Mathematical Modelling of Engineering Problems
Vol. 12, No. 4, April, 2025, pp. 1389-1398
Journal homepage: http://iieta.org/journals/mmep

Using Different Stress-Strain Models in Finite Element Analysis to Investigate the Relationship Between the Ultimate Strength of Cylindrical and Cubic Concrete Standard Specimens

Majed A. Khalaf, Jawad Abd Matooq*, Ansam Z. Thamer, Fareed H. Majeed

Department of Civil Engineering, University of Basrah, Basrah 61004, Iraq

Corresponding Author Email: jawad.abd-matooq@uobasrah.edu.iq

https://doi.org/10.18280/mmep.120429

Received: 5 December 2024
Revised: 6 February 2025
Accepted: 12 February 2025
Available online: 30 April 2025

Keywords:
ABAQUS, concrete damage plasticity, concrete cylinder, concrete cube, finite element method, stress-strain curve

ABSTRACT

A finite element simulation with concrete damage plasticity (CDP) model and four different stress-strain curves chosen from the literature, has been employed to investigate the relationship between the ultimate strength of cylindrical and cubic concrete standard specimens. The study used ABAQUS software to track the mechanical behavior of these two types of specimens for normal concrete of grades from 20 to 50 MPa under monotonic compression loading. The main result of the study is that the stress-strain curve proposed by Carreira, among the studied models, give the best fit of this relationship in comparing with the ratios adopted by Eurocode. The paper emphasizes that before adopting a specific concrete stress-strain curve for the numerical simulation of a complex member under complex conditions, it is essential to examine the accuracy of that model for more simpler cases. It is obvious from the four studied stress-strain models that the ratio of f_{cy}/f_{cu} is increasing with concrete grade, which means there is more attend for the two strengths to approach each other, however the Eurocode table does not track this increasing and give only oscillating data.

1. INTRODUCTION

The compressive strength is the most important property of concrete used in design calculations for plain and reinforced concrete elements. It is also used quantitatively or qualitatively to express the other properties or reflect the quality and durability of concrete. Different countries adopting different codes of engineering practice used different shapes and sizes of test specimens to obtain the characteristic compressive strength of concrete. The mostly used test specimens are the cylinders and cubes. Many countries use cylinder specimens with dimensions (D=150 mm, h=300 mm), such as the United States, Canada, France, Australia, South Korea, and other countries. On the other hand, countries such as the UK, Germany, South Africa, Iraq, and many others use 150mm cube specimens. It is the basic question: Which test specimen is more representative of the compressive strength of concrete in its actual state for different structural concrete members? The other important question is how to convert the test results of compressive strength between these two different-shaped standard samples when required. The cylinder compressive strength is more preferable, both in design calculation and academic studies. The cube sample, on the other hand, is more preferable from practical aspects to be used in laboratories. One of the reasons is the cylinder samples required capping at the two loaded faces to reduce the friction and stress concentration between the platen of the test machine and the upper and lower faces of the sample, whereas the cube sample does not require that capping.

Some countries such as Iraq, South Africa, and some of the European and other countries, used cubes as a standard test specimen, while their design codes such as EN 1992-1-1 [1], adopt the characteristic cylinder compressive strength in its design equations. So, they need to convert the cube results to cylinder equivalence before using them in design calculations. For this reason, the Eurocode EN 206 includes Table 1 [2], which is reproduced here as Table 1 and referred to as EN-Table throughout this study.

Table 1. Compressive strength classes for normal-weight and heavy-weight concrete (Table 12 of EN-206) [2]

Compressive Strength Class	Cylinder Strength *F*ck, Cyl (N/mm^2)	Cube Strength *F*ck, Cube (N/mm^2)	*F*ck, Cyl/*F*ck, Cube
C8/10	8	10	0.80
C12/15	12	15	0.80
C16/20	16	20	0.80
C20/25	20	25	0.80
C25/30	25	30	0.83
C30/37	30	37	0.81
C35/45	35	45	0.78
C40/50	40	50	0.80
C45/55	45	55	0.82
C50/60	50	60	0.83
C55/67	55	67	0.82
C60/75	60	75	0.80
C70/85	70	85	0.82
C80/95	80	95	0.84
C90/105	90	105	0.86
C100/115	100	115	0.87

Table 1 intend to provide the equivalency between the two different compressive strengths of cylindrical and cubic specimens. It can be noticed from Table 1 that the ratio of (f_{cy}/f_{cu}) has a relatively wide range of oscillated values from 0.78 to 0.87 without a clear trend relating to the increasing of concrete grade. So, it is important to explore better conversion values or formula to convert from cube to cylinder strength and vice versa when needed.

The factors affecting the (f_{cy}/f_{cu}) ratio are broad in manner, including mechanical and practical aspects such as (1) casting, curing, and testing procedure (2) specimen geometry and size. (3) level of strength (4) direction of loading (5) machine characteristics and loading rate (6) aggregate type and grading. These many factors make it difficult to reach a value or formula to convert between the two compressive strengths.

The current study suggests estimating the (f_{cy}/f_{cu}) ratio from numerical finite element simulation or at least combining this method with the others, generally experimental methods, to get the best fit of the required conversion factors. This is because the FEM, in some sense, neutralizes most of the external and practical test factors and keeps only the mechanical differences between the two specimens, such as shape and dimensions, and then gives a clean baseline of the relationship between the compressive strength of the cylindrical and cubic test specimens.

The finite element simulation used in the study implemented four of the well-known and mostly used concrete stress-strain curves from the literature. The simulation software ABAQUS with the concrete damage plasticity model CDP has been used to model the two types of specimens using the chosen concrete stress-strain curves.

The research, in addition to its main aim of reaching the best estimation of conversion factors, highlighted many points in the subject like: (1) The stress-strain curves throughout the literature are drawn from experiments on cylinder rather than cube specimens, and that is because they are better at representing the behavior of the different types of structural members, including the cubic specimen itself. (2) The finite element approach can accurately track the difference in behavior for fairly alike specimens subjected to the same type of loading and boundary conditions, and are different only in geometry. (3) The stress-strain curve should be carefully chosen through studying the behavior of different structural members.

