Impact of viscosity parameter on the concrete mechanical properties for numerical simulations using Concrete Damage Plasticity model

Victor Hugo Couto Xavier[1], Gabriel Hideki Honda Maeda[1], Lisiane Pereira Prado[2], Alex Micael Dantas de Sousa[1], André Luis Christoforo[2], Vinicius Borges de Moura Aquino[2].

(1)School of Engineering of Ilha Solteira, Ilha Solteira - SP (12516-410), Brazil,
(2)School of Engineering and Science of Guaratinguetá, Guaratinguetá - SP (15385-007), Brazil
São Paulo State University (UNESP)

Summary

In recent years, there has been significant growth in numerical models utilizing finite elements, particularly those employing the Concrete Damage Plasticity Model (CDP) to simulate concrete behavior. This study aimed to conduct a numerical investigation focused on assessing the impact of the viscosity parameter on the mechanical properties related to compressive and tensile strength in these models. Uniaxial compression and tension tests were simulated using Abaqus software to achieve this. The viscosity values in the numerical simulations were varied from 0 to 10^{-5}. It was observed that as the viscosity parameter increased, both the residual compressive and tensile strengths also increased. Moreover, the stress-strain curves for compression and tension began to diverge from the curves based on the input data used in the numerical models. In other words, the input data became incompatible with the output data from the simulations.

Keywords: viscosity, finite elements, concrete, plasticity

1 INTRODUCTION

Numerical simulation plays a crucial role in designing and analysing concrete structures, particularly those that lack standardized calculation methods. It enhances understanding of structural behavior and facilitates the development of safe and cost-effective solutions in civil engineering. This approach enables predicting structural responses under various loads and environmental conditions and during deterioration phases, thereby reducing the need for extensive experimental testing and associated costs. Applications of numerical simulation include analyzing load capacity and overall structural performance, studying the interaction between concrete and steel, and validating new materials like high-strength or fiber-reinforced concretes. Since the representation of a physical model through numerical simulation presents complexities, strategies and simplifications are adopted as a way of representing it, and simplifications are adopted to describe the object of the simulation to reduce computational costs [1].

Numerical modeling using the Finite Element Method (FEM) allows the discretization of materials into sub-domains. This approach can be simplified to an equivalent homogeneous model [2]. One of the software programs utilized for FEM modeling is Abaqus, and the results obtained from it depend significantly on the selection of specific parameters related to Concrete Damage Plasticity (CDP), particularly the dilatancy angle and viscosity [3]. In a CDP analysis, which constitutes a model considering both the plasticity and damage of the material to simulate the nonlinear behavior of concrete, several mandatory parameters must be considered. These parameters include the uniaxial stress-strain behavior models in compression and tension, the dilation angle ψ, modulus of elasticity, fracture energy, the ratio between equibiaxial and uniaxial compressive yield stress σ_{bu}/σ_{cu}, the shape factor K_c (which influences the shape of the yield surface in the deviatoric stress place under triaxial stress state) and the eccentricity parameter e [3].

The analysis of the viscosity of the material is an optional parameter in the CDP model. However, it is essential since the higher the value of the parameter used for analysis, the larger the damage zone in the finite elements, contributing to limiting the propagation of cracks. Therefore, this parameter influences the form of distribution and propagation of damage in the concrete, depending on the finite element mesh [3].

In Abaqus simulations, properties such as tensile and compressive strength can be evaluated. Considering that the studies and research in the literature generally do not address all these simulations, it is necessary to search for different works to assess the effect of varying viscosity values on concrete's tensile and compressive strength properties. It has been reported that the viscosity parameter is used for the visco-plastic regularization of the concrete constitutive equation in the Abaqus/Standard analysis, whose default value is zero [4], and affects the accuracy of the simulation results and convergence; therefore, in a study carried out with modeling in Abaqus by CDP, it was observed that the lower the viscosity coefficient, the greater the accuracy of the calculation result, but also the longer it takes, increasing the computational cost[5]. It has been pointed out that a high viscosity value (also called relaxation time) can lead to an overestimation of the tensile strength of concrete [3].

The authors [3] studied the influence of viscosity variation on CDP's tensile strength considering different viscosity values (0, 0.01, 0.001, and 0.0001). For a viscosity value equal to 0, an approximately vertical crack was observed along the entire notched cross-section of the sample, located in a line of elements, with the width of the damaged zone dependent on the finite element discretization. In this study, when increasing the viscosity value, changes were observed in the characteristics of the cracks and damage zones: For a value of 0.0001, a constant width of the damage zone was reported (approximately 5 mm); for higher viscosity values (0.001 and 0.01), a diffuse dispersion of the damage zone was observed, and for a viscosity value equal to 0.01, a circular damage zone was reported. Therefore, after the simulations, it was concluded that a damage zone spread across many finite elements is obtained using higher viscosity values, leading to a diffuse pattern of cracks and limiting their propagation. Furthermore, a recommended value of 0.0001 was reached for the viscosity parameter since using higher values could lead to cracking and damage patterns that do not correspond to reality.

In general, existing studies in the literature do not thoroughly address the effect of viscosity on tests such as compressive strength and tensile strength. Therefore, the primary objective of this work is to investigate this influence through a literature review, gathering data on the relaxation time (viscosity) used and its impact on structural behaviour. Additionally, the study aims to define the geometry of the elements to be analysed in the numerical model tests. The research also includes analyzing and calculating parameters used in the concrete damage plasticity (CDP) model, computational modeling using Abaqus software, and evaluating the results obtained. Ultimately, the main goal is also to understand the impact of viscosity on the compressive and tensile strength behaviour of concrete, which may influence the structural behaviour of reinforced concrete members such as beams, slabs, and columns.

