Influence of the Aggregate and Specimen Size on the Tensile Behavior of Notched Concrete Beams under Varying Strength Grades

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ABSTRACT

The influence of specimen size and maximum aggregate size on the tensile strength of notched C25, C45, and C60 grade concrete beams is investigated. Concrete beams with maximum aggregate sizes of 16 mm and 25 mm were subjected to three-point bending tests using three sample sizes (D1: 100 × 400 × 1200 mm, D2: 100 × 200 × 600 mm, D3: 100 × 100 × 300 mm). The results demonstrated that smaller specimens (D3) consistently exhibited higher tensile strengths than larger specimens (D1), with tensile strength increasing from 26% to 90% as specimen size decreased. The size effect was most pronounced in lower-grade concrete (C25) and diminished in higher-grade concrete (C60) due to enhanced fracture resistance and reduced sensitivity to microcracking. Smaller aggregates (16 mm) outperformed larger aggregates (25 mm) in tensile strength with a notable 17% improvement in D3 samples of C25 concrete. Conversely, larger aggregates demonstrated superior performance in larger C45 and C60 specimens due to their enhanced crack-bridging capacity. The interaction between specimen size and aggregate size highlights the importance of homogeneity and interfacial bonding in smaller specimens, whereas the crack-bridging ability of larger aggregates becomes more critical in larger specimens. These findings align with established fracture mechanics principles and underscore the necessity of considering size and aggregate effects in concrete design and testing to ensure accurate structural performance and reliability.

Keywords-concrete tensile strength; size effect; flexural performance; coarse aggregate size; fracture mechanics; notched beam

I. INTRODUCTION

Concrete is an essential material in construction and is prized for its durability, adaptability, and economic advantages [1]. It is formed by combining cement, water, and aggregates such as sand and gravel. Upon curing, concrete transforms into a solid, stone-like mass, rendering it indispensable for infrastructure development, including buildings, bridges, dams, and pavements [2]. Its ability to be cast into diverse shapes and sizes makes it suitable for a wide array of engineering and architectural applications. However, the mechanical properties of concrete are influenced by several factors, including specimen size, aggregate characteristics, and structural configuration [3]. A critical challenge in concrete engineering is understanding the 'size effect', which describes the dependence of concrete's mechanical properties on the size of the sample or structure. Larger concrete samples or structures often exhibit lower nominal strengths than smaller samples do because of increased material heterogeneity, stress redistribution, and crack propagation [4-5]. This phenomenon has been associated with several significant structural failures throughout history, including the collapse of the Malpasset arch dam in France in 1959. The failure was partly due to stress concentration and microcracking in the dam's concrete structure [6]. Similarly, the collapse of the Sleipner A offshore platform in Norway in 1991 has been attributed to inadequate fracture modeling of the concrete shafts, resulting in substantial financial losses [7]. Another prominent example is the failure of the Hyatt Regency walkway in Kansas City in 1981, where critical deficiencies in structural integrity and load-bearing capacity resulted in numerous fatalities [8]. These incidents underscore the need for thorough research into concrete mechanical behaviour to prevent future catastrophes.

Flexural tensile strength, an essential property of concrete, measures its resistance to bending forces. This property is particularly crucial in structural applications, as concrete is weak in tension compared with compression [9]. Several factors influence flexural tensile strength, including specimen size, geometry, and aggregate characteristics. The maximum aggregate size (dmax) significantly impacts tensile performance; smaller aggregates often improve strength because of better interfacial bonding, whereas larger aggregates may increase microcracking and porosity [10]. The notched samples were used to analyse fracture mechanics and calculate the crack propagation rate and stress intensity factor, considering the inevitable parameters required for fracture mechanics [11].

This study examined the combined influence of beam size, maximum aggregate size, and concrete grade on the flexural tensile behaviour of notched concrete beams The research design employs International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) draft recommendations and follows the American Society for Testing and Materials (ASTM) standards for three-point bending tests. Concrete beams of three geometrically proportional sizes, designated as D1, D2, and D3, were designed, as illustrated in Figure 1, incorporating two maximum aggregate sizes (dmax1 = 16 mm and dmax2 = 25 mm).

