Civil and Environmental Engineering
Vol. 20, Issue 2, 1221-1245, DOI: 10.2478/cee-2024-0089

COARSE AGGREGATE GRADING EFFECT ON THE CORRELATION BETWEEN COMPRESSIVE AND FLEXURAL STRENGTHS OF CONCRETE

Ahmed BOUFEDAH BADISSI[1,*], A. BEROUAL[1], M. BENTALHA[1]

[1] LMDC Laboratory, Department of Civil Engineering, Faculty of Science of Technology, Mentouri Brothers University (Constantine 1), Constantine 25000, Algeria
* corresponding Author: ahmed.boufedah.badissi@umc.edu.dz
ORCID ID: https://orcid.org/0000-0001-9941-1843

Abstract
Existing models relating compressive and flexural strengths often fail to align with our experimental findings. A preliminary study highlighted that many authors should have considered the influence of varying coarse aggregate grading. Consequently, an empirical investigation was conducted to assess the impact of coarse aggregate grading on compressive and flexural strengths and the interrelationship between these strengths through the tensile coefficient Kt. The central objective is formulating a suitable empirical equation for the fluctuating coarse aggregate grading that connects compressive and flexural strengths. The reliability of the proposed equations was evaluated using the integral absolute error (IAE). Results underscore that coarse aggregate grading exerts a noticeable effect on compressive and flexural strengths, with the latter being more susceptible. The relationship between these strengths is also influenced, exhibiting two distinct fields of variation. A novel parameter, FCR, is introduced to quantify coarse aggregate grading variance within these two fields. Optimal flexural strength outcomes are achievable by employing coarse aggregate grading with an FCR greater than five. Two equations associating compressive and flexural strengths are proposed, introducing two distinct values for the tensile coefficient Kt.

Keywords:
Compressive strength;
Flexural strength;
Coarse aggregate
Concrete
Tensile coefficient Kt

1. Introduction

Concrete, as a traditional construction material, has played a pivotal role in shaping the built environment for centuries. Its importance is deeply rooted in its versatility, durability, and widespread availability. However, with the emergence of new materials such as Fiber-Glass (FG) sandwich plates [1-2] and other advanced composites, the continued significance of concrete and its unique contributions to the construction industry persist.

In structural engineering and concrete technology, assessing material strength properties play a pivotal role in ensuring the durability and reliability of constructed infrastructures. This study embarks on a comprehensive exploration of various factors influencing the strength characteristics of concrete, with a particular focus on flexural strength (Ffs) and compressive strength (Fcs). Recognized as fundamental parameters in concrete mechanics, these strengths are not indispensable in conventional structural design and wield specific significance for diverse engineering applications.

The interplay between flexural and compressive strengths offers valuable insights into the material's performance under different loading conditions, providing a nuanced understanding of its mechanical behavior. Scholars such as Xu and Shi and Martínez-Molina, Torres-Acosta et al have contributed significantly to the discourse on concrete strength, emphasizing the crucial role these properties play in determining the material's overall integrity [3-4]. While compressive strength remains a standard benchmark in structural engineering, the study delves deeper into the often overlooked yet equally vital aspect – tensile strength – identified by Neville as particularly significant for specific engineering purposes [5].

The current scientific landscape reveals numerous studies exploring the interplay between Ffs and Fcs. The nature of concrete strength suggests a close interconnection between these types of strength [5]. The relationship is influenced by concrete strength levels and factors such as aggregate properties, mineralogy, admixture types, compaction, and curing conditions [6-8]. The impact of aggregate properties, particularly on cracking load and flexural strength, is explored, making this relationship independent of the type of aggregate used [5].

On the contrary, the relationship between flexural and compressive strength is contingent on the type of coarse aggregate utilized. This is because, except in high-strength concrete, aggregate properties, especially shape and surface texture exert a considerably smaller influence on ultimate strength in compression than strength in tension or the cracking load in compression [9]. Knab's research further substantiated this behavior [10].

Researchers have found the power regression model more suitable for a wide range of concrete strengths, with the most commonly used form being [3-15].

$$\mathrm{F_{fs}} = K_t(\mathrm{F_{cs}})^n \quad (1)$$

The tensile coefficient Kt varies from 0.034 to 0.94, while the power regression coefficient n ranges from 0.5 to 1.35. Different empirical relationships between Ffs and Fcs in concrete are summarized in Table 1. Although most design codes recommend a square root function to relate flexural strength to compressive strength, it has been reported that for a wide range of concrete strengths and high-performance concrete, the 2/3 power results in a more accurate prediction of concrete's flexural strength [8, 16-19]. According to Ahmed et al., the square root relationship used in many design codes is unsuitable for various concrete strengths [17]. Abdul and Wong have also concluded that the square root function recommended by most codes is inadequate for higher strength concrete [18]. Several researchers have used values other than square root and 2/3 power functions to predict flexural strength as a function of compressive strength [3, 20-21].

Considering the importance of compressive and tensile strengths, the study emphasizes the relationship between Ffs and Fcs. However, the relationship's contingency on the type of coarse aggregate is noted. Despite various influencing factors, the common practice relies on Fcs for estimating Ffs [11-12]. The lack of consensus on estimation methods prompts a systematic study to establish a new, more reliable model.

Table 1 regroups some models relating compressive and flexural strengths, already published by researchers and codes.

Table 1: Relationship between flexural and compressive strengths.

Equation type	Author/Code	Equation
Power of 0.5	Sbarounis, J.A (1984) [22]	$\mathrm{F_{fs}} = 0.62\ \mathrm{Fcs}^{0.5}$
	Graham and Scanlon (1986) [23]	$\mathrm{F_{fs}} = 0.33\ \mathrm{Fcs}^{0.5}$
	Legron and Paultre (2000) [13]	$\mathrm{F_{fs}} = 0.68\ \mathrm{Fcs}^{0.5}$
	India code (2000) [24]	$\mathrm{F_{fs}} = 0.626\ \mathrm{Fcs}^{0.5}$
	ACI code (2005) [12]	$\mathrm{F_{fs}} = 0.62\ \mathrm{Fcs}^{0.5}$
	Xiao et al (2006) [25]	$\mathrm{F_{fs}} = 0.75\ \mathrm{Fcs}^{0.5}$
	Saudi code (2007) [26]	$\mathrm{F_{fs}} = 0.7\ \mathrm{Fcs}^{0.5}$
	Logan et al (2009) [27]	$\mathrm{F_{fs}} = 0.5\ \mathrm{Fcs}^{0.5}$
	Kothai and Malathy (2012) [28]	$\mathrm{F_{fs}} = 0.657\ \mathrm{Fcs}^{0.5}$
Power of 2/3	Raphael (1984) [14]	$\mathrm{F_{fs}} = 0.342\ \mathrm{Fcs}^{2/3}$
	European code (2002) [29]	$\mathrm{F_{fs}} = 0.3\ \mathrm{Fcs}^{2/3}$
	Rashid et al (2002) [30]	$\mathrm{F_{fs}} = 0.42\ \mathrm{Fcs}^{2/3}$
	Ramadoss Perumal (2008) [31-32]	$\mathrm{F_{fs}} = 0.45\ \mathrm{Fcs}^{2/3}$
	Ahmed and shah (1984) [33]	$\mathrm{F_{fs}} = 0.44\ \mathrm{Fcs}^{2/3}$
Other than 0.5 and 2/3	Sarker et al (1997) [20]	$\mathrm{F_{fs}} = 0.564\ \mathrm{Fcs}^{0.55}$
	Bhanja and sengupta(2005) [34]	$\mathrm{F_{fs}} = 0.275\ \mathrm{Fcs}^{0.81}$
	Xu and Shi (2009)[3]	$\mathrm{F_{fs}} = 0.39\ \mathrm{Fcs}^{0.59}$

	Ramadoss Perumal (2015) [35]	$F_{fs} = 0.259\ Fcs^{0.834}$
	N.K.Amudhavalli and M.Poovizhiselvi (2017) [21]	$F_{fs} = 0.39\ Fcs^{1.35}$

Other researchers have chosen to adopt equations of either linear or exponential form. Mahmood et al chose used the following linear equation to represent the correlation between compressive and flexural strengths [36].

$$F_{fs} = 1.99 + 0.16\ F_{cs} \quad (2)$$

In a similar equation, Marín-Uribe, C. R., & Navarro-Gaete, R have chosen to use compressive strength on cubic specimens getting the following equation [37]:

$$F_{fs} = 1.389 + 0.0524\ F_{cu} \quad (3)$$

Prasad et al chose the following exponential equation [38]:

$$F_{fs} = 3.13\ e^{0.0086\ F_{cs}} \quad (4)$$

Hamah Sor et al for a self-compacting concrete reinforced with low-density waste Polyethylene fiber established a linear equation [39].

$$F_{fs} = 0.2055\ F_{cs} - 3.0617 \quad (5)$$

Abolhasani et al adopted a similar linear equation for a calcium aluminate cement concrete [40].

$$F_{fs} = 0.1711\ F_{cs} - 4.6414 \quad (6)$$

In this paper, the study investigates the effect of coarse aggregate grading on the mechanical properties of concrete, including flexural and compressive strengths. The goals include understanding the genuine contribution of coarse aggregate grading and identifying an effective model that relates the compressive and flexural strengths of concrete using Algerian local materials. The proposed models aim to develop more accurate and reliable predictions to represent this contribution.

The bibliographic study carried out confirms that the published models do not correspond to all possible variations in the particle size of coarse aggregates, so that a single model cannot represent the entire variation in the grain size of coarse aggregates.

Unlike all researchers, the coarse aggregate grading is represented by the different amounts of elementary coarse aggregate used in the mixture: the finer, the medium, and the larger coarse aggregate. The FCR ratio, defined as the ratio of finer to larger coarse aggregate was introduced to follow the variation of the completely coarse aggregate grading.

This research adds to the existing body of literature by providing numerical data and models that quantify the relationship between coarse aggregate grading and the relation between compressive and flexural strengths of Normal Strength Concrete. By establishing correlations and introducing the FCR factor, it offers a more detailed analysis and prediction tool.

1. Experimental work

1.1. Materials

Type CEM-II cement with a grade of 42.5, in compliance with NF EN 197-1[41], was utilized. Its chemical compositions are summarized in Table 2. The cement specific gravity was measured to be 3.1. Local crushed limestone has been selected as the coarse aggregate. Three size classes were utilized: Finer coarse aggregate (F_{CA}), Medium coarse aggregate (M_{CA}), and Larger coarse aggregate (L_{CA}). They have nominal maximum sizes of 8 mm, 16 mm, and 22.4 mm, respectively. A crushed limestone sand (S) with a particle size of 0/4 mm was used.

Table 2 Chemical Composition and Physical Properties of the Used Cement

Composition	Cao	Sio2	Al2o3	Fe2o3	Mgo	K2o	Na2o	Cl-	So3	Lolb	Cao	Sio2
[%]	55.85	27	6.13	3.12	0.95	/	/	0.1	3.5	2.4	55.85	27
Fineness: 399 m²/kg Specific gravity: 3.1 b LOS = Loss of Ignition												

Fig. 1 depicts the particle size distributions of sand, coarse aggregates F_{CA}, M_{CA}, and L_{CA}, as measured by mechanical sieving in accordance with NF EN 933-1[42].

According to the methods specified in 1097-6 [43], the particle densities of S, F_{CA}, M_{CA}, and L_{CA} were determined to be 2.6 Mg/m³.. The absorption, which varied depending on the aggregate class size, ranged from 0.12 to 1.48%. Regular tap water was uniformly used for preparing fresh concrete mixtures.

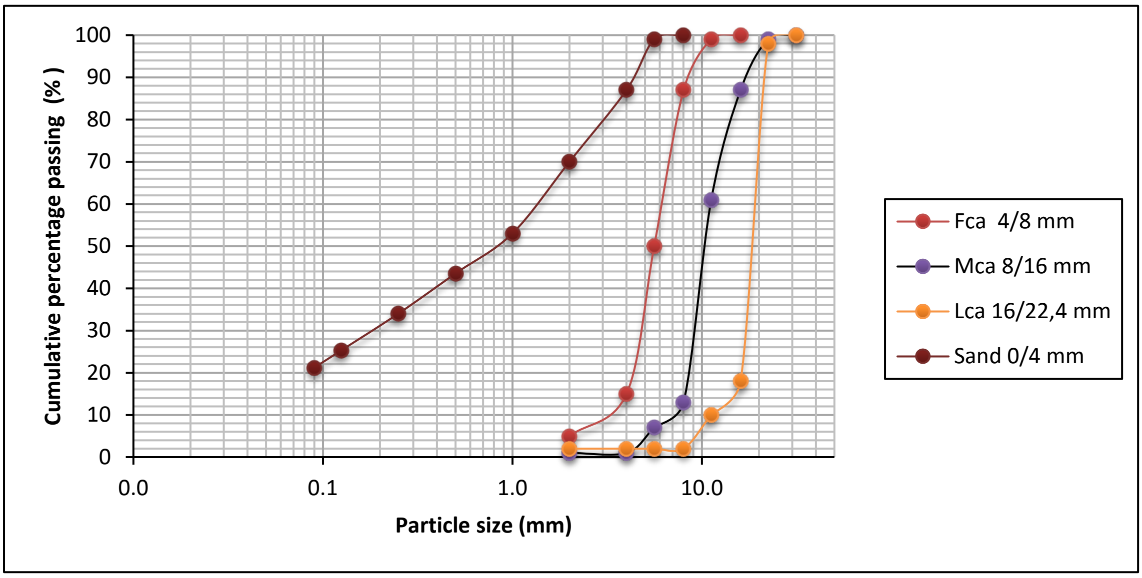

Fig. 1: Particle size distributions of Sand, F_{CA}, M_{CA} and L_{CA}

1.2. Experimental methods

An experimental plan was developed to investigate the impact of coarse aggregate grading on concrete properties. Twenty-five concrete mixtures were prepared using twenty-five different coarse aggregate grading. The water-to-cement ratio (w/c) and the coarse aggregate-to-sand ratio (G/S) remained unchanged for all mixtures. The same water, cement, and aggregate sources were used to maintain consistent quality and origin parameters for these materials. Only the coarse aggregate grading was modified to investigate the impact of this particle size distribution (PSD) on the mechanical behavior of concrete.