2. PREVIOUS STUDIES

The conversion factor or formula between the compressive strength of standard cylindrical and cubic test specimens has a very wide range in the literature. Numerous research studies agreed that the cube strength is bigger than the cylinder strength for the same concrete material at the same age, and most researchers noted that there is a trend to increase the (f_{cy}/f_{cu}) ratio with increasing the level of concrete strength [3-10].

Neville [11] provided a table of variation of the cylinder/cube strength ratio that goes from 0.77 up to 0.96. The increasing of this ratio was clearly increased with the grade of concrete. Elwell and Fu [12] presented a report entitled "Compression testing of concrete: Cylinders vs. cubes". They claimed that the past efforts could not reach an empirical formula to estimate the ratio of cylinder/cube strength. The recorded ratios of the past research were varying between about 0.65 and 0.9, although ratios outside this range have also been observed. They concluded based on their study that replacing cylinder testing with cube testing is not recommended.

Malaikah [13] conducted an experimental study by casting 260 samples of cylinders and cubes, dividing the test samples into groups. Groups II and III differed only in the source of fine and coarse aggregate. Group II gave an average (f_{cy}/f_{cu}) ratio of 0.83, while group III gave an average of 0.74. They concluded then that the mix design parameters influence the cylinder/cube strength ratio.

Sun and Fanourakis [14] performed an experimental study to evaluate the Cylinder-Cube Strength Relationship (CCSR) after noticing that several studies have shown that the general value of 0.8 is not a valid approximation to get the cylinder strength from the cube in South Africa. Cubes and cylinders were cast for 7, 28, and 56 curing days from 36 concrete mixes varying in strength. The results they got, as shown in Figure 1, have a large scatter and show no trend for the relationship between the two specimens results.

Yehia et al. [15] conducted experiments to investigate the effect of aggregate type and specimen configuration on the compressive strength of concrete; their results indicate that specimen shape has a noticeable effect on concrete strength, as the cylinder/cube ratio was ranging between 0.781 and 0.929.

Many researchers have studied the size effect on the compressive strength of concrete, and they found that the size effect is more evident in cubes than in cylinder specimens [16-18].

Based on the presented previous studies, it is evident that there is no universally accepted value or formula in the literature for converting between the compressive strengths of cylindrical and cubic concrete specimens.

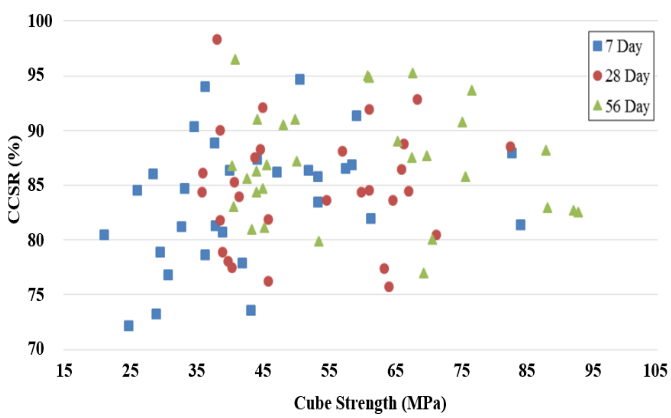


Figure 1. The effect of compressive strength on the CCSR [14]

3. THE USED STRESS-STRAIN MODELS

The nonlinear finite element programs steadily require the uniaxial stress-strain relationship for concrete in compression. This is necessary to track the stress state at each point in each stage of loading of the plain or reinforced concrete members and adopting this state in the plasticity and failure criteria.

Four distinguished stress-strain curve formulations were used in this study; all of them are constituted of one smooth equation. The chosen curves are conducted by Desayi and Krishnan [19], Popovics [20], Carreira and Chu [21], and

EN1992 [1].

The four stress-strain curves chosen for the study have been filtered from many others; firstly, they seem to the authors' knowledge more popular in the literature; secondly, they are distinct from each other in formulation as well as in shape, whereas some other curves were close to one of them; and thirdly, they are easy, smooth, and use only one parameter to formulate.

In the present study, for comparison reasons, the notation of the stress-strain curve equations was unified mostly according to Eurocode notation as depicted in Figure 2 and adopted in SI units where stress is in N/mm², as follows:

f_c: general stress value at any point on the curve.
ε_c: general strain value at any point on the curve.
f_{cm}: ultimate stress value on the curve.
ε_{c1}: strain value corresponding to peak stress f_{cm}.
ε_{cu1}: ultimate strain.
E_{it}: initial tangent modulus of the stress strain curve.
E_{cm}: secant modulus of elasticity at a point of 0.4 f_{cm}.
$E_m = f_{cm}/\varepsilon_{c1}$.

According to Majewski [22], a linear elasticity limit should be increased with concrete strength, and it could be assumed rather than experimentally determined. He proposed the following formula:

$$e_{lim} = 1 - \exp\left(-\frac{f_c}{80}\right) \leq 0.4\, f_{cm} \tag{1}$$

The above limit can be simply arbitrary assumed as:

$$\boldsymbol{e_{lim} = 0.4\, f_{cm}} \tag{2}$$

Eurocode 2 specifies the modulus of elasticity for concrete to be a secant in a range of 0-0.4 f_{cm} [1].

Desayi and Krishnan [19] proposed following equations for the stress-strain curve:

$$f_c = \frac{E_{it}\varepsilon_c}{1 + \left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)^2} \tag{3}$$

$$\varepsilon_{c1} = \frac{2\, f_{cm}}{E_{it}} \tag{4}$$

$$E_{it} = m\, E_m = 2E_m \tag{5}$$

Popovics [20] had proposed the following equations:

$$f_c = f_{cm} \times \frac{\varepsilon_c}{\varepsilon_{c1}} \times \frac{\beta}{\beta - 1 + (\frac{\varepsilon_c}{\varepsilon_{c1}})^\beta} \tag{6}$$

$$\beta = 0.058\, f_{cm} + 1 \tag{7}$$

Carreira and Chu [21] had proposed the following equations:

$$f_c = f_{cm}\left(\frac{\beta\left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)}{\beta - 1 + \left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)^\beta}\right) \text{ for } \beta \geq 1 \text{ and } \varepsilon_c \leq \varepsilon_{cu1} \tag{8}$$

$$\beta = \frac{1}{1 - \frac{f_{cm}}{\varepsilon_{c1}E_{it}}} \tag{9}$$

$$\varepsilon_{c1} = (1680 + 7.1 f_{cm}) \times 10^{-6} \tag{10}$$

$$E_{it} = \frac{f_{cm}}{\varepsilon_{c1}}\left(\frac{24.82}{f_{cm}} + 0.92\right) \tag{11}$$