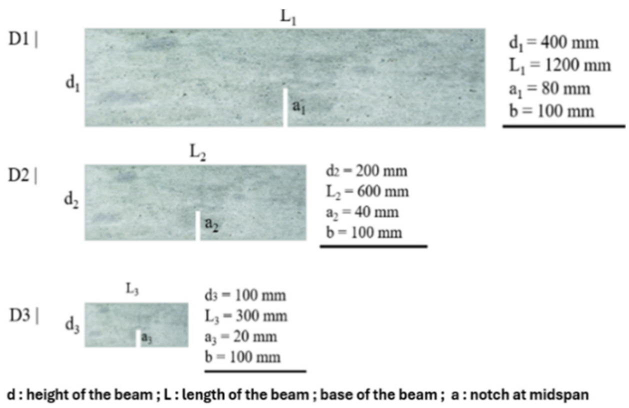


Fig. 1. Designed geometrically similar concrete beam samples (notches).

Additionally, three concrete grades, namely C25, C45, and C60, corresponding to compressive strengths of 25 MPa, 45 MPa, and 60 MPa respectively, were tested. By examining the interaction among these factors, this study aims to enhance the understanding of concrete fracture mechanics and contribute to the development of more reliable structural designs.

II. MATERIALS AND METHODS

A. *Material Properties*

1) *Cement, Superplasticizer, and Water*

The cement utilized in this study was CEM I 42.5 N ordinary Portland cement, complying with NF-EN 197-1, and served as the binder [12]. Potable tap water, without any additional treatment, was used for both mixing and curing the concrete.

A commercially available superplasticizer was utilized to enhance the workability and flowability of fresh concrete [13]. This admixture complies with the specifications outlined in the ASTM C494 Type G and EN 934-2 standards, ensuring its suitability for high-range water-reducing applications [14]. It has a specific gravity of 1.09 and is characterized by a clear color. Finally, potable tap water was used in the preparation of the concrete.

2) *Aggregate Properties*

For concrete fabrication, crushed natural coarse aggregates (with maximum aggregate sizes of $dmax_1$ = 16 mm and $dmax_2$ = 25 mm) were used alongside natural river sand as fine aggregates. The used aggregates are presented in Figure 2.

(a) (b) (c)

Fig. 2. Images of: (a) coarse aggregates with dmax1 (16 mm), (b) coarse aggregates with dmax2 (25 mm), (c) fine aggregates.

Coarse aggregates ranging from 5 mm to 25 mm were cleaned and dried to ensure compliance with BS 812:112 for Aggregate Impact Value (AIV) and BS 812:110 for Aggregate Crushing Value (ACV) standards, respectively [15-16]. The specific gravity and water absorption of both the fine and coarse aggregates were determined according to ASTM C128-15 and ASTM C127-15, respectively [17-18].

B. *Methods*

1) *Concrete Mix Design*

Three different concrete grades, C25, C45, and C60, were designed using a standard mix design method, and specimens were cast for two different maximum aggregate sizes [19]. The designations C25-16, C45-16, and C60-16 refer to concrete mixes with $dmax_1$ (16 mm), whereas C25-25, C45-25, and C60-25 correspond to $dmax_2$ (25 mm). The superplasticizer was incorporated into the C60 and C45 grades at dosages of 0.6% and 0.5% by cement weight, respectively. Table I details the mixed constituents for 1 m^3 of concrete.

TABLE I. MIX CONSTITUENTS AND QUANTITIES PER 1 m^3 CONCRETE

Concrete mix						
Grade	**C60**		**C45**		**C25**	
Maximum aggregate size (mm)	16	25	16	25	16	25
Cement CEM 1 42.5 N (kg/m^3)	622	715	477	440	407	298
Water (l/m^3)	205	236	200	185	267	197
River sand (0-5 mm) (kg/m^3)	661	505	716	635	806	708
Crushed coarse aggregates (5-16 mm) (kg/m^3)	913	-	912	-	1102	-
Crushed coarse aggregates (5-25 mm) (kg/m^3)	-	963	-	1080	-	1204
Superplasticizer (%)	0.6	0.6	0.5	0.5	-	-
Water-to-cement ratio	0.33	0.33	0.42	0.42	0.66	0.66

2) Experimental Program

To determine the mechanical properties of notched beams, three-point bending tests were conducted on simply supported beams. Three specimens of varying sizes were designed and tested: D1 (100 × 400 × 1200 mm), D2 (100 × 200 × 600 mm), and D3 (100 × 100 × 300 mm). Loading was applied via a hydraulic jack along with an appropriate load cell. Output data were recorded through a TDS-630 high-performance data logger.