Differences in particle size distribution result in varying particle shapes, distinct specific surface textures, and varying void characteristics, leading to differences in concrete's physical, mechanical, and durability characteristics.

The mix proportions used in this study are presented in Table 3Table 3 Constituents and proportions for all mixtures tested

Constituents	Cement [kg/m^3]	Coarse aggregate [kg/m^3]	Sand [kg/m^3]	Water [kg/m^3]	Water/cement	CA/S
Quantity	350	1038.5	695	198	0.566	1.494

1.3. Coarse aggregate grading

In this paper, the coarse aggregate for each concrete mixture consists of a combined coarse aggregate with sizes ranging from 4 mm to 22.4 mm, obtained by blending the three aggregates F_{CA}, M_{CA}, and L_{CA} at specific percentages.

The M_{CA} was varied from 10% to 80% in increments of 10%, resulting in eight combined aggregates. For each of these eight aggregates, five subclasses were derived based on the proportions of F_{CA} and L_{CA}. Following a preliminary study and considering the obtained values, three grading combinations that were either very similar or aberrant (corresponding to M_{CA}values of 30%, 40%, and 60%) were eliminated. This led to a focus on five primary grading combinations, corresponding to M_{CA} values of 10%, 20%, 50%, 70%, and 80%. In total, 25 mixtures with 25 different grading combinations were analysed in the study.

An efficient parameter, denoted as FCR (Finer to Larger coarse aggregate Ratio), has been introduced to establish a relationship between the variation in F_{CA} and L_{CA} that co-occurs with the variation in M_{CA}. FCR serves as a numerical tool used to interpret the impact of coarse aggregate grading variation, providing detail for each obtained subclass.

Equation 7 provides the formula used to evaluate the FCR ratio

$$\mathrm{FCR} = \frac{\%\,\mathrm{F_{CA}}}{\%\,\mathrm{L_{CA}}} \quad (7)$$

Table 4 summarizes the various percentages of elementary aggregates used to achieve the all studied grading.

Table 4 FCR and $\mathrm{M_{CA}}$ values used for different studied grading

$\mathrm{M_{CA}}$	FCR > 5	1 < FCR ≤ 5	FCR = 1	0.5 ≤ FCR < 1	FCR < 0.5
10	11	3	1	0.5	0.1
20	7	3.6	1	0.5	0.1
50	14	4	1	0.5	0.3
70	11	3	1	0.5	0.3
80	7	3	1	0.6	0.1

1.4. Mix proportions

1.4.1. Casting and conditioning of the specimens

Twenty-five concrete mixtures were tested to assess their hardened characteristics. The mixing process for all mixtures was conducted using a conventional pan concrete mixer, where the coarsest constituent (coarse aggregate) was mixed with the finest one (sand), followed by the addition of the next finest constituent (cement). A total of 150 specimens were tested, with 75 specimens allocated for the compressive strength test and another 75 for the flexural strength test.

The specimens were demolded 24 hours after casting and were subsequently cured at room temperature in an open-air environment until the age of the test. All specimens were tested at the age of 28 days.

1.4.2. Testing details

The three-point bending test was conducted to measure the flexural strength of prismatic specimens, following NF EN 12390-5 [44] standards. The span length and the cross-sectional dimensions of the specimen were 400 mm and 100 × 100 mm², respectively. Photo 1 depicts the specimen during the flexural test. The compressive strength test was carried out on 160 × 320 mm cylinder specimens in accordance with NF EN 12390-3 [45] guidelines. Photo 2 displays the specimens during the compressive test.

Photo 1: The testing equipment used to assess the flexural strength through a three-point bending test.

Photo 2: The testing equipment used to determine the compressive strength of cylindrical specimens.

2. Results and discussion

Two properties of hardened concrete were investigated: compressive strength and flexural strength.

2.1. Effect of coarse aggregate grading on concrete strength

2.1.1. Effect of coarse aggregate grading on the Compressive strength

Compressive strength tests were conducted on 160 mm diameter cylinders without capping, loaded uniaxially. Each reported strength value represents the average strength of three specimens, with values obtained falling within the range of 19 to 29.5 MPa.

The relationship between compressive strength and the variation of Medium coarse aggregate for various ranges of the FCR ratio is illustrated in Fig. 2 It can be observed from the results that higher compressive strength values were achieved when M_{CA} was set to 50% for almost all FCR ratios, whereas the lower values were obtained when the FCR ratio was less than 0.5.

A positive correlation between Fcs and M_{CA} is observed when M_{CA} is less than 50%; however, this correlation changes to a negative one when M_{CA} exceeds 50%. The optimal value for achieving the highest compressive strength is $\mathbf{M_{CA} = 50\%}$, except when FCR is equal to one. Compressive strength values within the range of 40% to 70% for M_{CA} are relatively good compared to the target C25/30 concrete.

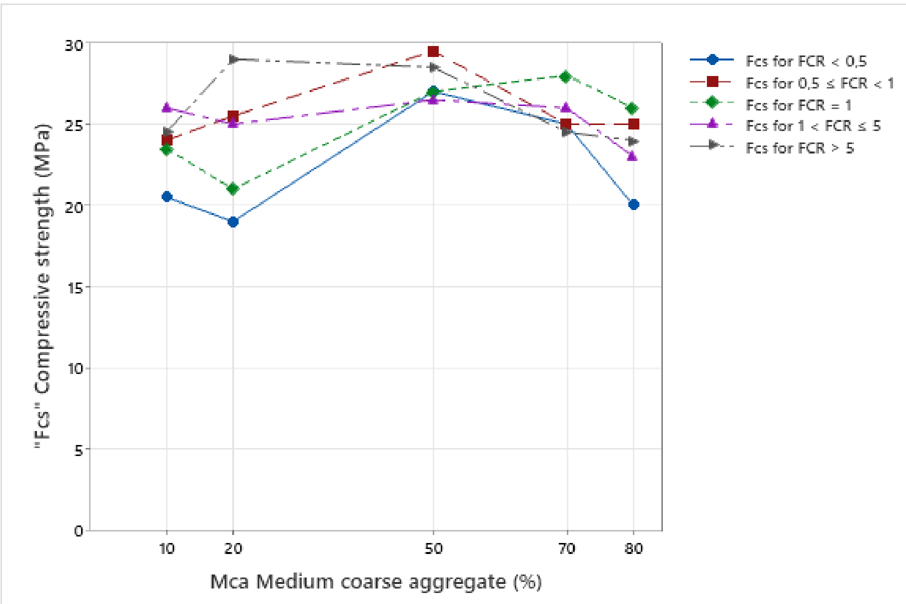

Fig. 2: Compressive strength versus M_{CA} with varying FCR

Fig. 3 depicts the relationship between compressive strength and variations in FCR for different quantities of Medium coarse aggregate.

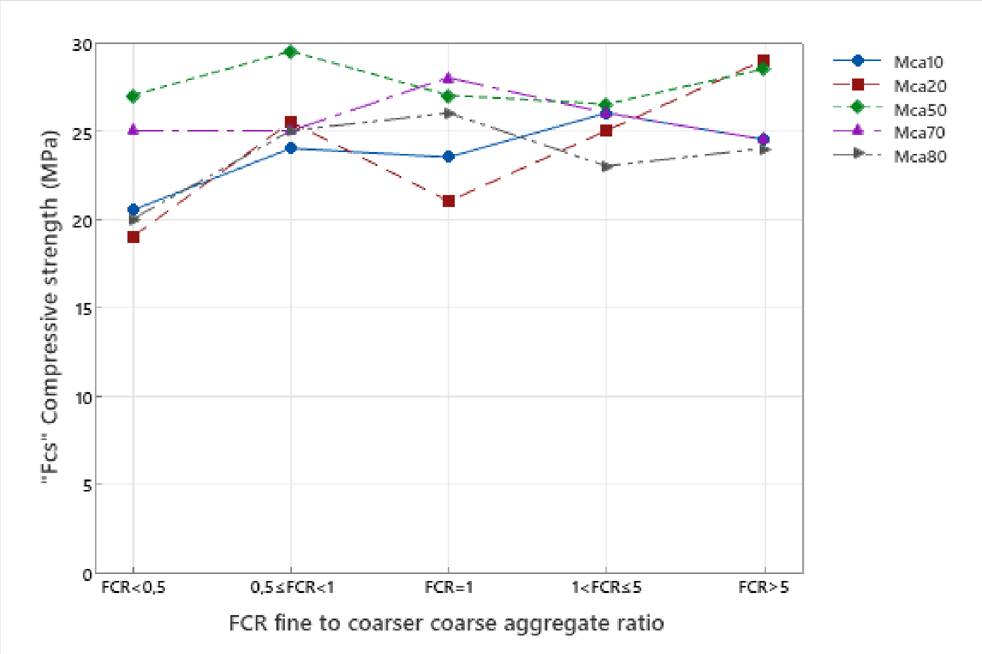

Fig. 3: Compressive strength versus FCR with varying M_{CA}

We observed a positive correlation between compressive strength and FCR when M_{CA} was at 10%, 20%, and 80%. However, at M_{CA} values of 50% and 70%, we observed a slight initial increase followed by a slight decrease in this relationship. The highest compressive strength values were achieved when M_{CA} was set to 50%.

In conclusion, we can affirm that the optimal range of M_{CA} for achieving good compressive strength in normal strength concrete is between 50% and 70%, regardless of the FCR ratio.

2.1.2. Effect of coarse aggregate grading on the flexural tensile strength

Flexural tensile strength tests were conducted using 100×100×400 mm prismatic specimens. Three samples were utilized to calculate the average strength. The results vary based on variations in M_{CA} and the FCR ratio, with values ranging from 3.3 to 4.8 MPa.

The relationship between flexural strength Ffs and variations in medium coarse aggregate M_{CA} for various ranges of the FCR ratio is depicted in Fig. 4.

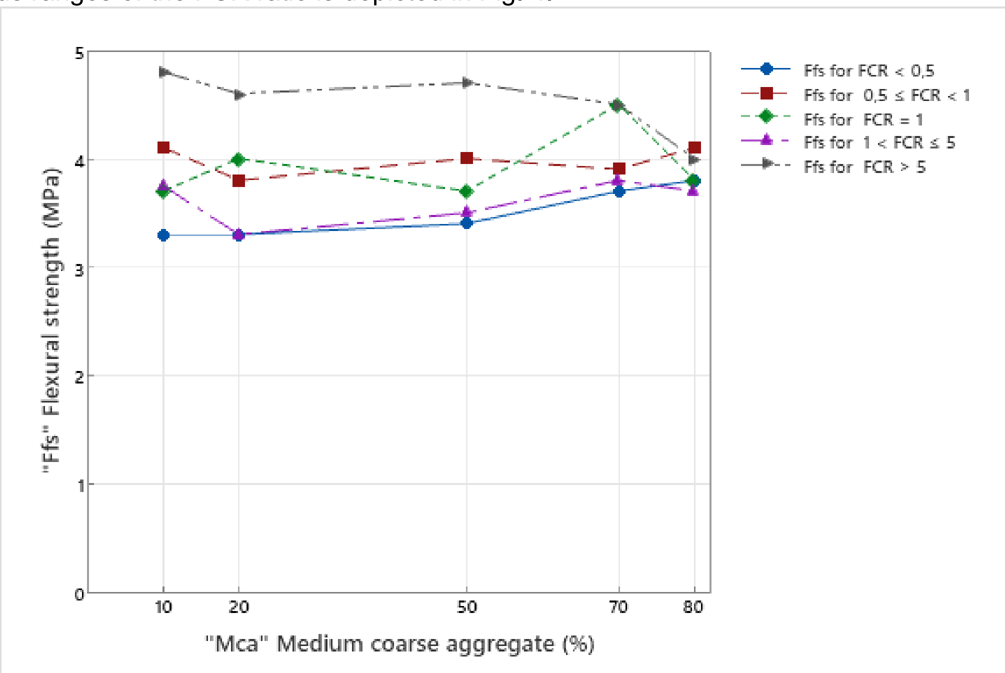

Fig. 4: Flexural strength as a function of M_{CA} with varying FCR ratios

There is a positive correlation between Ffs and $\mathrm{M_{CA}}$ when the FCR ratio is less than or equal to one. However, there is a non-significant variation when the FCR ratio falls within the range of one to five. Conversely, a negative correlation was observed when the FCR ratio exceeds five. These results clearly demonstrate the influence of the FCR ratio and the quantity of $\mathrm{M_{CA}}$ on flexural strength. The highest results were obtained when the FCR ratio exceeded five.