EN1992-1-1 [1] had adopted the following equations:

$$f_c = \frac{k\eta - \eta^2}{1 + (k-2)\eta}\, f_{cm} \tag{12}$$

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}} \tag{13}$$

$$k = 1.05\, E_{cm}\frac{|\varepsilon_{c1}|}{f_{cm}} \tag{14}$$

$$E_{cm} = 22000\left(\frac{f_{cm}}{10}\right)^{0.3} \tag{15}$$

$$\varepsilon_{c1} = 0.0007\,(f_{cm})^{0.31} \leq 0.0028 \tag{16}$$

$$\varepsilon_{cu1} = 0.0035 \text{ for } f_{cm} \leq 50 \text{ MPa} \tag{17}$$

$$\varepsilon_{cu1} = 0.0028 + 0.0027\left(\frac{98 - f_{cm}}{100}\right)^4 \text{ for } f_{cm} > 50 \tag{18}$$

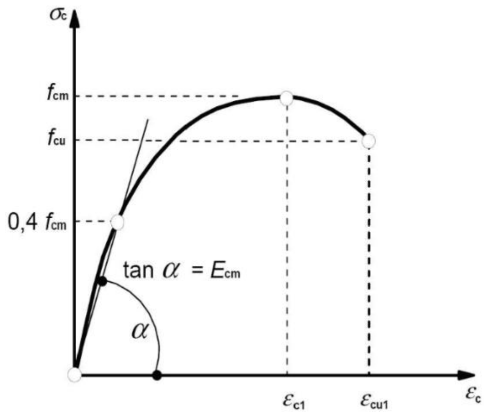


Figure 2. Concrete stress-strain curve for analysis of structures, according to EN1992 [1]

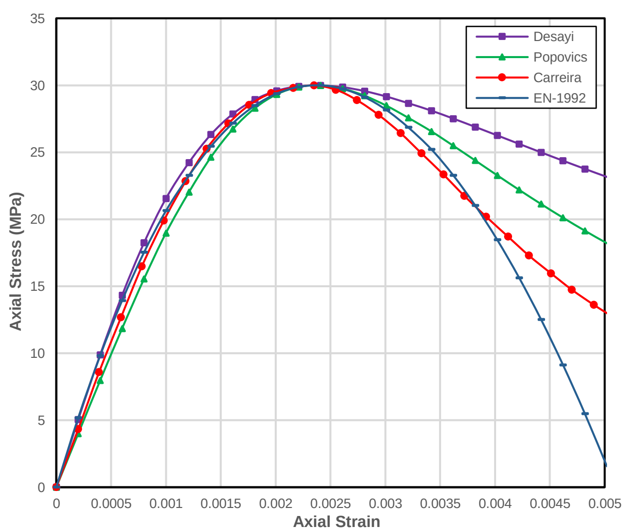


Figure 3. The four studied stress-strain curves for f_{cm}=30 MPa

Figure 3 shows the stress-strain curves of concrete with f_{cm}=30 MPa extracted from the above proposed equations. It is noticed from Figure 3 that the curves show slight differences in the ascending part and significant differences in the descending part.

4. ABAQUS AND DAMAGE PLASTICITY MODEL

The ABAQUS software adopted the damage plasticity model, originated by Lubliner et al. [23] and developed by Lee and Fenves [24]. It is formulated to represent rock-like material and has been thoroughly studied in literature for concrete.

Panahi and Genikomsou [25] attained a computational model validation on the two of the mostly used concrete models in the nonlinear finite element analysis, that is, the concrete damage plasticity (CDP) and the concrete smeared cracking (CSC). The analysis was done on both previously tested plain and reinforced concrete specimens under different loading conditions. The outcomes show that the CDP model predicts the response of specimens accurately, while the CSC model fails to capture the response of the analyzed specimens mainly due to convergence issues.

The concrete damage plasticity (CDP) model benefits from both plasticity and damage mechanics to represent both compression crushing and tensile cracking and capture the softening and deterioration of concrete. The model relies on a combination of stress-based plasticity formulated in the effective (undamaged) stress space combined with a strain-based damage model.

The damage plasticity decomposes the strain rate as following:

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} \tag{19}$$

where,

$\dot{\varepsilon}$ total strain rate

$\dot{\varepsilon}^{el}$ elastic part of strain rate

$\dot{\varepsilon}^{pl}$ plastic part of strain rate

Within the context of the scalar-damage theory, the stiffness degradation is isotropic and characterized by a single degradation variable, "*d*" [26] as shown in Figure 4 and expressed in the following equations:

$$\sigma = (1-d)\, D_o^{el}\, (\varepsilon - \varepsilon^{pl}) = D^{el}(\varepsilon - \varepsilon^{pl}) \tag{20}$$

$$D^{el} = (1-d)\, D_o^{el} \tag{21}$$

$$\sigma = (1-d)\bar{\sigma} \tag{22}$$

where,

d a scalar variable that indicate the stiffness degradation and take values ranges from zero (for undamaged material) to one (for fully damaged material).

D_o^{el} initial (undamaged) elastic stiffness of material.

D^{el} degraded elastic stiffness.

σ Cauchy stress.

$\bar{\sigma}$ effective stress.

The parameters required by the damage plasticity model in ABAQUS and used in the present study are summarized in Table 2.