Each beam featured notches of 20 mm, 40 mm, and 80 mm in depth, corresponding to the respective beam dimensions. The notches were incorporated to initiate cracking and facilitate the modeling of fractured behavior. Testing adhered to RILEM draft recommendations with a span-to-depth ratio of 2.5 and a notch depth-to-beam depth ratio of 0.2 [4]. The notch width was consistently set at 2 mm. Figure 3 illustrates the plywood formworks prepared for the study, along with the 2 mm metallic notch used in the experiments.

Accordingly, the support span length (l) and the beam depth (d) were defined as follows: D3 (l = 250 mm, d= 100 mm) , D2 (l = 500 mm, d= 200 mm) , D1 (l = 1000 mm, d= 400 mm). Figure 4 provides a detailed diagram of the test setup, and is adapted from the RILEM size–effect method for determining the fracture energy and process zone size of concrete [4].

Following ASTM D790, the beam tensile stress (σ_f) was evaluated using (1), where P is the load at the midpoint, l is the support span, b is the width of the sample, and d is the thickness of the sample [20].

$$\sigma_f = \frac{3Pl}{(2bd^2)} \quad (1)$$

Figure 5 shows concrete notched beam samples of different sizes and their respective test setups.

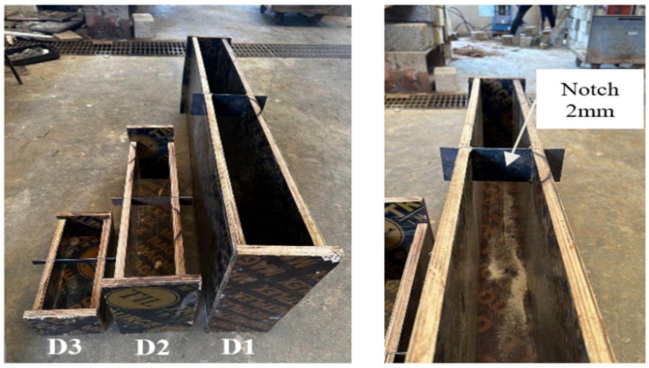


Fig. 3. Prepared plywood formworks and metalic notch of 2 mm.

The concrete mixtures (C25-16, C45-16, C60-16, C25-25, C45-25, and C60-25) were cast, and subsequently retained within their plywood formwork for 24 hours. Subsequently, the specimens were demolded and cured at ambient temperature (20–23 °C) until their evaluation at the age of 28 days. A total of 54 samples were prepared, as detailed in Table II.

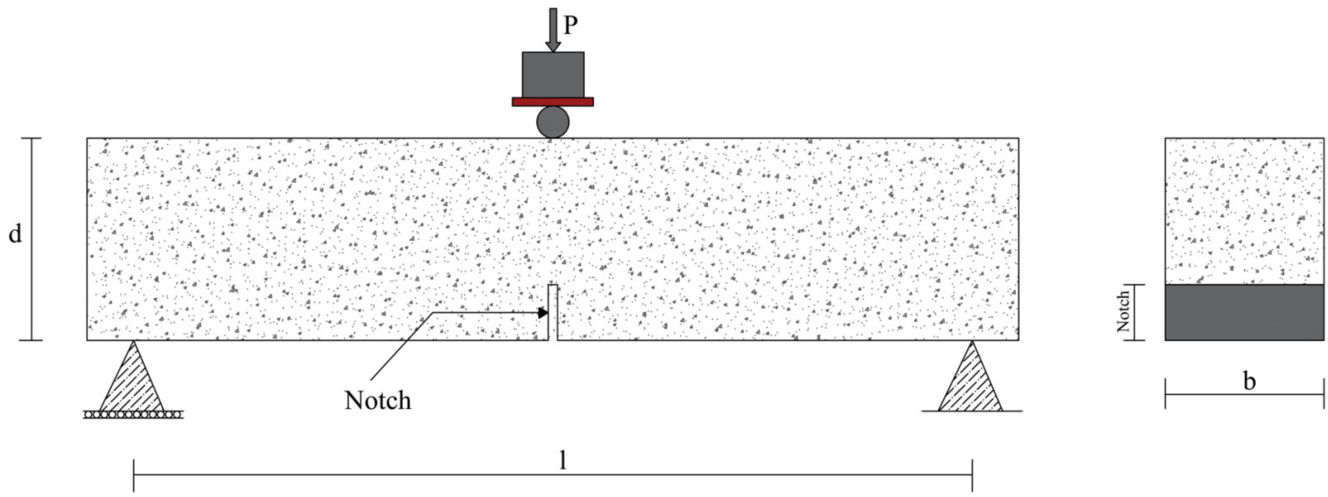


Fig. 4. Typical test setup for a notched beam sample.