The increase in flexural strength ranges from approximately 38% to 45% when the $\mathrm{M_{CA}}$ amount is less than or equal to 50%. Conversely, it falls within the range of 5% to 20% when the $\mathrm{M_{CA}}$ amount exceeds 50%.

From Fig. 5, it is evident that flexural strength increases with an increase in the FCR ratio. Therefore, a higher FCR ratio leads to more significant improvement in concrete flexural strength. An increase of 20% to 45.5% in flexural strength was observed when transitioning from an FCR ratio less than 0.5 to an FCR ratio exceeding 5. The highest results were achieved when the FCR ratio exceeded 5, and a significant enhancement of approximately 45.45% in flexural strength was noted compared to other FCR values, mainly the lower range of FCR values below 0.5, which yielded the lowest results.

The impact of the FCR ratio on flexural strength is evident. The highest Ffs consistently occurred in the aggregate grading with the highest FCR ratio. Furthermore, for mixes with the same FCR ratio, a negative correlation was observed between flexural strength and the quantity of $\mathrm{M_{CA}}$, the medium coarse aggregate.

A higher FCR ratio and a lower $\mathrm{M_{CA}}$ content led to an increase in Ffs, which in turn enhances the specific surface area, promoting stronger bonding among the aggregates and ultimately improving flexural strength.

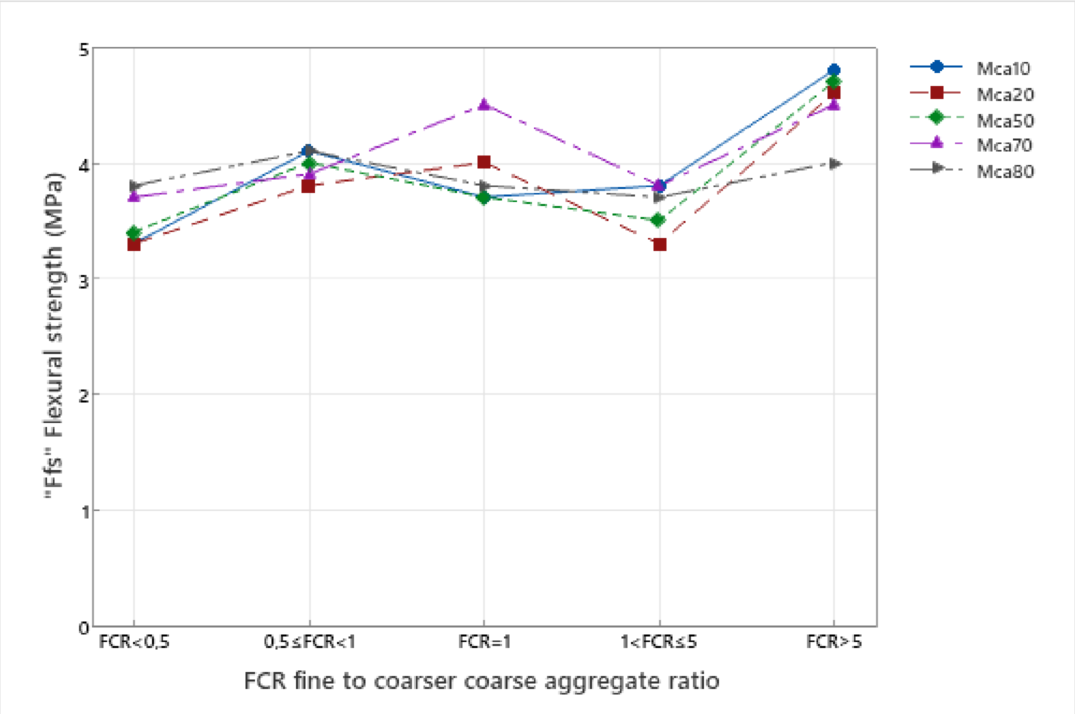

Fig. 5: Flexural strength as a function of FCR with varying $\mathrm{M_{CA}}$ levels

2.2. Effect of coarse aggregate grading on the tensile coefficient, Kt

2.2.1. Performance criteria

The Integral Absolute Error (IAE) was utilized to assess the performance of the proposed model. It served as a criterion for identifying the optimal model that closely aligns with experimental findings.

The equation for this performance criterion is provided below:

$$\mathrm{IAE} = \frac{\sum_i^n |e_i|}{\sum_{i=1}^n y_i} \times 100 \tag{8}$$

Where n represents the total number of measurements, ei stands for the difference between actual (measured) values and predicted values, and yi represents the actual values.

2.2.2. Effect of M_{CA} and FCR variation on the kt

In accordance with a statistical study, the tensile coefficient Kt was determined for each M_{CA}quantity and for each range of FCR ratios when Fcs is raised to the power of 0.5 and 2/3. The proposed value was selected to align with the outcome that yields the lowest IAE value.

Fig. 6 illustrates the variation of kt with changes in M_{CA} for both scenarios: when Fcs is raised to the power of 0.5 and 2/3. A similarity is observed between the curves representing the changes in kt when Fcs is elevated to these two different powers. Nevertheless, a slight disparity becomes noticeable in the region where M_{CA} falls between 10% and 20%.

The minimum kt value is achieved when M_{CA} is set to 50%, which corresponds to the highest Fcs values obtained. This observation is consistent with the previously obtained results for compressive strength, where the optimal composition for achieving higher compressive strength was when M_{CA} was equal to 50%.

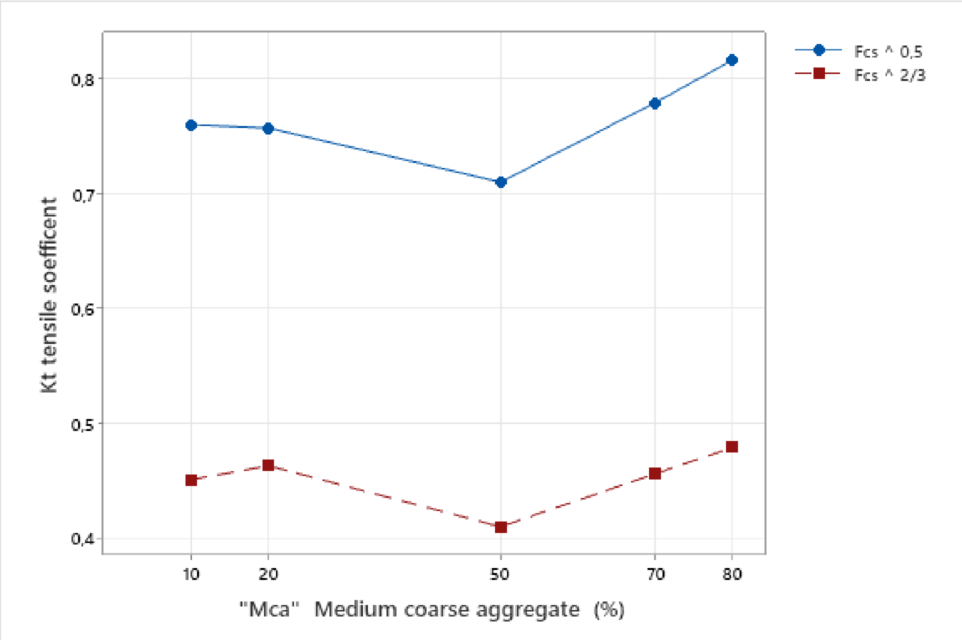

Fig. 6: Tensile coefficient 'Kt' with variations in M_{CA} when 'Fcs' is raised to the power of 0.5 and 2/3

Fig. 7 illustrates the variation of kt concerning changes in FCR when Fcs is raised to the power of 0.5 and 2/3. A notable similarity is observed between the curves depicting kt variation when Fcs is elevated to these two different powers. The minimum kt value was obtained when FCR was below 0.5, while the highest value was achieved when FCR exceeded five. These findings corroborate the earlier presented experimental data, confirming a negative correlation between flexural strength and the FCR ratio.

Furthermore, Fig. 7 clearly indicates that when FCR is less than or equal to five, the variation in kt is negligible, regardless of M_{CA}. However, a significant variation was recorded when FCR exceeded five. Consequently, we have employed two equations, instead of one, to establish a relationship between compressive strength and flexural strength, contingent on the fluctuations in the FCR ratio. One equation is applicable when FCR is less than or equal to five, and the second equation applies when FCR exceeds five.

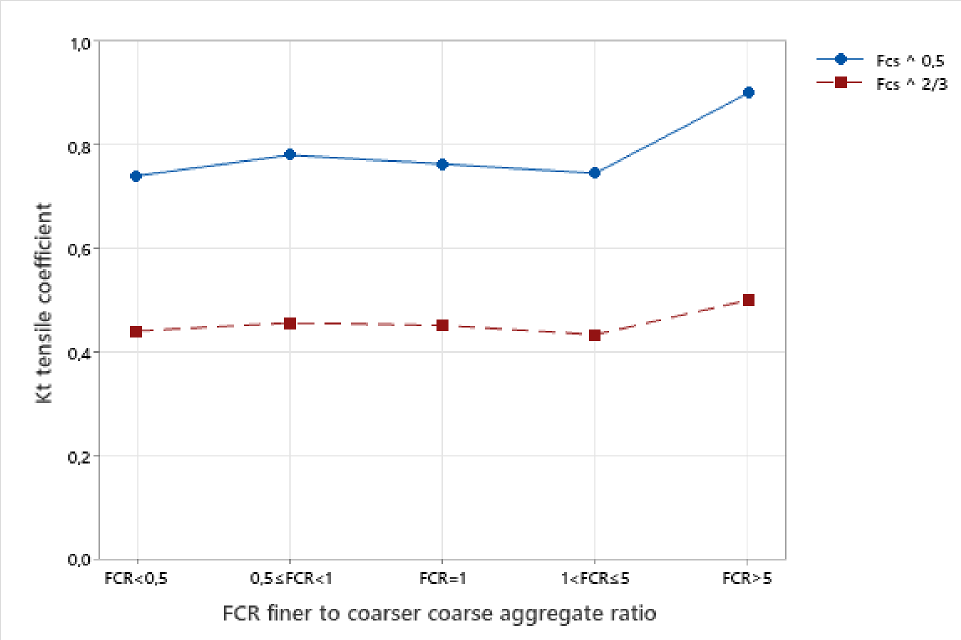

Fig. 7: Tensile coefficient Kt with variations in FCR when Fcs is raised to the power of 0.5 and 2/3

2.3. Proposition of a new tensile coefficient kt

2.3.1. Searching the appropriate value of kt

In the following section, we will present several models based on the tensile coefficient kt values, considering both cases of Fcs raised to the power of 0.5 and 2/3, as well as distinguishing between when FCR exceeds five and when it is less than or equal to five. These models have undergone statistical analysis to identify the most representative one, which will then be proposed as the final model.

Subsequently, we will compare these final proposed models with existing models from the literature to evaluate their performance. In other words, this comparison aims to assess how well the new models align with experimental results in comparison to previously published models. Some of the existing models are not formulated with Fcs raised to the power of 0.5 or 2/3, so we have examined them to understand why they may deviate from the mainstream.

Based on the results obtained, we have selected the most representative model to be proposed as an author-proposed model.

2.3.1.1. Fcs in the power of 2/3

2.3.1.2.

Fig. 8 presents the various proposed models for the case of Fcs raised to the power of 2/3 when FCR exceeds five. Models with Kt values lower than 0.5 evidently do not align with the experimental data obtained. This is further confirmed by the significantly high IAE values associated with these models.

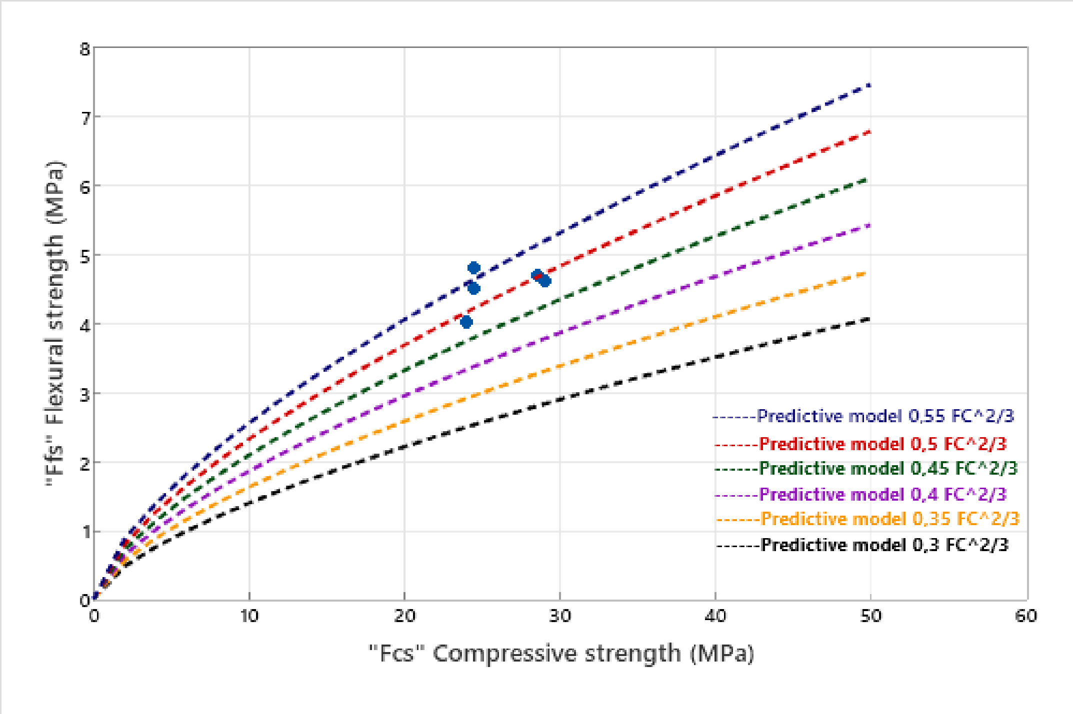

Fig. 8: Comparison of experimental data when FCR > 5 and the proposed model $Fcs^{2/3}$

Fig. 9 illustrates the variations in IAE for different models as presented in Fig. 8. A lower IAE value signifies a more representative model. the model with kt equal to 0.5 best represents the experimental data when FCR exceeds five and Fcs is raised to the power of 2/3. Consequently, the model $\mathbf{Ffs} = \mathbf{0.5\ Fcs^{2/3}}$ is selected to represent the experimental data when FCR exceeds five.