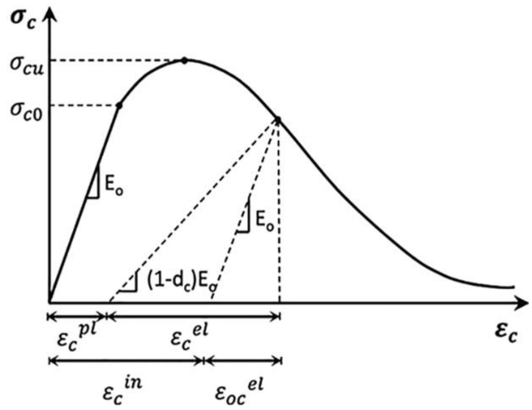


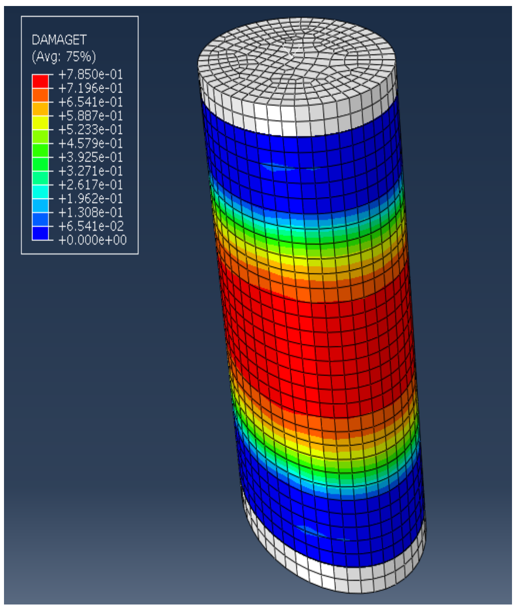
Figure 4. Stress-strain according to damage plasticity

Table 2. Parameters of CDP model used in the study

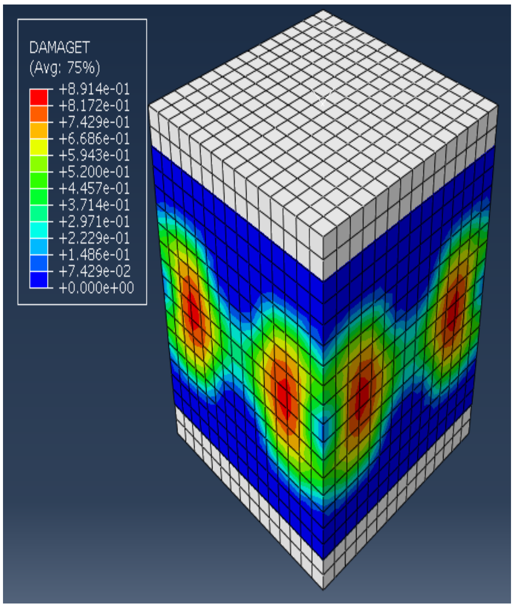
Parameter Name	Value
Dilatation angle	35
Eccentricity	0.1
f_{b0}/f_{c0}	1.16
k	0.667
Viscosity parameter	0.001

5. FINITE ELEMENT MODELLING OF SPECIMENS USING ABAQUS

The concrete specimens have been modeled by using the 8-node linear hexahedral element with reduced integration, C3D8R, from the ABAQUS library. In addition to concrete, two steel plates with a thickness of 20mm have been used above and beneath the samples to distribute the load evenly on the upper and lower faces of the specimens and give boundary conditions similar to that of the compression test. The element type of the steel plates was also C3D8R to give the best compatibility of the finite element mesh. A mesh size of 10mm has been chosen for all cases. The modulus of elasticity and Poisson ratio of steel are taken as 200GP and 0.3, respectively, while for concrete, the Poisson ratio is taken as 0.15 while the modulus of elasticity is calculated according to the equations of each model.



(a)



(b)

Figure 5. Mesh and damage distribution pattern of the two specimens in ABAQUS

A displacement control loading was applied on the upper plate. The contact of the upper and lower plates with the concrete specimens' faces was represented as "hard" and the friction coefficient of lateral movement between the two materials was taken equal to 0.3. The strain was calculated through division of the relative displacement at the top and bottom faces of the concrete over the initial sample height. The stress was calculated by dividing the reaction recorded at the lower plate over the sample cross-sectional area.

Figure 5 shows the ABAQUS representation of the two specimens with damage distribution pattern over the mesh of the concrete and steel upper and lower plates.

6. RESULTS AND DISCUSSION

For each model of the studied stress-strain curves, seven grades of concrete have been formulated (f_{cm}=20, 25, 30, 35, 40, 45, and 50 MPa). These seven curves have been used in ABAQUS in the finite element simulation for both cylindrical and cubic specimens. The behavior of the specimens under monotonic compression loading for the four stress-strain models and all 7 grades of concrete has been recorded in the form of stress-strain curves as shown in Figures 6-13.