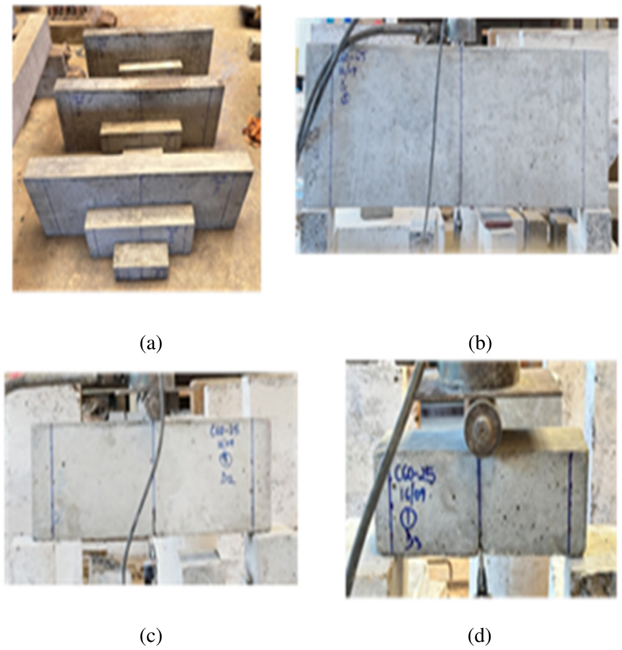


Fig. 5. (a) Concrete notched beam samples by size, (b) specimen test setup for D1, (c) specimen test setup for D2, (d) specimen test setup for D3.

TABLE II. SPECIMEN SIZE AND NUMBER OF SAMPLES PER MIXTURE

Concrete grade	C25		C45		C60	
Maximum aggregate size (mm)	16	25	16	25	16	25
D1 (100×400×1200 mm)	3	3	3	3	3	3
D2 (100×200×600 mm)	3	3	3	3	3	3
D3 (100×100×300 mm)	3	3	3	3	3	3

III. RESULTS AND DISCUSSION

A. Characterization of Material Properties

The physical properties of the aggregates are presented in Table III.

TABLE III. AGGREGATE PHYSICAL PROPERTIES

Property	Coarse aggregates	Fine aggregates
Aggregate specific gravity	2.54	2.69
Water absorption	3.09%	1.21%
Fineness modulus	-	2.81
ACV	17.41%	-
AIV	12.43%	-

Figures 6(a) and 6(b) present the particle size distributions of the coarse aggregates with maximum sizes (dmax) of 16 mm and 25 mm, respectively, whereas Figure 6(c) depicts the particle size distributions of the fine aggregates. Based on the analysis, the fine aggregates were classified within the medium size, with fineness modules ranging between 2.6 and 2.9.

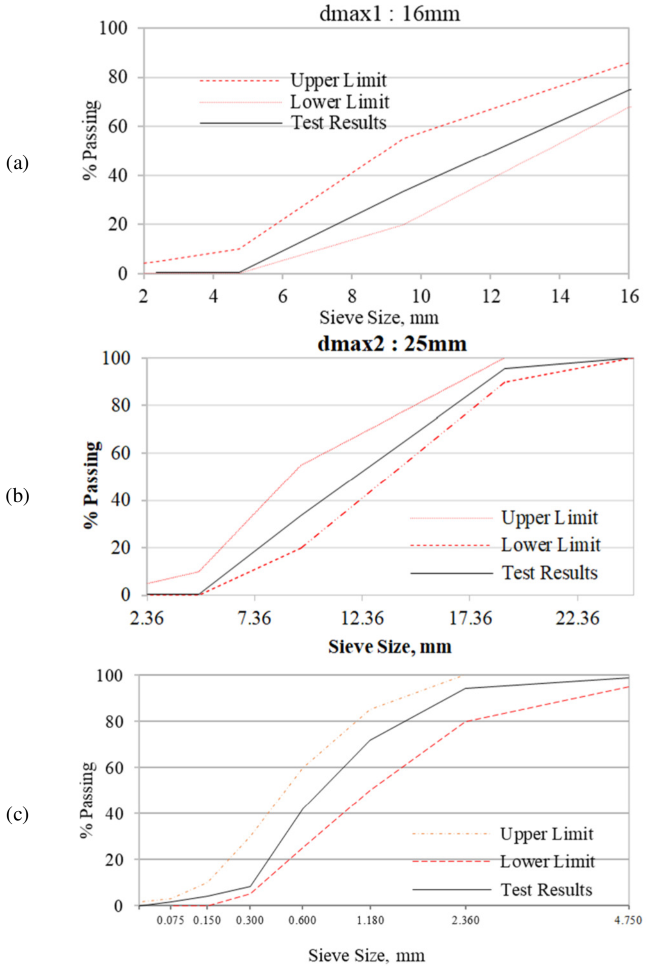


Fig. 6. (a) Particle size distribution for coarse aggregates with dmax1, (b) dmax2, and (c) fine aggregates.