Fig. 9 illustrates the variations in IAE for different models as presented in Fig. 8. A lower IAE value signifies a more representative model. It is evident that the model with kt equal to 0.5 best represents the experimental data when FCR exceeds five and Fcs is raised to the power of 2/3. Consequently, the model $\mathbf{Ffs} = \mathbf{0.5\ Fcs^{2/3}}$ is selected to represent the experimental data when FCR exceeds five.

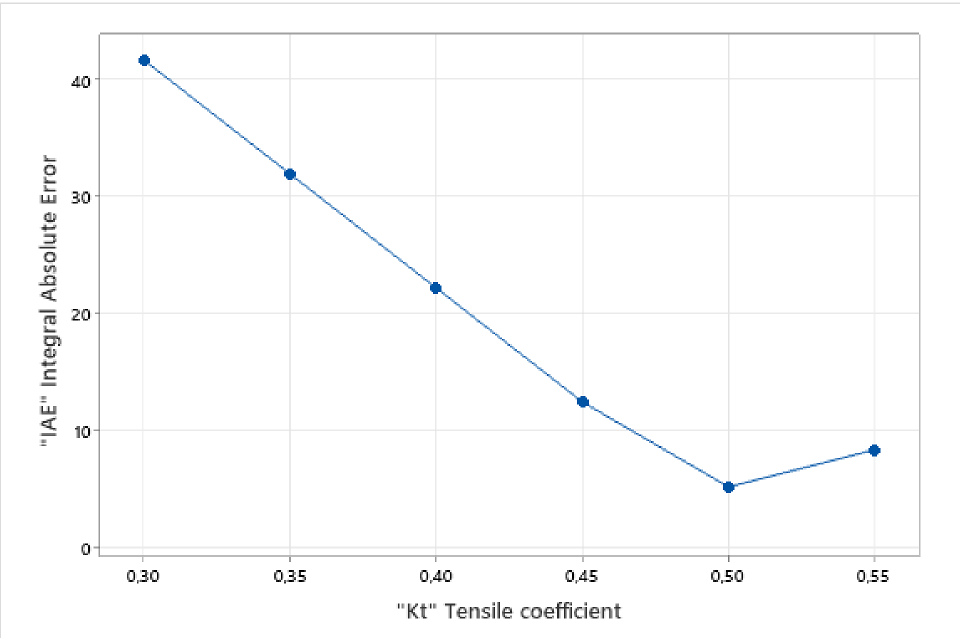

Fig. 9: IAE vs Kt when FCR exceeds five and Fcs is raised to the power of 2/3

Fig. 10 displays various proposed models in the case of Fcs to the power of 2/3 when FCR is less than or equal to five. Models with Kt values lower than 0.44 evidently do not align with the experimental data. This is further confirmed by the significantly high IAE values obtained.

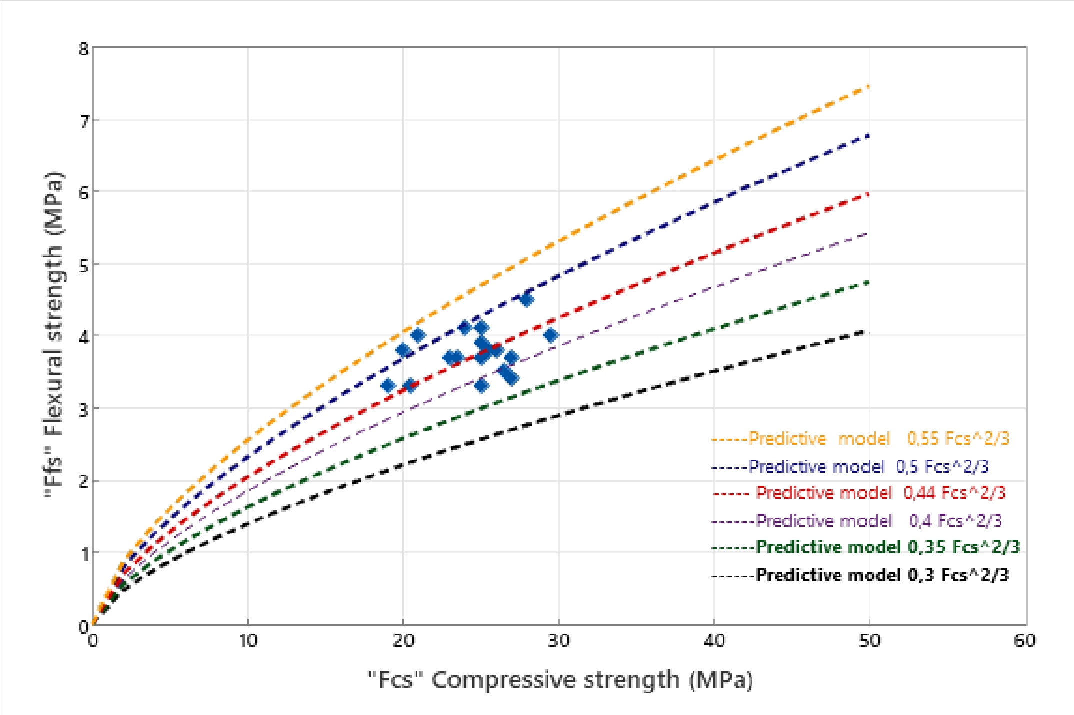

Fig. 10: Proposed models when FCR is less than or equal to five for Fcs to the power of 2/3

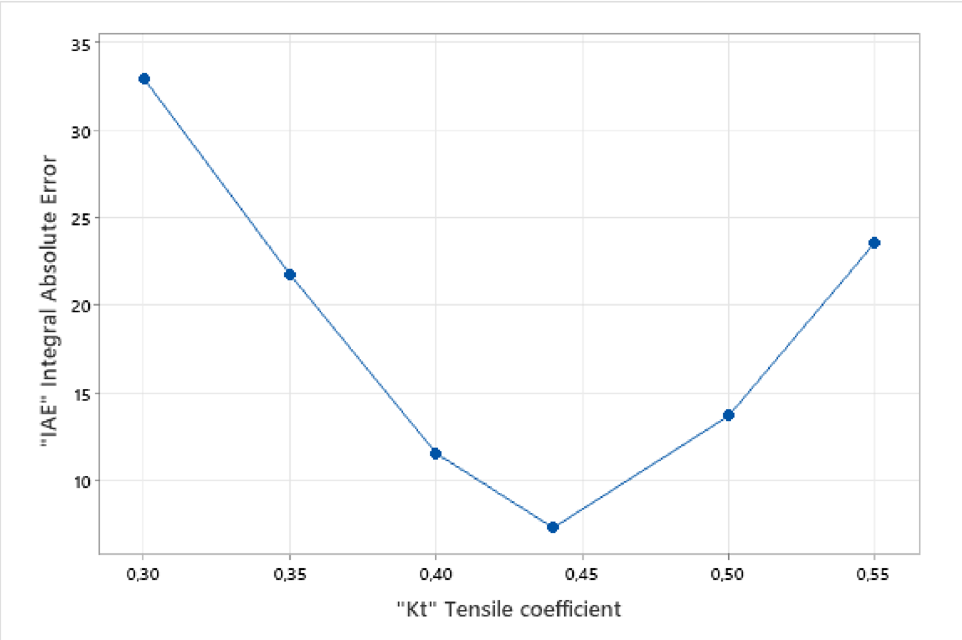

Fig. 11: IAE vs. Kt when FCR is less than or equal to five and Fcs to the power of 2/3

Fig. 11 illustrates the variations in IAE for various models presented in Fig. 10. A lower IAE value indicates a model that better represents the experimental data. the model with Kt equal to 0.44 proves to be the most representative of the experimental data when FCR is less than or equal to five and Fcs is raised to the power of 2/3.

Consequently, the model $F_{\text{fs}} = 0.44\ \text{Fcs}^{0.5}$ is selected to represent the experimental data when FCR is less than or equal to five.

2.3.1.3. Fcs in the power of 0.5

Fig. 12 depicts the various proposed models for Fcs raised to the power of 0.5 when FCR exceeds five. Models with Kt values less than 0.8 evidently do not align with the experimental data. This is further substantiated by the significantly high IAE values obtained.

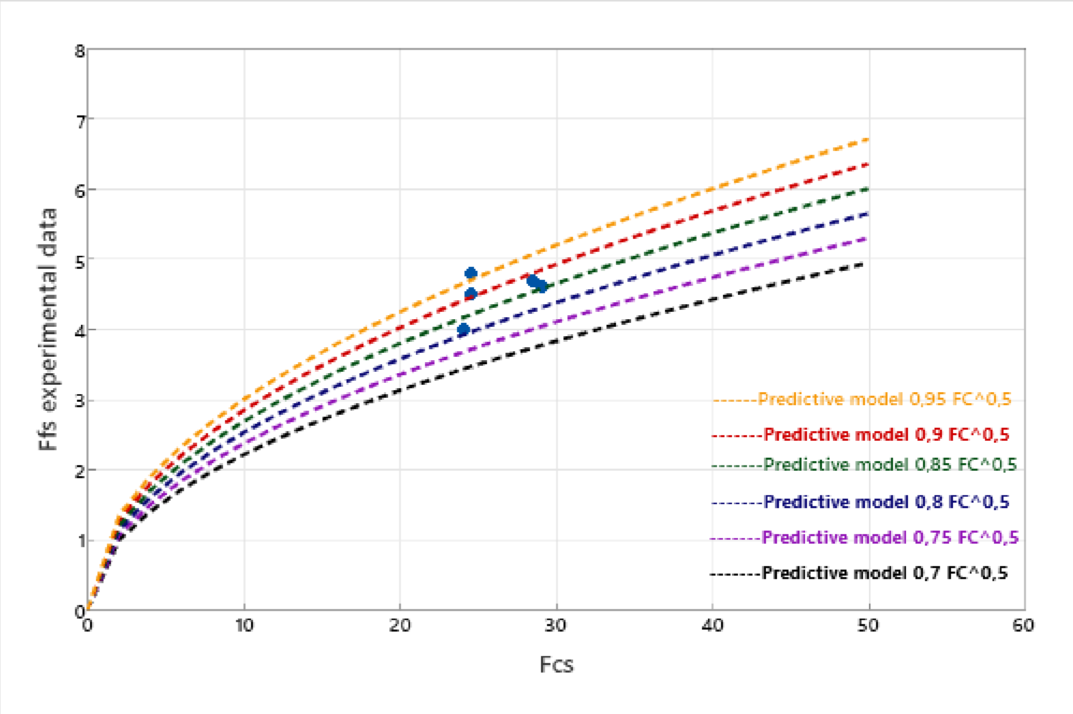

Fig. 12: Comparison of experimental data when FCR > 5 and the proposed model $\mathrm{Fcs}^{0.5}$

Fig. 13 illustrates the variations in IAE for different models presented in Fig. 12. A lower IAE value indicates a more representative model. It is evident that the model with Kt equal to 0.9 proves to be the most representative of the experimental data when FCR exceeds five, and Fcs is raised to the power of 0.5. Consequently, the model $F_{fs} = 0.9\, F_{cs}{}^{0.5}$ is selected to represent the experimental data when FCR is greater than five.