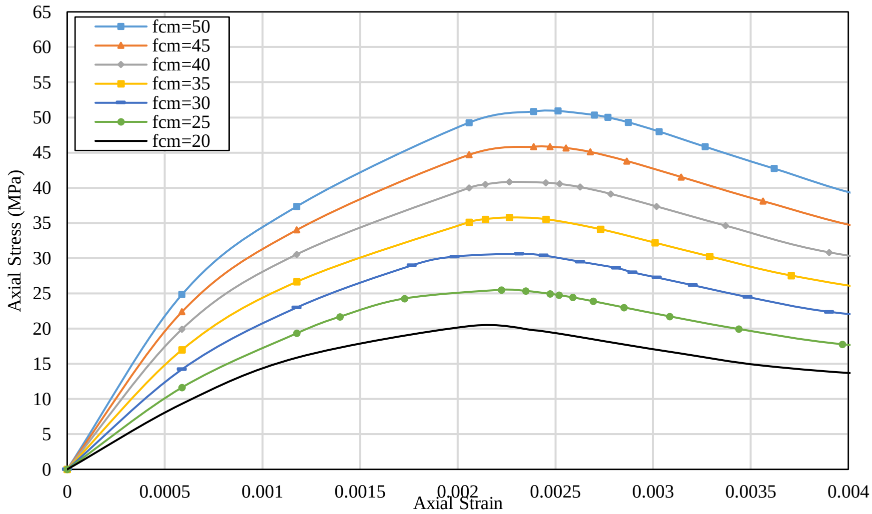


Figure 6. Stress-strain curves of cylinders using Desayi model

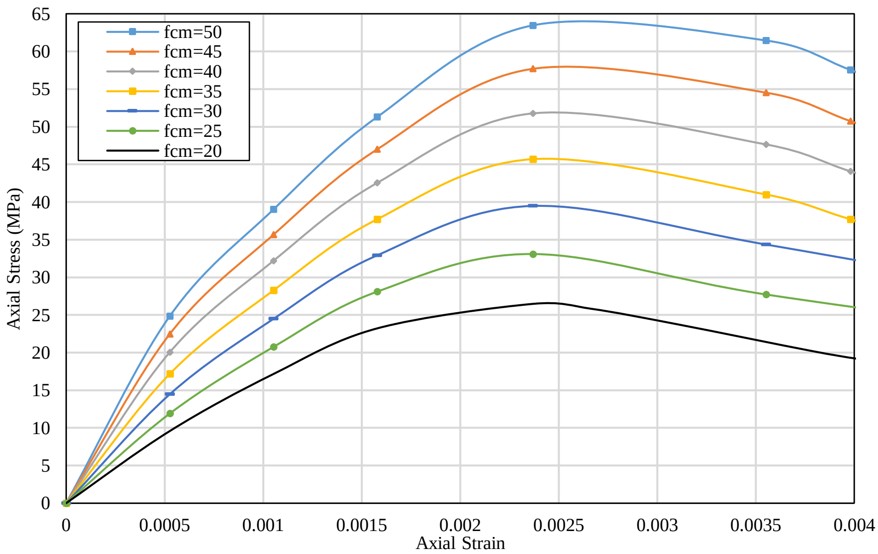


Figure 7. Stress-strain curves of cubes using Desayi model

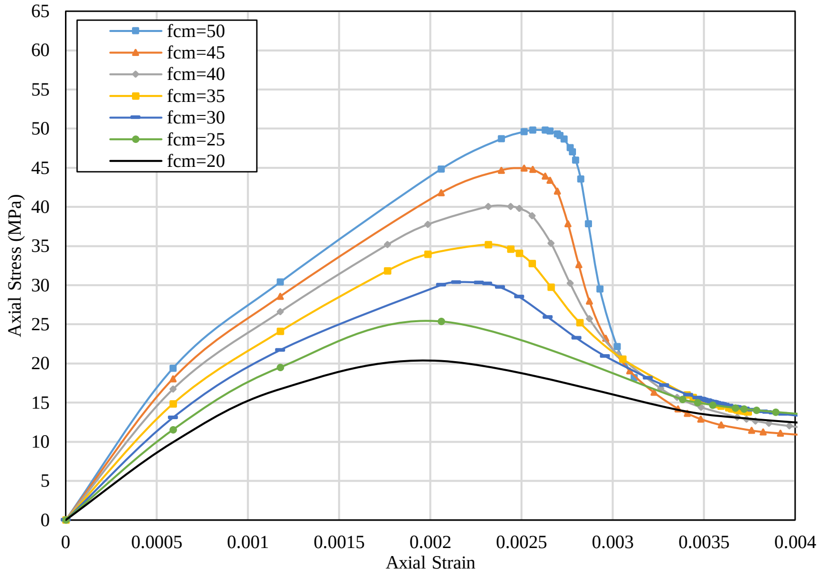


Figure 8. Stress-strain curves of cylinders using Popovics model

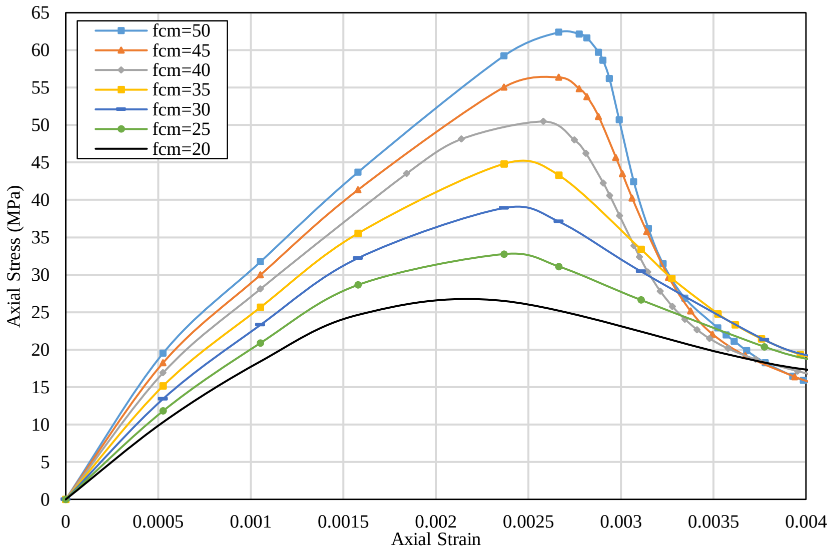


Figure 9. Stress-strain curves of cubes using Popovics model

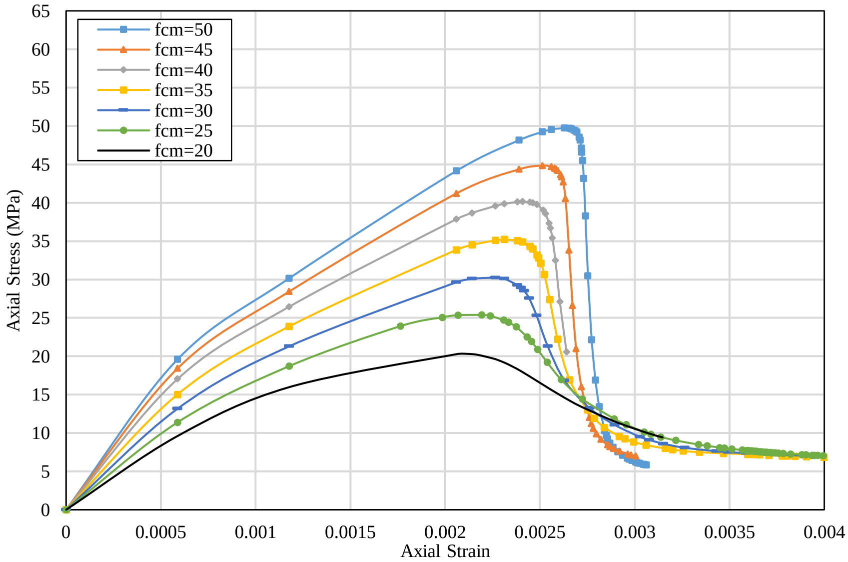


Figure 10. Stress-strain curves of cylinders using Carreira model

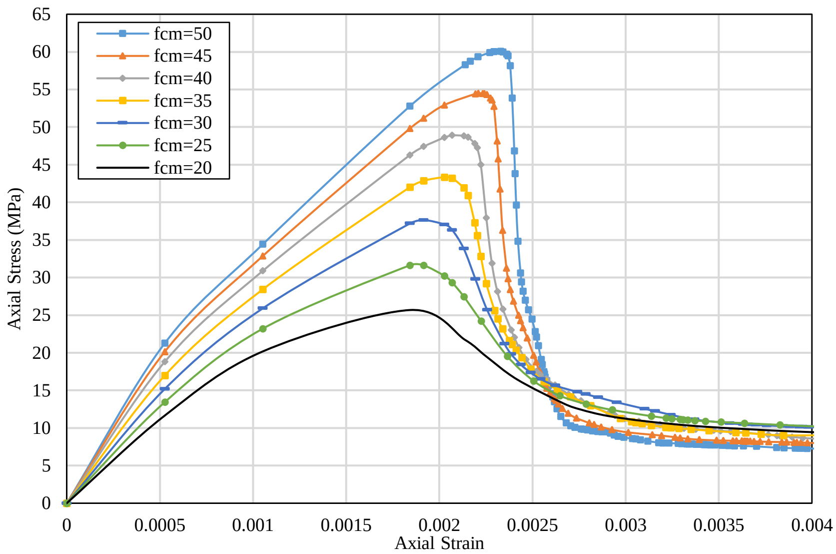


Figure 11. Stress-strain curves of cubes using Carreira model

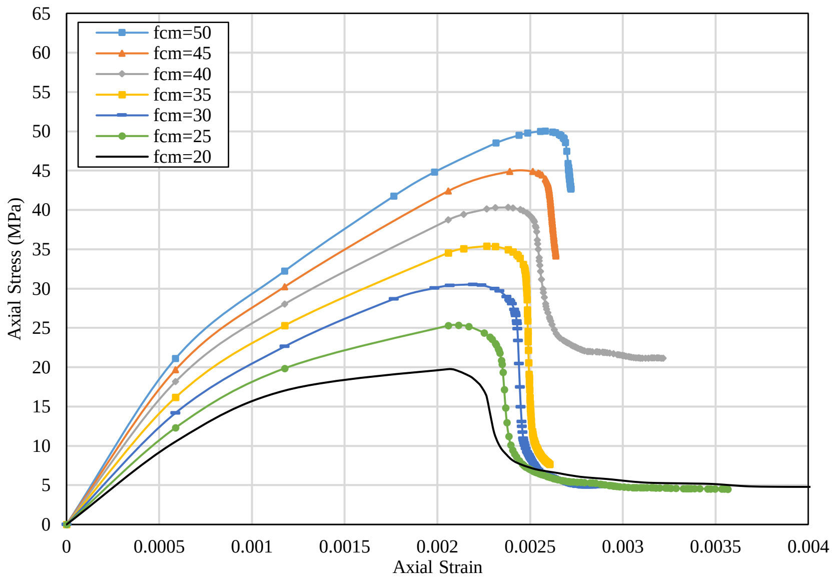


Figure 12. Stress-strain curves of cylinders using EN1992 model

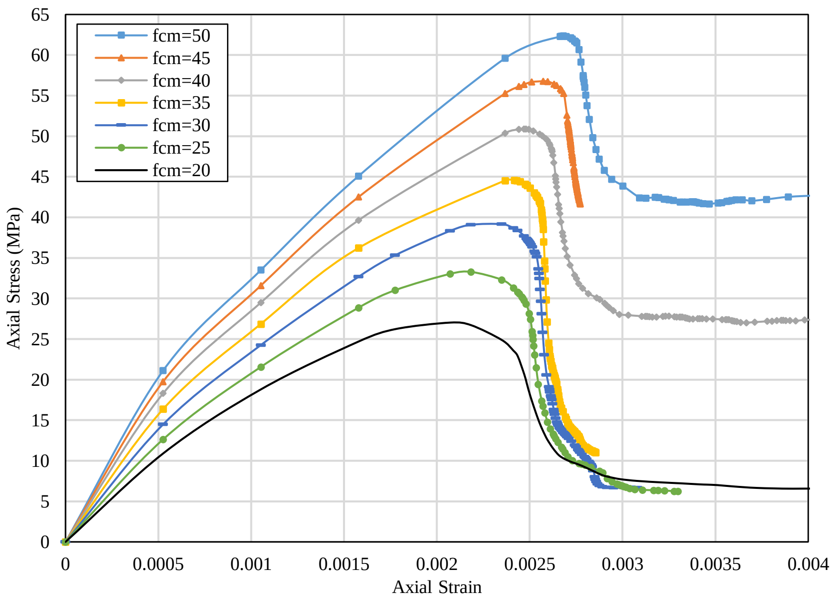


Figure 13. Stress-strain curves of cubes using EN1992 model

Table 3. The ultimate strength of cylinders and cubes for the four used models

f_{cm}	Desayi		Popovics		Carreira		EN1992	
	f_{cy}	f_{cu}	f_{cy}	f_{cu}	f_{cy}	f_{cu}	f_{cy}	f_{cu}
20	20.51	26.47	20.41	26.51	20.32	25.68	20.50	27.09
25	25.52	33.09	25.36	32.77	25.38	31.64	25.35	33.29
30	30.64	39.48	30.41	39.11	30.24	37.65	30.53	39.18
35	35.79	45.69	35.21	44.91	35.22	43.35	35.39	44.57
40	40.84	51.77	40.09	50.46	40.15	48.91	40.32	50.91
45	45.84	57.71	45.01	56.36	44.88	54.49	44.91	56.79
50	50.91	63.51	50.01	62.41	49.81	60.05	50.02	62.39
MSD	0.543		0.074		0.060		0.131	

Table 3 shows the values of the ultimate strength of cylinders (f_{cy}) and cubes (f_{cu}) obtained from the finite element simulation.