Furthermore, the AIV and ACV results indicate that the coarse aggregates exhibit adequate strength and are suitable for construction applications.

B. Effect of the Specimen Size on the Tensile Strength

Table IV presents the recorded maximal forces (Pmax) and the corresponding tensile strength values for notched concrete beams, considering different specimen sizes and aggregate sizes (dmax) across all concrete grades (C25, C45, C60). The influence of beam dimensions and concrete grade on tensile strength across all tested concrete grades and coarse aggregate sizes is illustrated in Figure 7. The tensile strength of the concrete beams is significantly influenced by the specimen size [21]. Smaller beams (D3: 100 × 100 × 300 mm) consistently exhibited the highest tensile strength across all the concrete grades and aggregate sizes, whereas larger beams (D1: 100 × 400 × 1200 mm) demonstrated the lowest tensile strength. In the C25 grade, the tensile strength increased by approximately 40% from D1 (1.290 MPa) to D3 (1.801 MPa) for beams with 25 mm aggregates and by 26% for beams with 16 mm aggregates (from 1.665 MPa to 2.100 MPa). The pronounced size effect in C25 can be attributed to the increased heterogeneity and microcracking propensity in larger samples, which results in greater stress redistribution around the notches [22]. The C45 grade also demonstrated a significant size effect, although it was less pronounced than that in C25. For the 25 mm aggregates, the tensile strength increased by 33% from D1 (2.275 MPa) to D3 (3.035 MPa), whereas for the 16 mm aggregates, the tensile strength increased by approximately 6% (from 2.416 MPa to 2.563 MPa). The reduced sensitivity to size effects observed in C45 can possibly be attributed to its improved material homogeneity and superior mechanical properties compared to C25. For the C60 grade, tensile strength increases between D1 and D3 were 12% for beams with 25 mm aggregates (from 3.014 MPa to 3.385 MPa) and 90% for beams with 16 mm aggregates (from 1.627 MPa to 3.096 MPa). Smaller beams benefit from delayed crack propagation and reduce stress concentration at the notch tips. Additionally, the reduced difference between the tensile strengths in D1 and D3 for larger aggregates highlights the crack-bridging capacity of these aggregates in high-strength concrete [23].

TABLE IV. RECORDED MAXIMAL FORCES AND CORRESPONDING TENSILE STRENGTH OF NOTCHED CONCRETE BEAMS

Concrete grade	Beam size	dmax (mm)	Maximal force (kN)	Tensile strength (MPa)
C25	D1	16	17.76418855	1.665
	D2		9.307788483	1.745
	D3		5.600267401	2.100
	D1	25	13.75470006	1.290
	D2		8.986659702	1.685
	D3		4.801078818	1.801
C45	D1	16	25.76961995	2.416
	D2		13.34833299	2.503
	D3		6.832914198	2.563
	D1	25	24.26606176	2.275
	D2		15.27180381	2.864
	D3		8.092652134	3.035
C60	D1	16	17.35782147	1.627
	D2		14.47261523	2.714
	D3		8.255198965	3.096
	D1	25	32.14958304	3.014
	D2		17.18843371	3.223
	D3		9.027296409	3.385

This size effect aligns with the Size Effect Law (SEL) for quasi-brittle materials, where the nominal strength decreases with increasing specimen size due to increased material heterogeneity and stress redistribution [24]. Larger notches in D1 beams (80 mm depth) exacerbate stress concentration, facilitating crack initiation and propagation at lower stress levels. Smaller notches in D3 beams (20 mm depth) delay crack propagation and increase fracture toughness.

C. Impact of Aggregate Size on Tensile Strength

Figures 8-10 illustrate the effect of the aggregate size on the tensile strength across different beam dimensions. The data points represent the average tensile strength for each combination of aggregate size (16 mm, 25 mm) and specimen size. The results indicate that the coarse aggregate size significantly influences tensile strength, with variations being observed across concrete grades and beam dimensions.