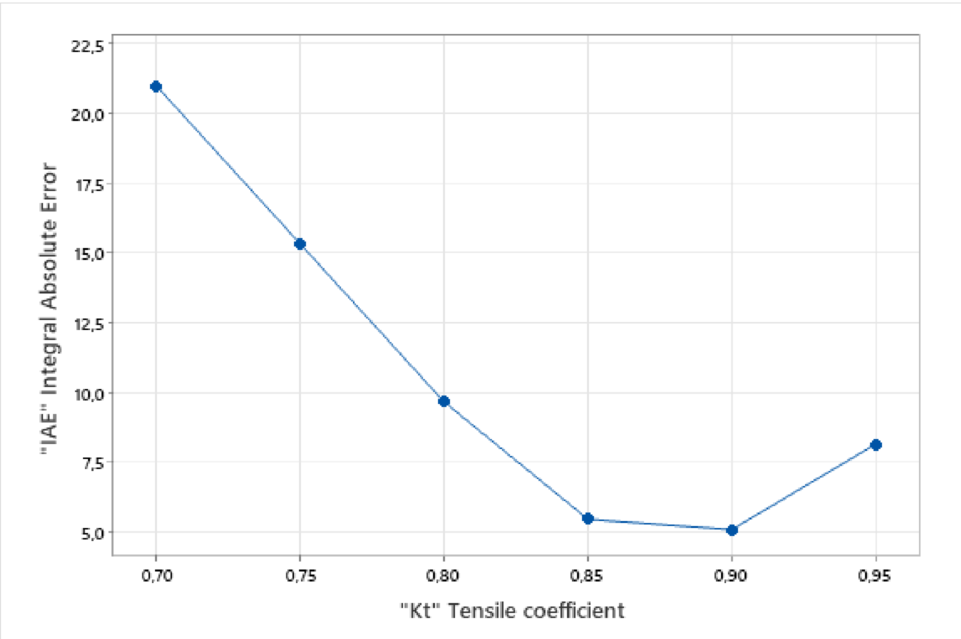

Fig. 13: IAE vs. Kt when FCR is greater than five and Fcs raised to the power of 0.5.

Fig. 14 illustrates the various proposed models for Fcs raised to the power of 0.5 when FCR is less than or equal to five. Models with Kt values less than 0.65 evidently do not align with the experimental data. This is further substantiated by the significantly high IAE values obtained.

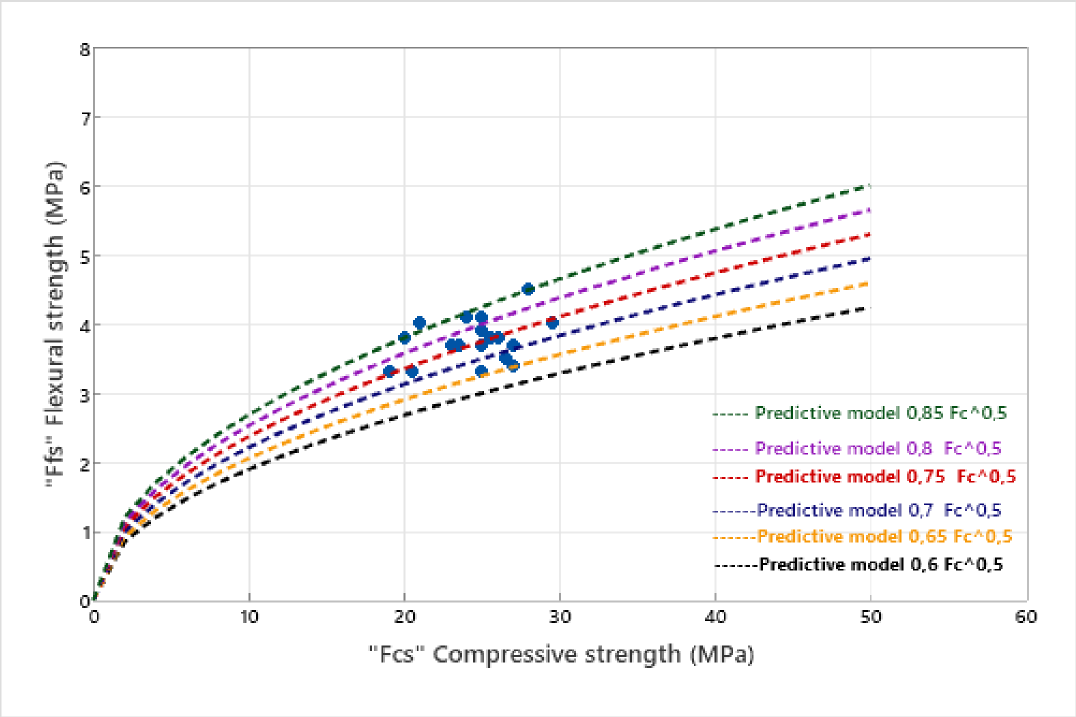

Fig. 14: Proposed models when FCR is less than or equal to 5 for Fcs raised to the power of 0.5.

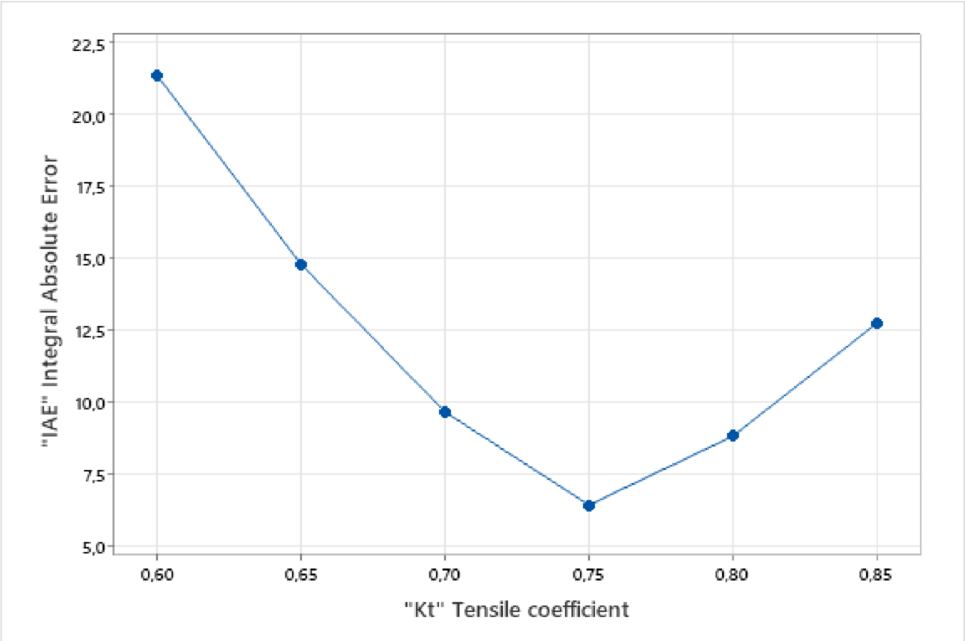

Fig. 15: IAE vs. Kt when FCR is less than or equal to five and Fcs is raised to the power of 0.5.

Fig. 15 illustrates the variations in IAE for different models presented in Fig. 14. A lower IAE value indicates a more representative model. It is evident that the model with Kt equal to 0.75 proves to be the most representative of the experimental data when FCR is less than or equal to five, and Fcs is raised to the power of 0.5.

Consequently, the model $F_{fs} = 0.75\ F_{cs}{}^{0.5}$ is selected to represent the experimental data when FCR is less than or equal to five.

2.4. Comparison with values already published in the literature

2.4.1. Models with Fcs in the power of 0.5

Fig. 16 reveals that many published models significantly deviate from accurately representing experimental data. Specifically, the Indian code, the ACI code, Sbarounis, Logan et al., and Graham [10, 20-22, 25] consistently underestimate the flexural strength when FCR is less than or equal to five. In contrast, Kothai and Malathy, Legron and Paultre, and the Saudi code [11, 24, 26] provide estimations that closely align with our obtained results, with respective IAEs of 13.92, 11.48, and 9.68. Additionally, Xiao et al. [23] have published results identical to our proposed model, with an IAE of 6.45. The critical difference lies in that Xiao considers the model for all possible aggregate grading, whereas our model specifically represents aggregate grading with FCR less than or equal to five.

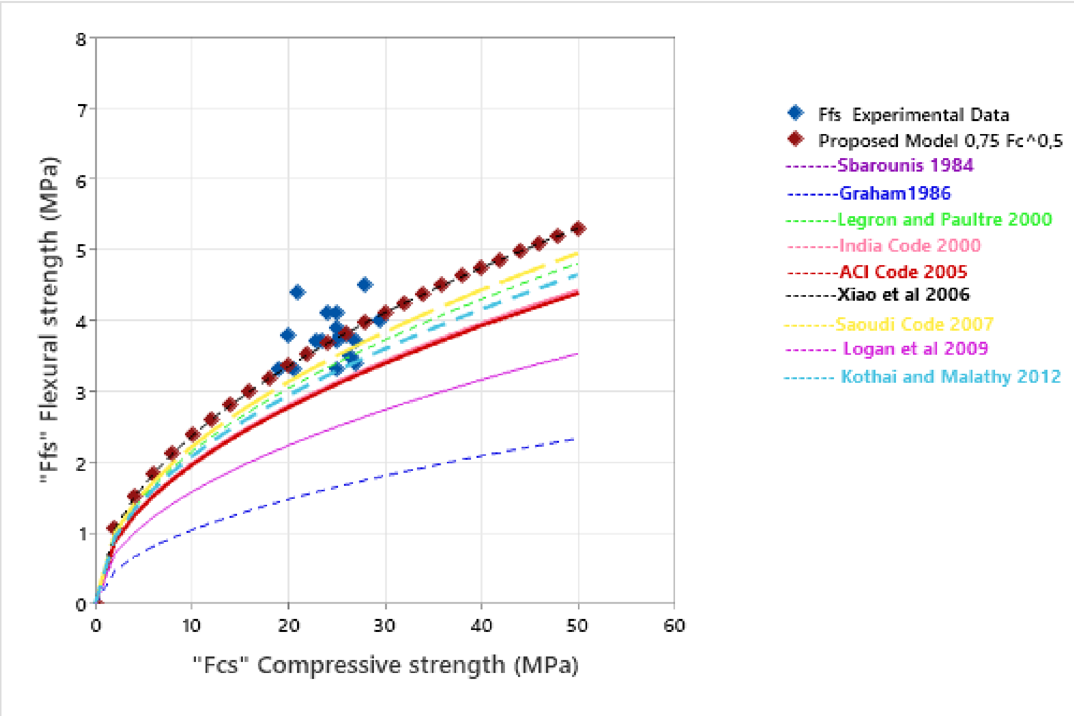

Fig. 16: Experimental data when FCR ≤ 5 Vs the proposed and published models with $\mathrm{Fcs}^{0.5}$

Moving to Fig. 17, it becomes evident that for aggregate grading with FCR greater than five, along with Fcs raised to the power of 0.5, no published model matches our obtained flexural strength values. Only our proposed model proves to be representative in this case, boasting an IAE of 5.09, while IAEs for published models range from 15.3 to 62.73.

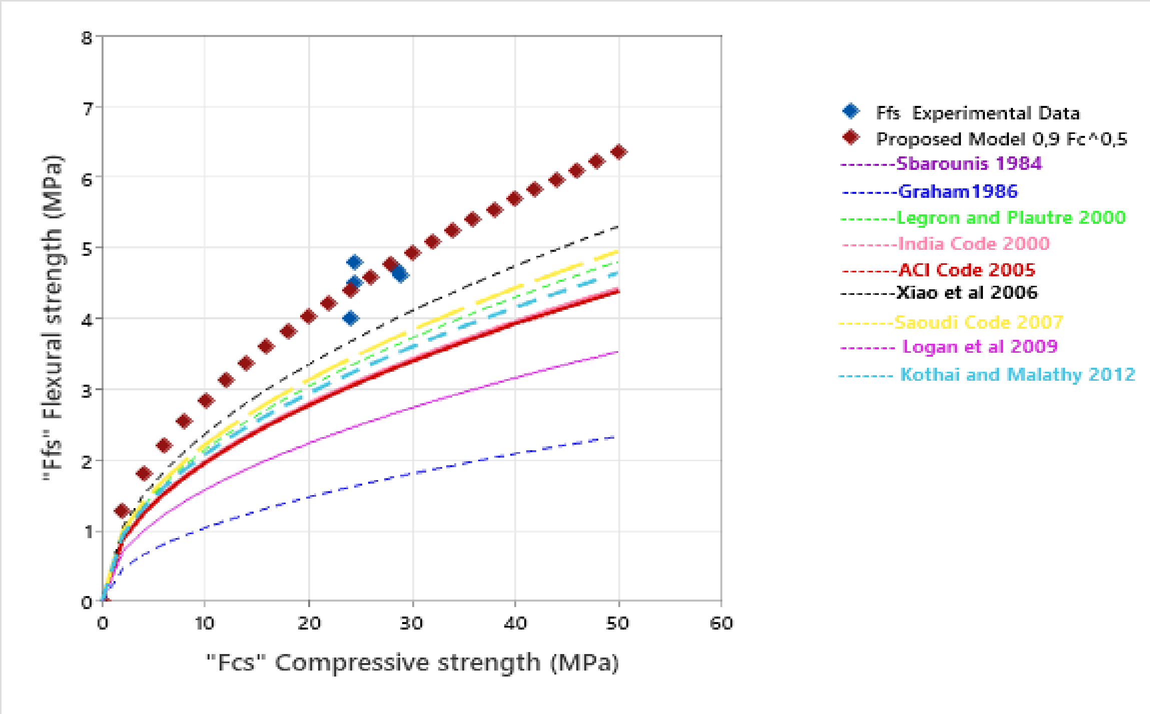

Fig. 17: Experimental data when FCR > 5 Vs the proposed and published models with $F_{cs}^{0.5}$

2.4.2. Models with Fcs in the power of 2/3

Fig. 18 reveals that the Euro code and Raphael models [12, 27] significantly deviate from our representation of experimental data. These models consistently underestimate the flexural strength of concrete with aggregate grading featuring an FCR less than or equal to five.

