concrete, f_c', is taken in megapascals (MPa) to ensure consistency in calculations of modulus of elasticity and other derived properties. Tensile and compressive strengths have a strong linear relationship in all of the studies, with correlation values greater than 0.99, confirming this empirical relationship. However, this study's significantly lower constant (k = 0.39) suggests a comparatively lower tensile strength for the same level of compressive strength. Variations in microstructural integrity, the type of aggregates utilized, or the preparation process of the concrete mix under test could all be responsible for this discrepancy. In conclusion, the findings show that concrete's splitting tensile strength is significantly impacted by its compressive strength, supporting the conventional square-root relationship but also emphasizing material-specific differences seen in practical applications.

3.5.2 Relation between Modulus of Elasticity and Compressive Strength

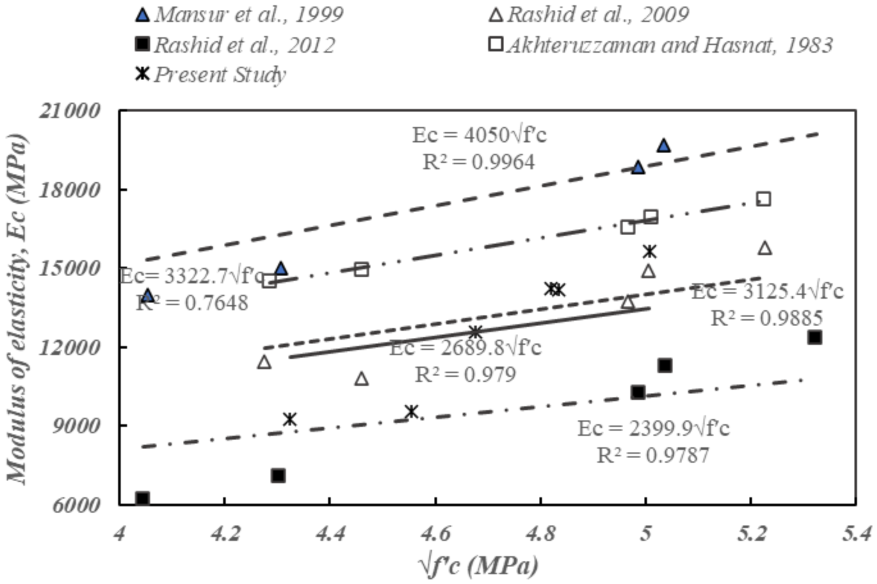


Figure 8: Splitting Tensile Strength vs Compressive Strength

Figure 8 illustrates the relationship between the modulus of elasticity (E_c) and the compressive strength (f_c') of concrete, expressed by the empirical form $E_c = k\sqrt{f_c'}$. The results from the present study are compared with established correlations proposed by Akhtaruzzaman and Hasnat (1983), Mansur et al. (1999), Rashid et al. (2009), and Rashid et al. (2012). The regression equations obtained from the respective studies are as follows:

Mansur et al. (1999) : $E_c\ (MPa) = 4000\sqrt{f_c'}$, R^2=0.9964 (5)
Rashid et al. (2009) : $E_c\ (MPa) = 3125.4\sqrt{f_c'}$, R^2=0.9885 (6)
Akhtaruzzaman and Hasnat (1983) : $E_c\ (MPa) = 3322.7\sqrt{f_c'}$, R^2=0.7648 (7)
Rashid et al. (2012) : $E_c\ (MPa) = 4050\sqrt{f_c'}$, R^2=0.9964 (8)
Present Study : $E_c\ (MPa) = 2689.8\sqrt{f_c'}$, R^2=0.979 (9)

For the above equations (5–9), the specified compressive strength of concrete, f_c', is taken in megapascals (MPa) to ensure consistency in calculations of modulus of elasticity and other derived properties. All datasets demonstrate a strong positive correlation, validating the empirical dependency of the modulus of elasticity on the square root of compressive strength. However, the lower coefficient (k = 2689.8) observed in the present study indicates a comparatively reduced stiffness, which can be attributed to differences in aggregate stiffness, concrete density, mix proportion, or curing environment. Overall, the results are in good agreement with previously reported models, reaffirming that E_c is predominantly governed by f_c', although the magnitude of k may vary with the material composition and microstructural characteristics of the concrete.

4. CONCLUSIONS

Based on the above results and discussions, following conclusions may be drawn:

i. The well-graded 1:1:2 mix achieved the highest compressive strength of 25.07 MPa, 21% higher than uniform-graded and 8% higher than gap-graded concrete for same mix ratio, while gap-graded mixes also gained 15.34% strength from the 1:2:4 to 1:1:2 mix, highlighting the benefits of proper gradation and richer mix proportions.
ii. Splitting tensile strength improved by about 10–35% for well-graded aggregates compared to uniform graded, and gap-graded aggregates for different mix ratios.
iii. The modulus of elasticity increased with improved gradation and richer mixes, reaching 15.63 GPa for well-graded 1:1:2 concrete, compared to only 7.80 GPa for uniform-graded 1:2:4 concrete.
iv. Overal, well-graded aggregates and richer mix proportions significantly improve mechanical performance of concrete, enhancing strength, and stiffness through better particle packing, reduced voids, and stronger aggregate–paste bonding.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Department of Civil Engineering, DUET, for providing the necessary laboratory facilities and financial support to carry out this research work.

DECLARATION OF USE OF AI

The authors used artificial intelligence (AI) only to improve the language, grammar, clarity, and structure of the written content. The research concepts, methodology, data analysis, result interpretation, and technology findings were developed independently and without the use of AI technologies. The authors meticulously reviewed and confirmed every aspect of the work to ensure accuracy, originality, and compliance with academic and ethical standards.

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