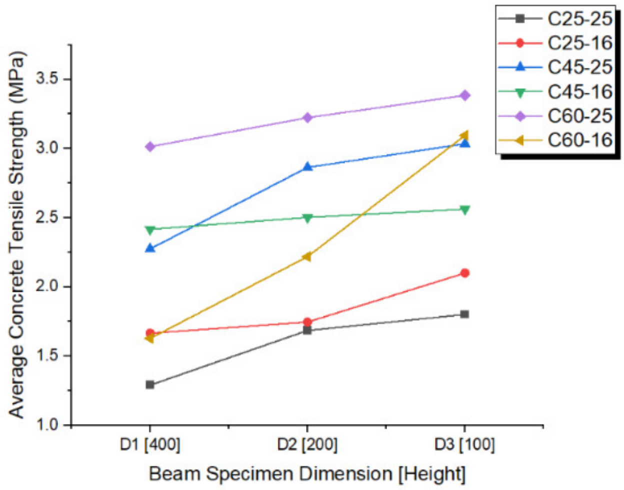


Fig. 7. Effect of the specimen size and concrete grade on the tensile strength.

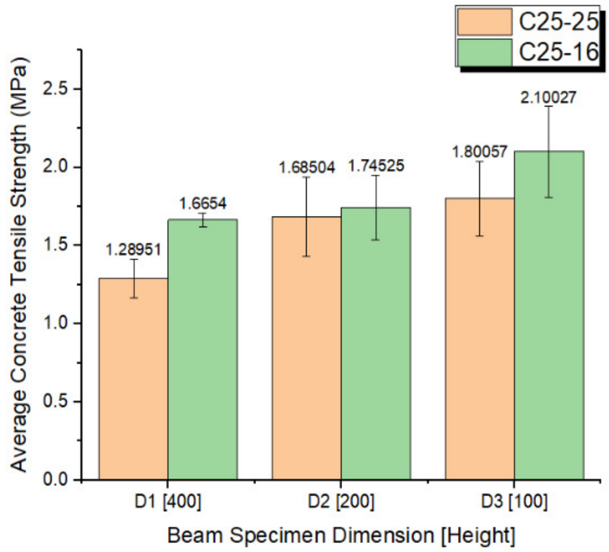


Fig. 8. Influence of aggregate size on the tensile strength of C25-25 and C25-16 concrete grades across increasing specimen sizes.

Beams incorporating 16 mm coarse aggregates consistently demonstrated higher tensile strengths compared to those containing 25 mm coarse aggregates. Specifically, D3 beams with 16 mm aggregates achieved a 17% greater tensile strength than those with 25 mm aggregates (2.100 MPa vs. 1.801 MPa). This trend can be attributed to better interfacial bonding and reduced porosity in smaller aggregates, which enhance the tensile performance. However, the impact of aggregate size was not uniform across all the concrete grades. In C45 concrete, the effect of the aggregate size varied depending on the beam dimensions. Larger aggregates demonstrated slightly greater tensile strengths in larger beams (e.g., D1 beams: 2.275 MPa for 25 mm aggregates vs. 2.416 MPa for 16 mm aggregates), whereas smaller aggregates performed better in smaller beams (e.g., D3 beams: 3.035 MPa for 25 mm aggregates vs. 2.563 MPa for 16 mm aggregates). This indicates that the interplay between the crack-bridging capacity and matrix homogeneity becomes more critical in medium-strength concrete.

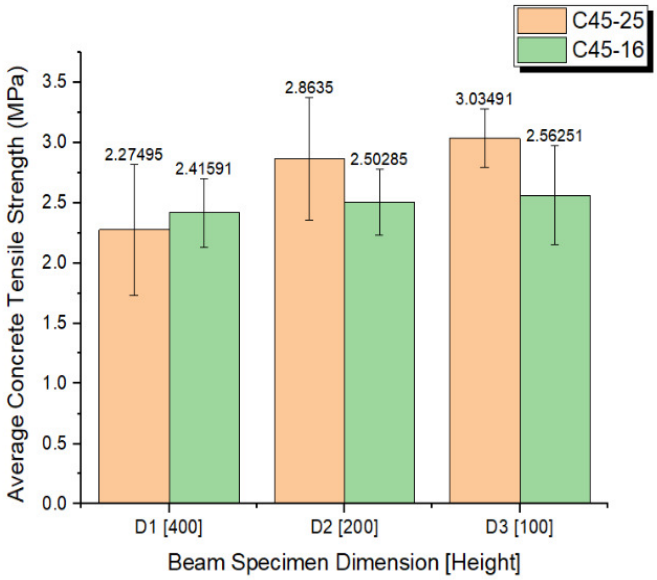


Fig. 9. Influence of aggregate size on the tensile strength of C45-25 and C45-16 concrete grades across increasing specimen sizes.