On the other hand, Rashid et al. and Ramadoss Perumal [28, 30] have proposed models that closely resemble our proposed model, However a statistical study would be needed to determine the exact differences and confirm that our model aligns more closely and is more representative. Their respective IAEs are 8.71 and 7.6. Ahmed and Shah [31] have published results identical to our proposed model, boasting an IAE of 7.3. The primary distinction lies in their model's consideration of all possible coarse aggregate grading, whereas ours specifically represents coarse aggregate grading with an FCR less than or equal to five.

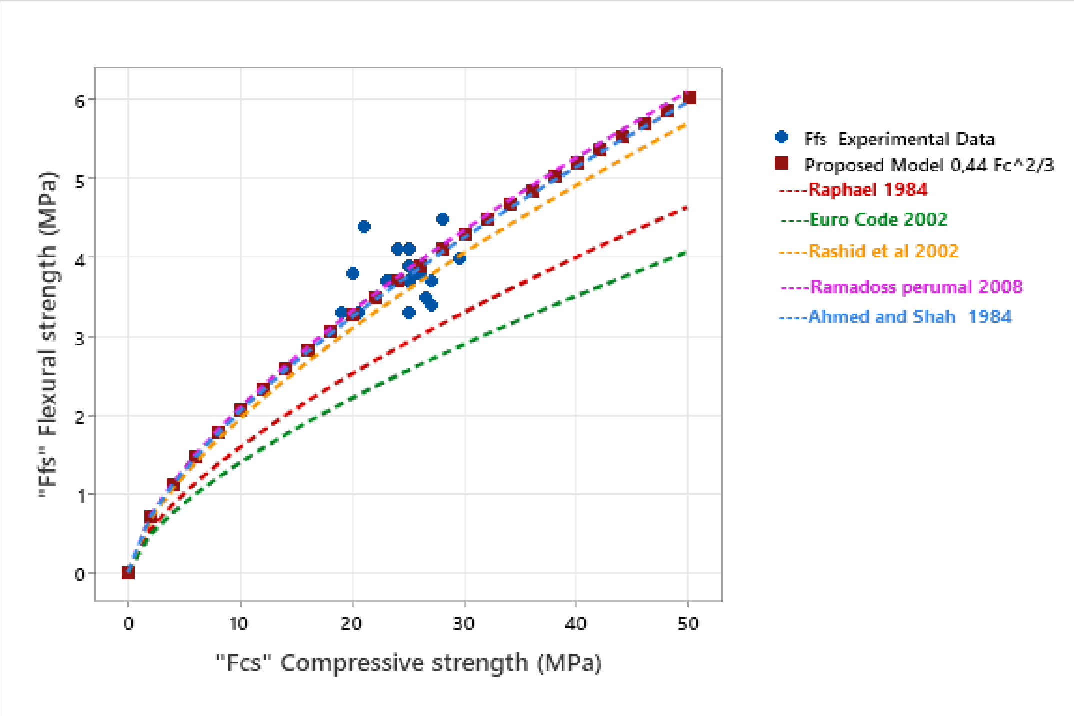

Fig. 18: Experimental data when FCR ≤ 5 Vs the proposed and published models with $F_{cs}{}^{2/3}$

Fig. 19 reveals that none of the published models align with our obtained flexural strength data for coarse aggregate grading featuring an FCR greater than five when Fcs is raised to the power of 2/3. However, Ramadoss, as well as Ahmed and Shah [30, 31], have introduced models that come closest to our obtained results. Nevertheless, our proposed model stands out as the sole and most representative option in this scenario. The IAEs for published models range from 12.47 to 41.64, whereas our proposed model boasts an IAE of 5.22.

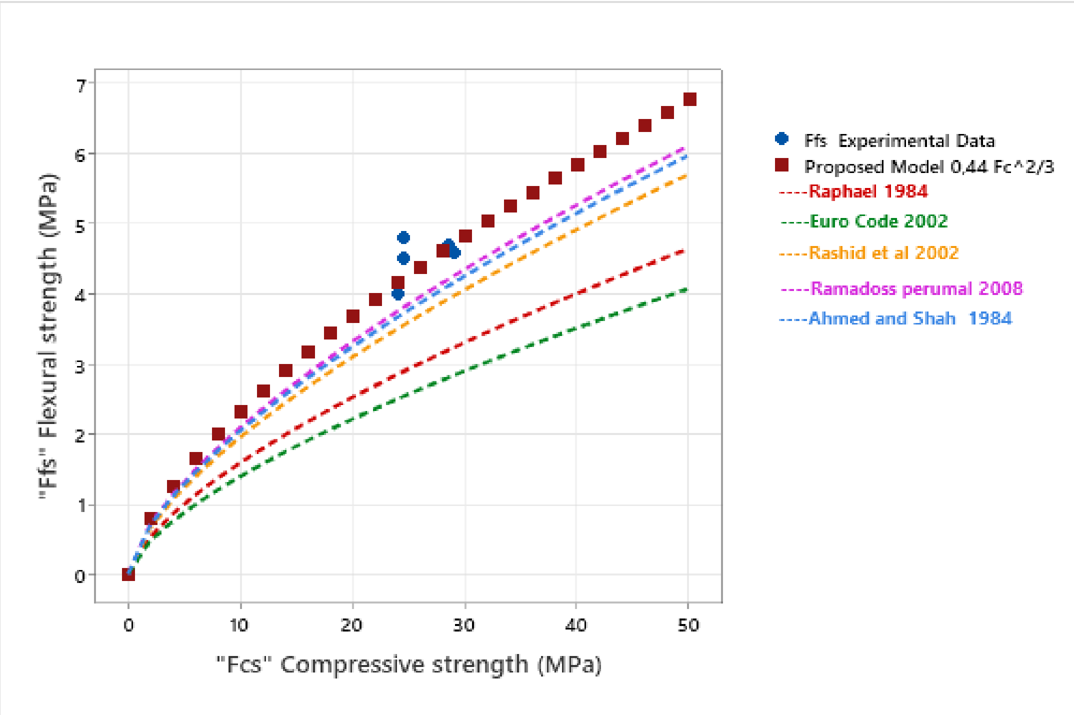

Fig. 19: Comparison of experimental data when FCR > 5, the proposed and published models of $F_{cs}{}^{2/3}$

2.4.3. Models with Fcs in the power other than 0.5 and 2/3

Numerous published models deviate from employing either the power of 0.5 or the power of 2/3. In the context of this study, we evaluated five models, observing that their IAEs ranged from 8.24 to 21.8 when FCR was less than or equal to five, and from 5.86 to 29.35 when FCR exceeded five. Our proposed models yielded IAEs of 7.3 and 6.45 for FCR values less than or equal to five, and 5.22 and 5.09 for FCR values exceed five.

Fig. 20 provides a comparison between published models utilizing Fcs values other than 0.5 and 2/3, and our proposed model incorporating Fcs raised to the power of 2/3 when FCR exceeds five. The results clearly indicate that only Xu et al. [1] present a model comparable to our proposed one when FCR is greater than five. This can be readily observed in the statistical results, where our proposed model has an IAE of 5.22, while Xu's IAE is 5.86. Consequently, the proposed model remains the optimal choice for representing flexural strength when FCR exceeds five.

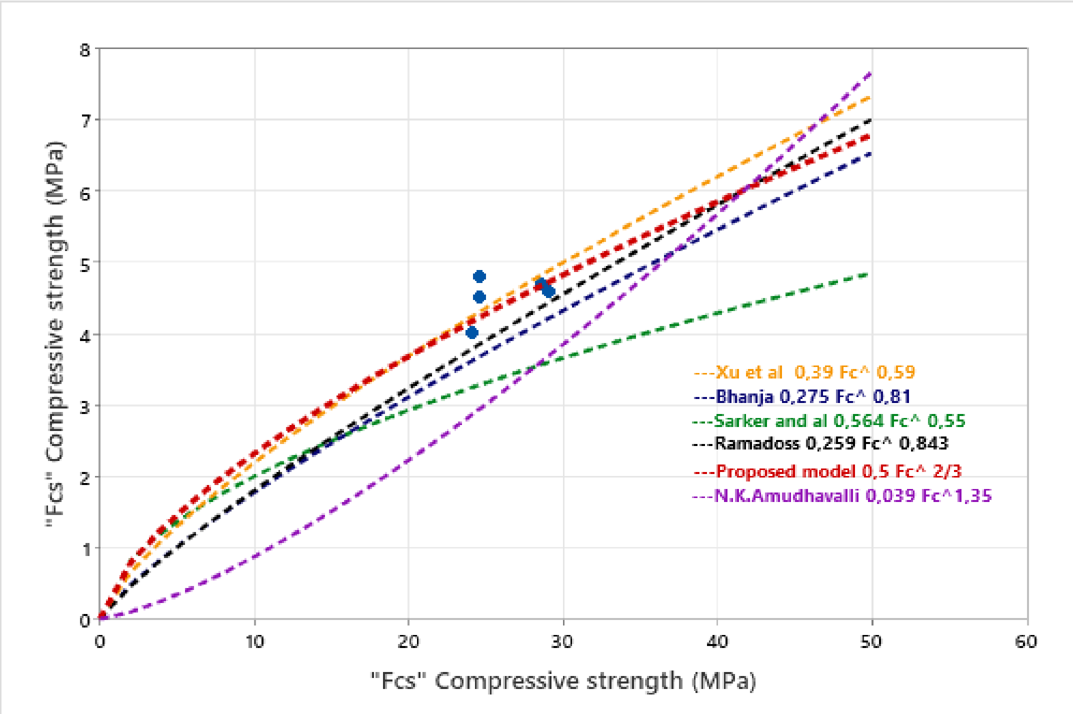

Fig. 20: Findings when FCR > 5, proposed model $\mathbf{F_{cs}}^{2/3}$, and published models other than $\mathbf{F_{cs}}^{2/3}$ and $\mathbf{F_{cs}}^{0.5}$

Fig. 21 illustrates the comparison between published models using Fcs values other than 0.5 and 2/3 and the proposed model employing Fcs to the power of 0.5 when FCR exceeds five. The same result was achieved, with Xu[1] closely aligning with the proposed model, as evidenced by their respective IAEs of 5.09 and 5.86.

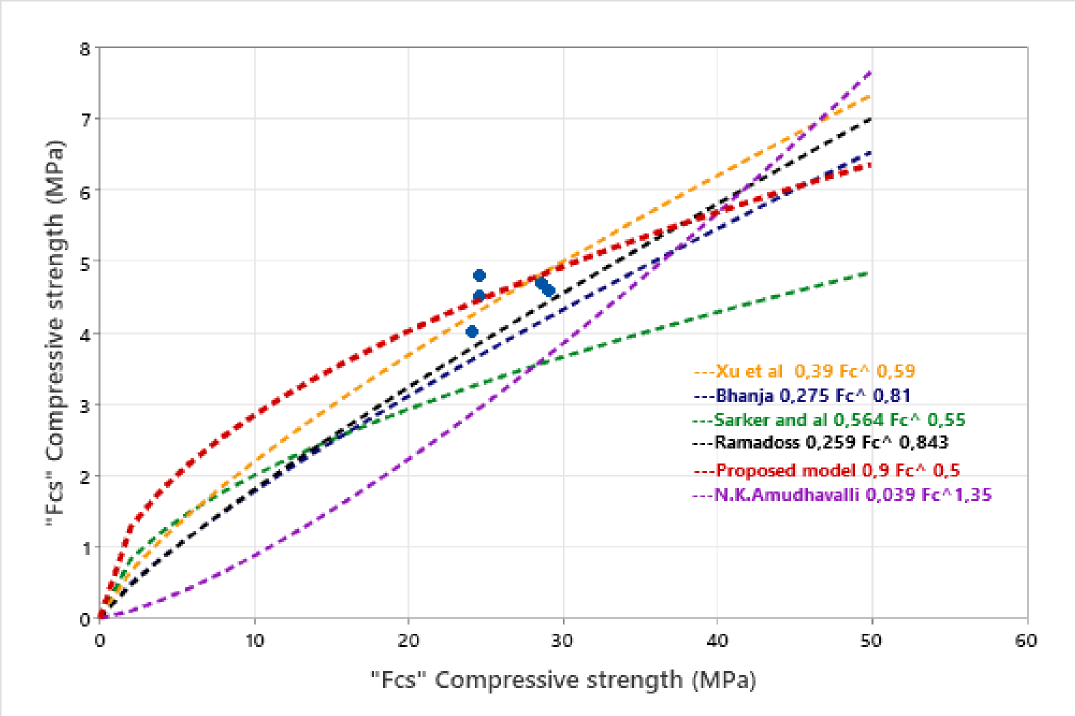

Fig. 21: Findings when FCR > 5, proposed model $F_{cs}{}^{0.5}$ and published models other than $F_{cs}{}^{2/3}$ and $F_{cs}{}^{0.5}$