The ratios of the cylinders to cubes strength (f_{cy}/f_{cu}) according to the studied models in addition to the Eurocode table are shown in Figure 14.

The four models have estimated the compressive strength of the cylinder (f_{cy}) in the FE program very well, as shown by the Mean Squared Deviation (MSD) in Table 3. The Carreira model gave the best estimation for f_{cy} with MSD = 0.060, then Popovics with MSD=0.074. However, the four models show more scatter estimations for the compressive strength of the cubes (f_{cu}) as indicated in Figure 14. This point specifically shows the challenge about which one of the four models is the best in estimating both f_{cy} and f_{cu} and then gives the best conversion factor between the two values of strength.

It is obvious from Figure 14 that the ratio of f_{cy}/f_{cu} is increasing with the increasing of the concrete grade for all four models, which is the case noticed in experimental studies in the literature; however, this ratio is oscillating for EN-Table. The values in the EN-Table were just proposed by Eurocode to be used in practical and quality measurements and not to be used in modeling or in finite element simulation.

It is also noticed from Figure 14 that the Carreira model has represented the relation between cylinder and cube strengths fairly well, and it is about to give the mean value of the EN-Table. The average of this ratio in the Carreira model is equal to 0.811, and for EN-Table it is equal to 0.810. Whereas the average values for the Desayi, Popovics, and EN-1992 models are equal to 0.784, 0.786, and 0.778, respectively, which are slightly less than the average of Carreira and EN-Table and also less than the practical widely used value of 0.8.

It is interesting to notice that the stress-strain curve obtained experimentally and then simulated in mathematical form from cylindrical specimens is the "best" to represent the behavior of concrete members, including the cube specimen. While the stress-strain curve extracted from cube specimens fails to represent the behavior of concrete members, including the cube itself.

It is also noticed from the results in Table 3 that all four stress-strain models have estimated the cylinder strength in FE model fairly well, however three of these models (Desayi, Popovics, ad EN1992) seem to slightly overestimate the cube strength, while Carreira model seems to give better estimation to the cube strength.

Comparing the ultimate strength given by the four models with the cylinder given grades shows that the FEM models tend to slightly overestimate the strength with an average of (+2.1%, +0.8%, +0.6%, and +1.1%) MPa for Desayi, Popovics, Carreira, and EN1992, respectively. The Carreira model gives the least deviation from the given cylinder grades.

For cubes, on the other hand, we don't have the true value of strength, however, according to the results shown in Figure 14, it is noticed that the three models of Desayi, Popovics, and EN1992 are overestimating the strength of cubes even more than overestimating of cylinder strength, while Carreira model in this respect and additionally when compared with EN-Table curve had given the best estimation of cube specimens strength and then the best estimation of the cylinder/cube strength ratio.

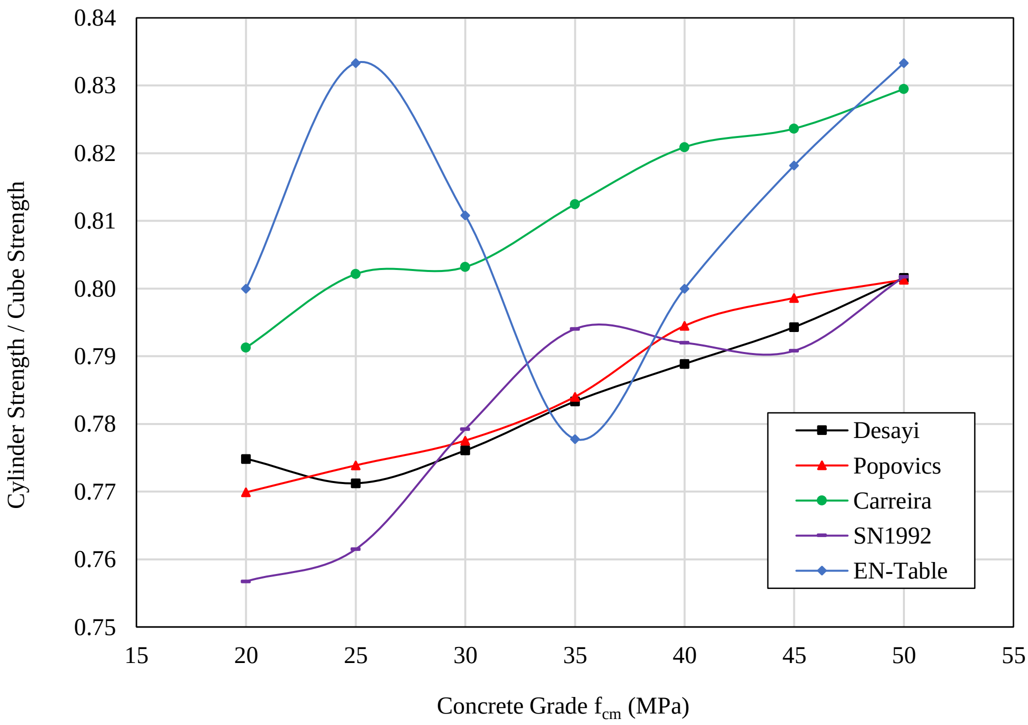


Figure 14. (f_{cy}/f_{cu}) according to studied models

7. CONCLUSIONS

1) Previous studies showed clearly that it is difficult to describe the relationship between the cylindrical and cubic compressive strength by one conversion factor or formula due to many factors that affect their values.
2) The finite element simulation with the CDP model can accurately track the difference in behavior between the two specimens which are fairly alike in material, loading, and boundary conditions and differ only in geometry.
3) It is obvious from the four studied stress-strain models that the ratio of f_{cy}/f_{cu} is increasing with concrete grade, which means there is more tendency for the two strengths to approach each other; however, the Eurocode table does not track this trend and gives only oscillating data.
4) The study showed that the Carreira stress-strain curve is the best among the four studied models to be used in finite element simulation to calculate the ultimate strength of both cylinder and cube specimens. It is better in the cylinder specimen case because it gave, on average, the least deviation (+0.6%) from the given grade values. And it is better for cube specimens because it has the least overestimation of cube strength, as it gave the largest values of the f_{cy}/f_{cu} ratios of an average of 0.811, which is also the closest value to the average obtained from EN-Table of 0.810.