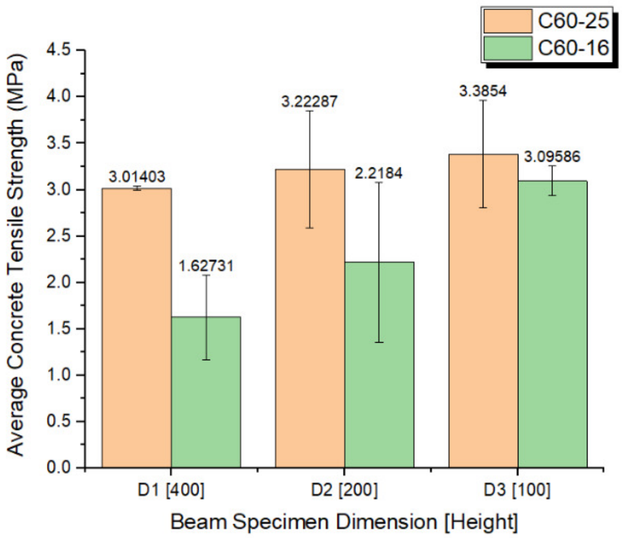
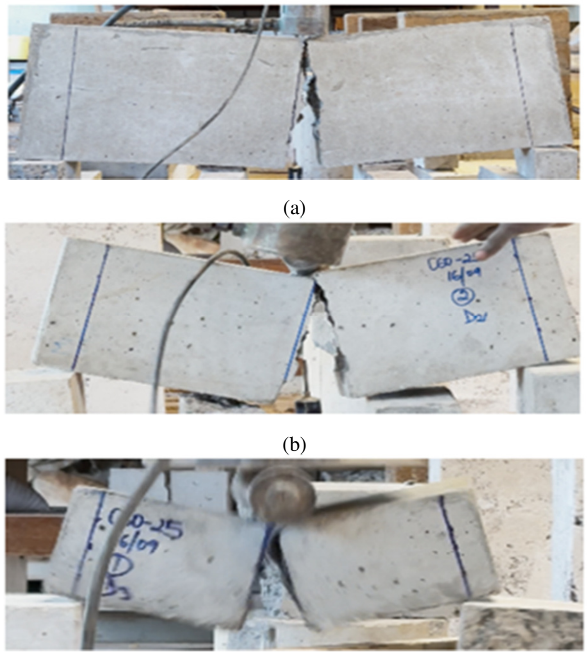


Fig. 10. Influence of aggregate size on the tensile strength of C60-25 and C60-16 concrete grades across increasing specimen sizes.

Regarding high-strength C60 concrete, the influence of aggregate size followed a different trend. Larger aggregates generally resulted in higher tensile strength in larger beams (e.g., D1 beams: 3.014 MPa for 25 mm aggregates vs. 1.627 MPa for 16 mm aggregates). However, in smaller beams (D3), the tensile strength difference between aggregate sizes was minimal (3.385 MPa for 25 mm aggregates vs. 3.096 MPa for 16 mm aggregates). This can be attributed to the dense microstructure of C60 concrete, which mitigates stress concentrations more effectively, reducing the impact of aggregate size on crack development.

Figure 11 shows the failure type across different sample sizes. The flexural failure observed in all samples was bending failure, which was primarily influenced by the initial crack introduced during casting. This preexisting defect acted as a stress concentration point, weakening the beams and reducing their ability to withstand tensile forces. Overall, beams containing 25 mm aggregates exhibited a more brittle failure compared to those incorporating a 16 mm maximum aggregate size. This study's observations are consistent with other experimental findings [25].



(a)

(b)

(c)

Fig. 11. Images of: (a) flexural failure of a large beam (D1: 100 × 400 × 1200 mm), (b) flexural failure of a medium beam (D2: 100 × 200 × 600 mm), and flexural failure of the smallest beam (D3: 100 × 100 × 300 mm).