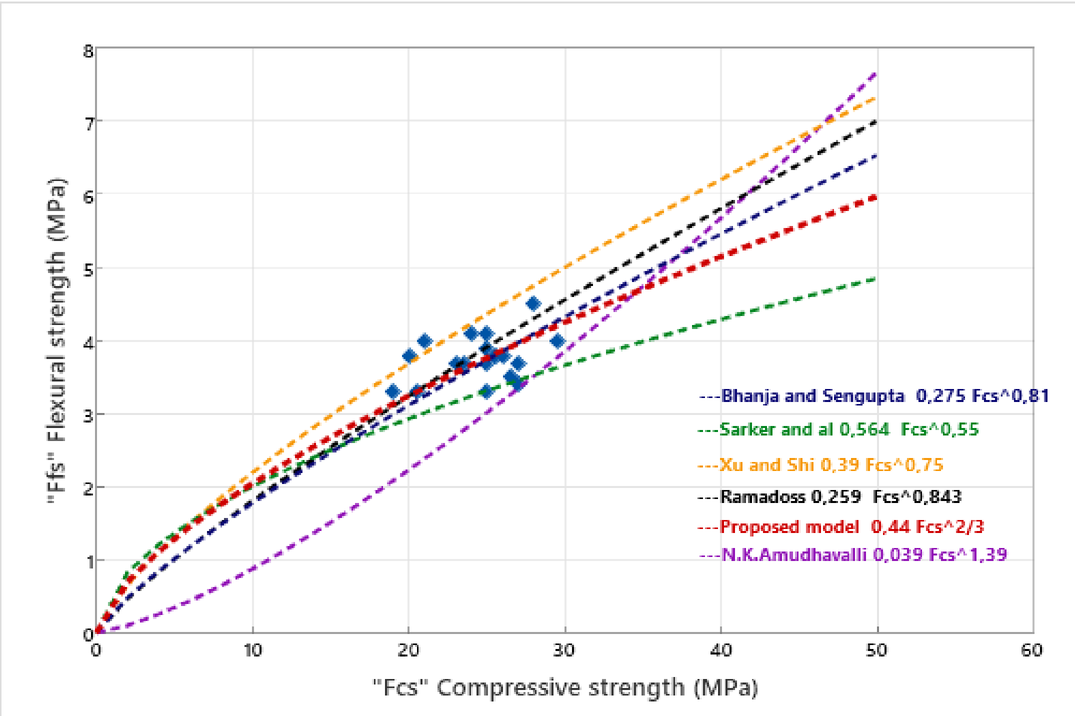

Fig. 22: Findings when FCR ≤ 5, proposed model $F_{cs}{}^{2/3}$ and published models other than $F_{cs}{}^{2/3}$ and $F_{cs}{}^{0.5}$

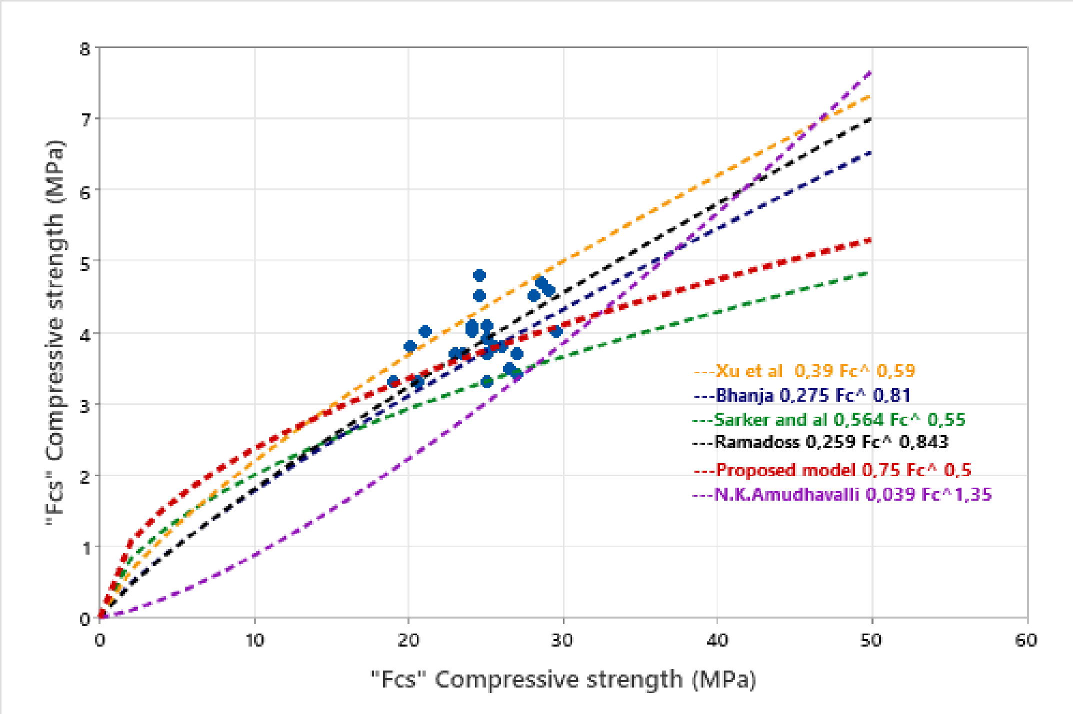

Fig. 23: Findings when FCR ≤ 5, proposed model $F_{cs}{}^{0.5}$ and published models other than $F_{cs}{}^{2/3}$ and $F_{cs}{}^{0.5}$

Fig.s 22 and 23 respectively depict the comparison between published models using Fcs values other than 0.5 and 2/3 and the proposed models with Fcs raised to the power of 2/3 and 0.5 when FCR is less than or equal to five.

The results obtained reveal that only the models by Ramadoss and Bhanja [30, 32] are the most representative when compared to other published models. They exhibit IAEs of 8.75 and 8.24 respectively, while the proposed model has an IAE of 6.45 when Fcs is raised to the power of 0.5 and 7.3 when Fcs is raised to the power of 2/3. Consequently, our proposed models maintain their superiority in representing flexural strength when the coarse aggregate grading has an FCR of less than or equal to five.

As a result, we have developed four proposed models: two when FCR exceeds five and two when FCR is less than or equal to five. These models encompass Fcs values raised to the power of 0.5 and 2/3. A statistical study demonstrates that the most representative model is the one with Fcs raised to the power of 0.5 in both cases of FCR.

When FCR exceeds five, the IAE is 5.22 for the model employing Fcs raised to the power of 2/3 and 5.09 for the model employing Fcs raised to the power of 0.5. In scenarios where FCR is less than or equal to five, the IAEs are 7.3 and 6.45 respectively for the two models. Thus, in both cases, the most representative model is the one with Fcs raised to the power of 0.5. This choice aligns with certain codes, such as the Indian code, British code, and the ACI code, which prefer to employ Fcs raised to the power of 0.5 in the formulas connecting flexural strength and compressive strength.

2.5. Choosing the most reliable model between the two proposed models

Fig. 24 presents two proposed models for representing flexural strength when FCR exceeds five, one with Fcs raised to the power of 0.5 and the other with Fcs raised to the power of 2/3. While these two models appear quite similar, from a statistical perspective, the model with Fcs raised to the power of 0.5, having an IAE of 5.09, proves to be more representative than the model with Fcs raised to the power of 2/3, which has an IAE of 5.22.

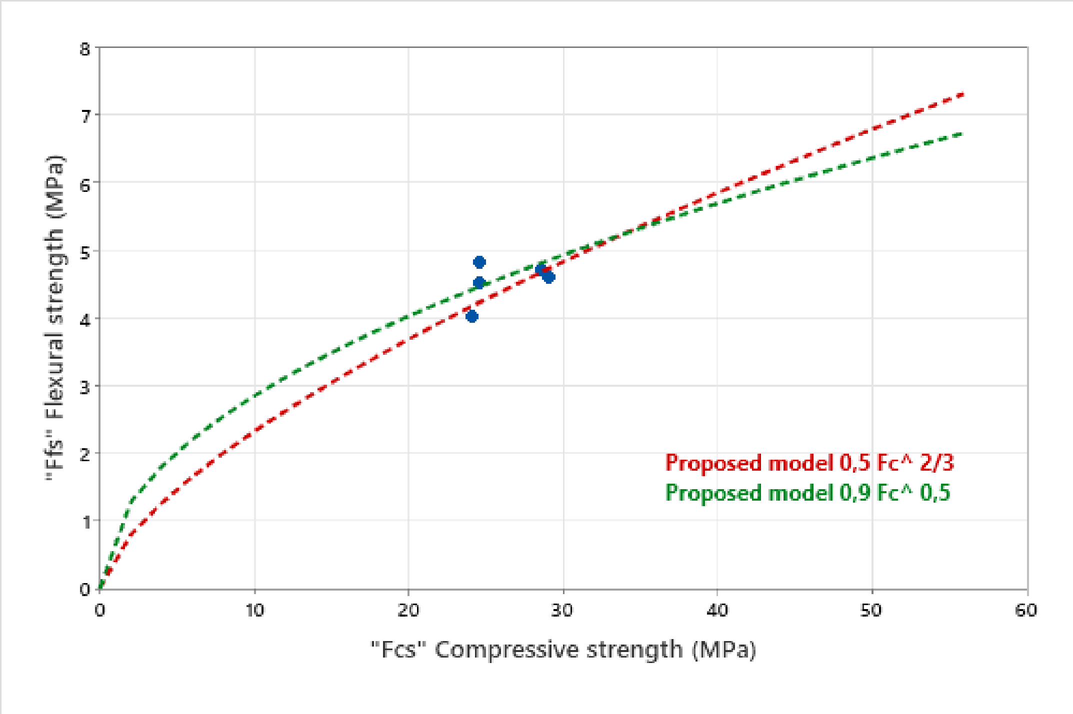

Fig. 24: The two proposed models when FCR exceeds five

Fig. 25 illustrates the two proposed models for representing flexural strength when FCR is less than or equal to five, employing both Fcs raised to the power of 0.5 and Fcs raised to the power of 2/3. The two models are quite similar, particularly when Fcs falls within the range of 20 to 30 MPa. However, from a statistical standpoint, the model utilizing Fcs raised to the power of 0.5, with an IAE of 6.45, proves to be more representative than the model employing Fcs raised to the power of 2/3, which has an IAE of 7.3.

As a result, the model employing Fcs raised to the power of 0.5 emerges as the most representative choice and is thus selected as the proposed model in this study. This finding aligns with the preferences of various codes, including the European code, ACI code, Indian Code, and the British code, as well as the choices made by certain researchers who favour the power of 0.5 over the power of 2/3.

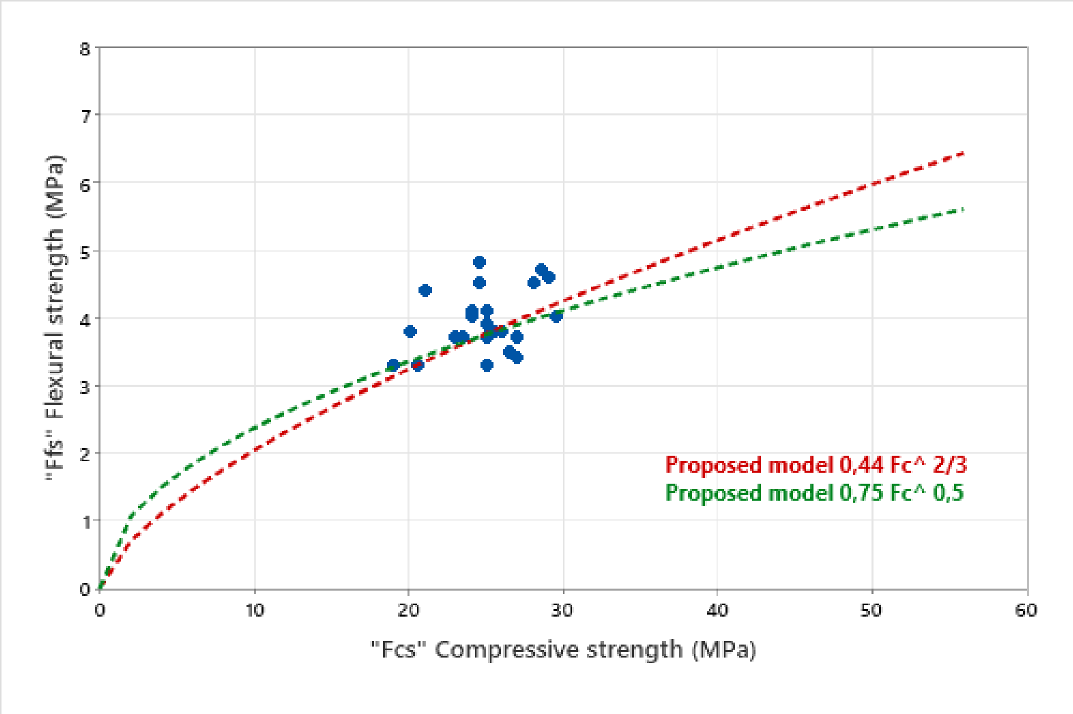

Fig. 25: The two proposed models when FCR is less than or equal to five.

In conclusion, this study introduces two models, both utilizing Fcs raised to the power of 0.5. The first model applies when FCR is less than or equal to five, with a coefficient of $\mathbf{k_t = 0.75}$, while the second model employs $\mathbf{k_t = 0.9}$ for cases where FCR exceeds five. These models will be subsequently compared to published models, evaluating their alignment with our experimental results in comparison to the existing literature

3. Conclusion

This paper investigates the influence of coarse aggregate grading on the mechanical properties of concrete. The medium-coarse aggregate and the ratio of finer to larger coarse aggregate (FCR) are two parameters used to characterize the variability in coarse aggregate grading. Compressive and flexural strength tests were conducted, and new models relating these two properties were introduced.