REFERENCES

[1] BS EN 1992-1-1. (2023). Eurocode 2. Design of concrete structures - General rules and rules for buildings, bridges and civil engineering structures. British Standards Institution, London. https://doi.org/10.3403/30430557

[2] EN 206-1. (2003). Concrete-Part 1: Specification, performance, production and conformity. https://knowledge.bsigroup.com/search?query=BS%20 EN%20206-1.

[3] Mansur, M.A., Islam, M.M. (2002). Interpretation of concrete strength for nonstandard specimens. Journal of Materials in Civil Engineering, 14(2): 151-155. https://doi.org/10.1061/(ASCE)0899-1561(2002)14:2(151)

[4] Yi, S.T., Yang, E.I., Choi, J.C. (2006). Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete. Nuclear Engineering and Design, 236(2): 115-127. https://doi.org/10.1016/j.nucengdes.2005.08.004

[5] Indelicato, F., Paggi, M. (2008). Specimen shape and the problem of contact in the assessment of concrete compressive strength. Materials and Structures, 41: 431-441. https://doi.org/10.1617/s11527-007-9256-7

[6] Sim, J.I., Yang, K.H., Kim, H.Y., Choi, B.J. (2013). Size and shape effects on compressive strength of lightweight concrete. Construction and Building Materials, 38: 854-864. https://doi.org/10.1016/j.conbuildmat.2012.09.073

[7] Abd, M.K., Habeeb, Z.D. (2014). Effect of specimen size and shape on compressive strength of self-compacting concrete. Diyala Journal of Engineering Sciences, 7(2): 16-29. https://doi.org/10.24237/djes.2014.07202

[8] Tam, C.T., Babu, D.S., Li, W. (2017). EN 206 conformity testing for concrete strength in compression. Procedia Engineering, 171: 227-237. https://doi.org/10.1016/j.proeng.2017.01.330

[9] De Brito, J., Kurda, R., Raposeiro da Silva, P. (2018). Can we truly predict the compressive strength of concrete without knowing the properties of aggregates? Applied Sciences, 8(7): 1095. https://doi.org/10.3390/app8071095

[10] Talaat, A., Emad, A., Tarek, A., Masbouba, M., Essam, A., Kohail, M. (2021). Factors affecting the results of concrete compression testing: A review. Ain Shams Engineering Journal, 12(1): 205-221. https://doi.org/10.1016/j.asej.2020.07.015

[11] Neville, A.M. (2011). Properties of Concrete. Pearson Education Limited. https://www.scribd.com/document/350943966/Properties-of-Concrete-by-A-M-Neville.

[12] Elwell, D.J, Fu, G. (1995). Compression testing of concrete: Cylinders vs. Cubes; New York State Department of Transportation, State Campus: Albany, NY, USA, Report FHWA/NY/SR-95/119. https://rosap.ntl.bts.gov/view/dot/38089.

[13] Malaikah, A.S. (2005). Effect of specimen size and shape on the compressive strength of high strength concrete. Pertanika Journal of Science & Technology, 13(1): 87-96. http://psasir.upm.edu.my/id/eprint/58152/1/JST%20Vol.%2013%20%281%29%20Jan.%202005%20%28View%20Full%20Journal%29.pdf#page=89.

[14] Sun, R.W., Fanourakis, G.C. (2016). The strength relationship between the cube and cylinder. Fib. The International Federation for Structural Concrete, pp. 1-8. https://hdl.handle.net/10210/217507.

[15] Yehia, S., Abdelfatah, A., Mansour, D. (2020). Effect of aggregate type and specimen configuration on concrete compressive strength. Crystals, 10(7): 625. https://doi.org/10.3390/cryst10070625

[16] Tokyay, M.U.S.T.A.F.A., Özdemir, M. (1997). Specimen shape and size effect on the compressive strength of higher strength concrete. Cement and Concrete Research, 27(8): 1281-1289. https://doi.org/10.1016/S0008-8846(97)00104-X

[17] Turkel, A., Ozkul, M.H. (2010). Size and wall effects on compressive strength of concretes. ACI Materials Journal, 107(4): 372. https://doi.org/10.14359/51663863

[18] Muciaccia, G., Rosati, G., Di Luzio, G. (2017). Compressive failure and size effect in plain concrete cylindrical specimens. Construction and Building Materials, 137: 185-194. https://doi.org/10.1016/j.conbuildmat.2017.01.057

[19] Desayi, P., Krishnan, S. (1964). Equation for the stress-strain curve of concrete. Journal of the American Concrete Institute, 61: 345-350. https://api.semanticscholar.org/CorpusID:138606101.

[20] Popovics, S. (1973). A numerical approach to the complete stress-strain curve of concrete. Cement and Concrete Research, 3(5): 583-599. https://doi.org/10.1016/0008-8846(73)90096-3

[21] Carreira, D.J., Chu, K.H. (1985). Stress-strain relationship for plain concrete in compression. Journal Proceedings, 82(6): 797-804. https://doi.org/10.14359/10390

[22] Majewski, S. (2003). The Mechanics of Structural Concrete in Terms of Elasto-Plasticity. Publishing House of Silesian University of Technology, Gliwice.

[23] Lubliner, J., Oliver, J., Oller, S., Onate, E. (1989). A plastic-damage model for concrete. International Journal of Solids and Structures, 25(3): 299-326. https://doi.org/10.1016/0020-7683(89)90050-4
[24] Lee, J., Fenves, G.L. (1998). Plastic-damage model for cyclic loading of concrete structures. Journal of Engineering Mechanics, 124(8): 892-900. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:8(892)
[25] Panahi, H., Genikomsou, A.S. (2022). Comparative investigation of concrete plasticity models for nonlinear finite-element analysis of reinforced concrete specimens. Practice Periodical on Structural Design and Construction, 27(2): 04021083. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000670
[26] ABAQUS: Abaqus analysis user's manual. Dassault Systèmes Simulia Corporation, 2022. http://130.149.89.49:2080/v2016/pdf_books/CAE.pdf.