The aggregate size influences crack formation and propagation through two primary opposing effects: crack susceptibility and crack bridging. Larger aggregates increase the spacing between particles, potentially leading to greater crack susceptibility due to stress concentrations [26]. When tensile stress is applied, cracks are more likely to initiate in regions where the load transfer between aggregates is insufficient. This effect is particularly pronounced in medium- and lower-strength concretes, where the matrix is less dense, facilitating the propagation of microcracks. However, larger aggregates also enhance crack-bridging capabilities, which improves load transfer and energy dissipation. This effect is particularly beneficial in high-strength concrete, where a stronger matrix more effectively accommodates stress concentrations [27]. The presence of larger aggregates increases the fracture resistance, allowing longer cracks to bridge and delay failure.

Additionally, the strong bond between cement paste and aggregates in high-strength concrete ensures that cracks do not propagate easily, maintaining structural integrity. Larger aggregates in larger beams play a key role in stress concentration mitigation, reducing the likelihood of premature cracking [28]. Their ability to act as stress diffusers enables concrete to absorb and redistribute loads, minimizing crack propagation. This phenomenon is particularly evident in large-scale concrete structures, where the stress distribution is crucial. The crack bridging effect of larger aggregates is particularly beneficial in larger specimens, as extended crack lengths necessitate more robust load transfer mechanisms. This contributes to enhanced structural integrity, thereby improving the resistance of concrete elements to tensile failure [29].

While larger aggregates may initially increase crack susceptibility, their crack-bridging capabilities provide significant benefits in terms of load transfer and energy dissipation. The effectiveness of larger aggregates in stress mitigation depends on the concrete matrix properties, beam dimensions, and overall structural design considerations. Therefore, optimizing aggregate selection should account for both crack susceptibility and bridging efficiency to enhance tensile strength and durability.

IV. CONCLUSIONS

This study provides a comprehensive analysis of the influence of specimen size and maximum aggregate size on the tensile strength of notched concrete beams across different strength grades. Through extensive experimental investigations, it was demonstrated that the size effect and aggregate characteristics significantly impact the flexural tensile performance of concrete.

Smaller specimens exhibited higher tensile strength, with increases of 40% and 26% for 25 mm and 16 mm aggregates in C25, 33% and 6% in C45, and 12% and 90% in C60, highlighting a more pronounced size effect in lower-grade concrete. Additionally, 16 mm aggregates enhanced the tensile strength by 17% in smaller C25 samples (D3), whereas 25 mm aggregates performed better in larger C45 and C60 samples (D1), demonstrating their crucial crack-bridging role in high-strength concrete.

Unlike many prior studies that focused primarily on the size effect on the compressive strength or flexural properties of beam samples, this research extends the understanding of fracture mechanics by evaluating the tensile behaviour of notched concrete beams with increasing sample dimensions and aggregate sizes. The experimental results not only confirm the fundamental principles of the Size Effect Law (SEL) in quasi-brittle materials, but also introduce a more refined understanding of the aggregate size–beam size interaction, a topic that has received limited attention in the literature.

Authors in [3, 24] explored fracture mechanics and the size effect theory, and the findings align with and expand upon this work, reinforcing the notion that larger concrete samples exhibit lower nominal strength due to increased material heterogeneity and stress redistribution. However, in contrast to prior studies, this research provides empirical evidence on the influence of aggregate size on this trend, emphasizing the role of smaller aggregates in enhancing interfacial bonding and improving the tensile performance of smaller beams. Authors in [23-30] investigated the effects of aggregate size on concrete compressive strength; nevertheless, in contrast to their findings, this study establishes a direct relationship between aggregate size, specimen dimensions, and flexural tensile behaviour. The results demonstrate that larger aggregates enhance load transfer mechanisms in high-strength concrete as beam dimensions increase.

This research bridges a critical knowledge gap by systematically analysing the interplay between aggregate size, increasing specimen sizes, and varying concrete grades in notched beam configurations, which are more representative of real-world structural failures, allowing further insights from numerical investigations. It offers practical insights for structural engineers and material scientists, emphasizing the need for tailored mix designs based on beam dimensions and loading conditions. This work also suggests that concrete standards should consider specimen-dependent variations in tensile strength when designing experimental setups for material characterization [31-32].

By providing a detailed experimental validation of theoretical size effect models and their interaction with coarse aggregate selection, this study contributes to both structural safety and performance optimization in concrete engineering. Future research could extend these findings by incorporating environmental factors, long-term durability assessments, and numerical modeling to further enhance the predictive capabilities of fracture mechanics in concrete structures.

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