Based on the results and discussion presented, the following conclusions were derived:

• $\mathrm{M_{CA}}$ positively impacts compressive strength until it reaches an optimal value ($\mathrm{Mca} = 50\%$). The range of 50% to 70% for medium coarse aggregate is most suitable for achieving compressive solid strength.

• FCR and compressive strength exhibit a positive correlation when the $\mathrm{M_{CA}}$ amount is less than or equal to 50%, while there is no significant effect when $\mathrm{M_{CA}}$ exceeds 50%.

• A slight negative correlation between $\mathrm{M_{CA}}$ and flexural strength is observed when FCR exceeds five. However, there is no significant effect when the FCR is less than or equal to five.

• The highest flexural strength is achieved when FCR exceeds five, regardless of the $\mathrm{M_{CA}}$ amount

• Based on a statistical analysis using the integral absolute error, various values of the tensile coefficient were examined to derive the most representative models for our experimental results, accounting for variations in $\mathrm{M_{CA}}$ and FCR.

• The variation in $\mathrm{M_{CA}}$ negatively impacts the tensile coefficient Kt when it falls below 50%, but its influence becomes positive when $\mathrm{M_{CA}}$ exceeds 50%

• When FCR is less than or equal to five, the variation is not significant, In contrast it becomes significant when FCR exceeds five, leading to the proposal of two values of Kt to account for the potential variation in coarse aggregate grading.

• We propose two equations that relate compressive and flexural strengths, depending on the two obtained tensile coefficients (Kt). We have selected only two models to encompass the entire range of coarse aggregate gradation variations.

- When FCR is less than or equal to five: $F_{fs} = 0.75\ F_{cs}{}^{0.5}$
- When FCR exceeds five: $F_{fs} = 0.9\ F_{cs}{}^{0.5}$

The proposed models encompass the entire range of coarse aggregate grading variations, surpassing all the models mentioned in this study. They exhibit the lowest values of IAE, indicating superior performance when compared to all other models.

4. Acknowledgments

The authors gratefully acknowledge the civil engineering department at Mentouri Brothers University, the LMDC laboratory at the same university, and the ENG, the national company for aggregate, for their support in providing the materials and giving us the opportunity to use their laboratory and benefit from their experience and their personal experimental help.

5. References

[1] Bouhadra, A. – Menasria, A. – Rachedi, M.A. (2021) 'Boundary conditions effect for buckling analysis of porous functionally graded nanobeam,' Advances in Nano Research, 10(4), p. 313. https://doi.org/10.12989/anr.2021.10.4.313.
[2] MENASRIA, A. - ZERARI, M. - BELHADJ, M. - YAKOUBI, M. - AMARA, A.: A four-unknown refined plate theory for dynamic analysis of FG-sandwich plates under various boundary conditions, Steel and Composite Structures, 36(3), p. 355, 2020, https://doi.org/10.12989/scs.2020.36.3.355.
[3] XU, B. W. - SHI, H. S.: Correlations among mechanical properties of steel fiber reinforced concrete, Construction and Building Materials, 23(12), p. 3468-3474, 2009, https://doi.org/10.1016/j.conbuildmat.2009.08.017.
[4] MARTÍNEZ-MOLINA, W. - TORRES-ACOSTA, A. A. - JÁUREGUI, J. C. - CHÁVEZ-GARCÍA, H. L. - ALONSO-GUZMÁN, E. M. - GRAFF, M. - ARTEAGA-ARCOS, J. C.: Predicting Concrete Compressive Strength and Modulus of Rupture Using Different NDT Techniques, Advances in Materials Science and Engineering, 2014, p. 1-15, 2014, https://doi.org/10.1155/2014/742129.
[5] NEVILLE, A. M.: Properties of concrete, Pearson Education, 5th ed., British Library, 2011.
[6] ARİOĞLU, N. - GİRGIN, Z. C. - ARİOĞLU, E.: Evaluation of Ratio between Splitting Tensile Strength and Compressive Strength for Concretes up to 120 MPa and its Application in Strength Criterion, ACI Materials Journal, 103(1), p. 18-24, 2006.
[7] PUL, S.: Experimental investigation of tensile behaviour of high strength concrete, Indian Journal of Engineering & Materials Sciences, 15, p. 467-472, 2008.
[8] AHMED, M. - MALLICK, J. - ABUL HASAN, M.: A study of factors affecting the flexural tensile strength of concrete, Journal of King Saud University - Engineering Sciences, 28(2), p. 147-156, 2016, https://doi.org/10.1016/j.jksues.2014.04.001.
[9] JONES, R. - KAPLAN, M. F.: The effect of coarse aggregate on the mode of failure of concrete in compression and flexure, Magazine of Concrete Research, 9(26), p. 89-94, 1957, https://doi.org/10.1680/macr.1957.9.26.89.
[10] KNAB, L. I. - CLIFTON, J. R. - INGS, J. B.: Effects of maximum void size and aggregate characteristics on the strength of mortar, Cement and Concrete Research, 13(3), p. 383-390, 1983, https://doi.org/10.1016/0008-8846(83)90038-8.
[11] ACI 363R-10 (2010): Report on High-Strength Concrete, American Concrete Institute, Farmington Hills, MI, USA, 2010.
[12] ACI 318 (2014): Building code requirements for structural concrete and commentary, American Concrete Institute, Farmington Hills, MI, USA, 2014.
[13] LEGERON, F. - PAULTRE, P.: Prediction of Modulus of Rupture of Concrete, ACI Materials Journal, 97(2), p. 193-200, 2000, https://doi.org/10.14359/823.
[14] RAPHAEL, J. M.: Tensile Strength of Concrete, ACI Journal Proceedings, 81(2), p. 158-165, 1984, https://doi.org/10.14359/10653.
[15] JUKI, M. I. - AWANG, M. - ANNIS, M. M. K. - BOON, K. H. - OTHMAN, N. - ABDUL KADIR, A. - ROSLAN, M. A. - KHALID, F. S.: Relationship between Compressive, Splitting Tensile and Flexural Strength of Concrete Containing Granulated Waste Polyethylene Terephthalate (PET) Bottles as Fine Aggregate, Advanced Materials Research, 795, p. 356-359, 2013, https://doi.org/10.4028/www.scientific.net/AMR.795.356.
[16] CAMPOS, R. - LARRAIN, M. M. M. - ZAMAN, M. - POZADAS, V.: Relationships between compressive and flexural strengths of concrete based on fresh field properties, International

Journal of Pavement Research and Technology, 14(2), p. 161-167, 2021, https://doi.org/10.1007/s42947-020-1074-0.
[17] AHMED, M. - HADI, K. M. el - HASAN, M. A. - MALLICK, J. - AHMED, A.: Evaluating the co-relationship between concrete flexural tensile strength and compressive strength, International Journal of Structural Engineering, 5(2), p. 115-131, 2014, https://doi.org/10.1504/IJSTRUCTE.2014.060902.
[18] ABDUL RAZAK, H. - WONG, H. S.: Asian Journal of Civil Engineering (Building and Housing), Asian Journal of Civil Engineering (Building and Housing), 5(1), p. 85-99, 2004.
[19] YUSUF, I. T. - JIMOH, Y. A. - SALAMI, W. A.: An appropriate relationship between flexural strength and compressive strength of palm kernel shell concrete, Alexandria Engineering Journal, 55(2), p. 1553-1562, 2016, https://doi.org/10.1016/j.aej.2016.04.008.
[20] SARKAR, S. - ADWAN, O. - MUNDAY, J. G. L.: High Strength Concrete: an Investigation of the Flexural Behaviour of High Strength RC Beams, The Structural Engineer, 75(7), 1997.
[21] AMUDHAVALLI, N. K. - POOVIZHISELVI, M.: Relationship between Compressive Strength and Flexural Strength of Polyester Fiber Reinforced Concrete, International Journal of Engineering Trends and Technology, 45(4), p. 158-160, 2017, https://doi.org/10.14445/22315381/IJETT-V45P234.
[22] SBAROUNIS, J. A.: Multistory Flat Plate Buildings, Concrete International, 6(2), p. 70-77, 1984.
[23] GRAHAM, C. J. - SCANLON, A.: Deflection of reinforced concrete slabs under construction loading, Structural engineering report SER 117, 1984, https://doi.org/https://doi.org/10.7939/R3S17SW9H.
[24] IS 456 (2000): Code of practice for plain and reinforced concrete, Bureau of Indian Standard, New Delhi, India, 2000.
[25] XIAO, J.-ZH. - LI, J.-B. - ZHANG, CH.: On relationships between the mechanical properties of recycled aggregate concrete: An overview, Materials and Structures, 39(6), p. 655-664, 2006, https://doi.org/10.1617/s11527-006-9093-0.
[26] SB CODE - 304 (2007): Structural—Concrete Structures, The Saudi Building Code Structural Technical Committee (SBCSTC), Saudi Arabia, 2007.
[27] LOGAN, A. - MIRMINAR, A. - RIZKALLA, S. - ZIA, P. - WONCHANG, C.: Short-Term Mechanical Properties of High-Strength Concrete, ACI Materials Journal, 106(5), p. 413-418, 2009, https://doi.org/10.14359/51663141.
[28] KOTHAI, L. - MALATHY, R.: Strength studies on self compacting concrete with manufactured sand as partial replacement of natural sand, European Journal of Scientific Research, 89, p. 490-496, 2012.
[29] EUROCODE (2002): Design of concrete structures—Part 1-1: General rules and rules for buildings, European Committee for Standardization, Brussels, Belgium, 2002.
[30] RASHID, M. A. - MANSUR, M. A. - PARAMASIVAM, P.: Correlations between Mechanical Properties of High-Strength Concrete, Journal of Materials in Civil Engineering, 14(3), p. 230-238, 2002, https://doi.org/10.1061/(ASCE)0899-1561(2002)14:3(230).
[31] RAMADOSS, P.: Combined effect of silica fume and steel fiber on the splitting tensile strength of high-strength concrete, International Journal of Civil Engineering, 12(1), p. 96-103, 2014, http://ijce.iust.ac.ir/article-1-801-en.html.
[32] RAMADOSS, P.: Studies on high-performance steel fiber reinforced concrete under static and impact loads, 2007, http://hdl.handle.net/10603/31379.
[33] SHAH, S. P. - AHMAD, S. H.: Structural Properties of High Strength Concrete and its Implications for Precast Prestressed Concrete, PCI Journal, 30(6), p. 92-119, 1985, https://doi.org/10.15554/pcij.11011985.92.119.
[34] BHANJA, S. - SENGUPTA, B.: Influence of silica fume on the tensile strength of concrete, Cement and Concrete Research, 35(4), p. 743-747, 2005, https://doi.org/10.1016/j.cemconres.2004.05.024.
[35] PERUMAL, R.: Correlation of Compressive Strength and Other Engineering Properties of High-Performance Steel Fiber–Reinforced Concrete, Journal of Materials in Civil Engineering, 27(1), 2015, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001050.
[36] MAHMOOD, W. - MOHAMMED, A. S. - ASTERIS, P. G. - KURDA, R. - ARMAGHANI, D. J.: Modeling Flexural and Compressive Strengths Behaviour of Cement-Grouted Sands Modified with Water Reducer Polymer, Applied Sciences, 12(3), p. 1016, 2022, https://doi.org/10.3390/app12031016.
[37] MARÍN-URIBE, C. R. - NAVARRO-GAETE, R.: Empirical relationships between compressive and flexural strength of concrete containing recycled asphalt material for pavement applications using

different specimen configurations, Materiales de Construcción, 71(342), e249, 2021, https://doi.org/10.3989/mc.2021.11520.

[38] PRASAD, V. - SABRI, M.M.S. - DEVI, S. - NAJM, H.M. - MAJEED, S. - QAIDI, S.M.A.: Mechanical and microstructural properties of self-healing concrete based on Hay Bacillus, Magazine of Civil Engineering, 2023, Article no. 12204, DOI: 10.34910/MCE.122.4.

[39] HAMAH SOR, N. - ALI, T. K. M. - VALI, K. S. - AHMED, H. U. - FARAJ, R. H. - BHEEL, N. - MOSAVI, A.: The behavior of sustainable self-compacting concrete reinforced with low-density waste Polyethylene fiber, Materials Research Express, 9(3), p. 035501, 2022, https://doi.org/10.1088/2053-1591/ac58e8.

[40] ABOLHASANI, A. - ASLANI, F. - SAMALI, B. - GHAFFAR, S. H. - FALLAHNEJAD, H. - BANIHASHEMI, S.: Silicate impurities incorporation in calcium aluminate cement concrete: mechanical and microstructural assessment, Advances in Applied Ceramics, 120(2), p. 104-116, 2021, https://doi.org/10.1080/17436753.2021.1889755.

[41] NF EN 197-1 (2000): Cement part 1: composition, specifications and conformity criteria for common cements, European Committee for Standardization, France, 2000.

[42] NF EN 933-1 (1997): Tests for geometrical properties of aggregates–Part 1: Determination of particle size distribution, European Committee for Standardization, France, 1997.

[43] NF EN 1097-6 (2001): Tests for mechanical and physical properties of aggregates–Part 6: Determination of particle density and water absorption, European Committee for Standardization, France, 2001.

[44] NF EN 12390-5 (2001): Testing hardened concrete–Part 5: Flexural strength of test specimens, European Committee for Standardization, France, 2001.

[45] NF EN 12390-3 (2003): Testing hardened concrete–Part 3: Compressive strength of test specimens, European Committee