2 MATERIAL AND METHODS

The methodology used consisted of three main stages: (i) Numerical simulation and (ii) Comparative study and analysis of results.

The geometries of the elements were based on these studies, and the CDP parameters used were consistent with those of the authors mentioned. For concrete density, a value of 2400 kg/m^3 was used following the standards set by ABNT NBR 8953: 2015 [6].

2.1 Numerical simulation of compression

In numerical modeling compression stresses, concrete's mechanical properties were inputted to create the stress versus strain curve, and the CDP constants were referenced from Oliveira [1]. As the element's geometry, a 3D cylindrical model with dimensions of 100 mm in diameter and 200 mm in height was used.

Table 1 Mechanical properties of conventional concrete for compression test – Adapted of Oliveira [1]

Average compressive strength (f_{cm}) (MPa)	Average tensile strength (f_{tm}) (MPa)	Modulus of elasticity (E_c) (MPa)
35.7	2.7	32,288.0

To establish the stress and strain curves in both compression and tension and characterize the damage behaviour in the CDP, we employed the calculation model developed by Carreira and Chu [7], which is based on equations (1) and (2).

$$\sigma_c(\varepsilon_c) = f_{cm}(\frac{\beta.\left({}^{\varepsilon_{cm}}/_{\varepsilon_{cl}}\right)}{\beta-1+\left({}^{\varepsilon_{cm}}/_{\varepsilon_{cl}}\right)^{\beta}} \quad (1)$$

$$\beta = \frac{1}{1-\frac{f_{cm}}{\varepsilon_{cl}.E_{ci}}} \quad (2)$$

Where:
ε_{cm} – tension corresponding to the compression force
ε_{cl} – strain corresponding to maximum compressive strength (f_{cm})
E_{ci} – Modulus of elasticity tangent
f_{cm} – Average compressive strength

Equation (3) was used to calculate the parameters of compression damage (d_c) [8].

$$d_c = 1 - \frac{\sigma_c}{f_{cm}} \quad (3)$$

σ_c – compression stress.

The values from Table 2 were used as input parameters in the CDP plasticity model to define the materials and perform calibration. This calibration depends on several factors, including the dilatancy angle (ψ), the eccentricity (e), the f_{bo}/f_{co} ratio, and the K_c coefficient. The boundary conditions were established with the loading applied along the upper cross-section of the cylindrical specimen. The base of the cross-section was selected as the support boundary condition, with the reference point set at the center of both bases of the 3D cylindrical sample.

Table 2 Input parameters in Concrete Damage Plasticity - Adapted of Oliveira [1]

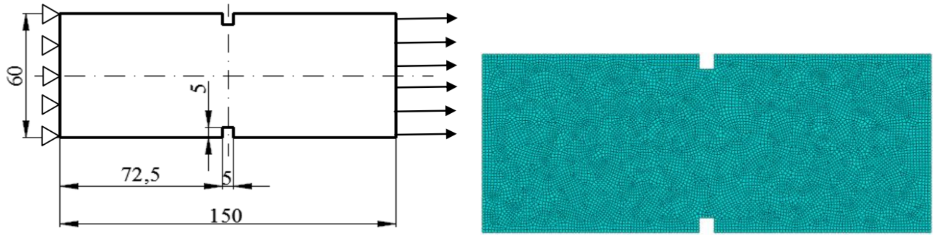
ψ	e	f_{bo}/f_{co}	K_c
38°	0.1	1.16	0.6667

2.2 Numerical simulation of traction

The work of Szczecina and Winnicki [3] was used as a basis for the mechanical properties of concrete in the tensile test model (Table 3). A 2D beam model was created, with a height of 60 mm, a length of 160 mm, and a notch of 5 mm at the top and bottom as shown in Fig. 1-a. The boundary conditions were defined as two-restraint supports on the left corner and linearly distributed loading on the right corner (Fig. 1-a). A finer mesh was required for the numerical model than the compression model. Therefore, a mesh size of 1 mm was determined in the CPS4R model (Fig. 1-b). The values used in calibrating the plasticity of the CDP for the tensile test were the same as those used in the compression test (Table 3).

Table 3 Mechanical properties of conventional concrete for traction test - Adpated of Szczecina and Winnicki [3]

Average compressive strength (f_{cm})	Modulus of elasticity (MPa) (E_c)	Poisson coefficient
40	35,000.0	0.2



a) Geometric representation with boundary conditions and loading

b) Representation of the CPS4R model mesh

Fig. 1 2D beam model for tensile testing. Units: mm. Adapted from [3].

The tensile stress-strain behavior of concrete was simulated based on the Hordijk [9] model, which considers the fracture energy (G_f). The expression proposed by *fib* Model Code (2010) [10] was used to calculate the fracture energy, which was calculated according to Eq. 4. The fracture energy of concrete is the energy needed to propagate a crack in a concrete structure. It is defined as the energy required to create one unit area of a crack.

Once the fracture energy was determined, the tensile stress-crack opening relationship was calculated according to equation (5) by Fib Model Code (2010) [10].

$$G_F = 73 f_{cm}{}^{0.18} \tag{4}$$

G_F – fracture energy
f_{cm} – average compressive strength.

$$\sigma_t(w) = f_{tm}\left\{\left[1+\left(c_1\frac{w}{w_c}\right)^3\right]e^{-c_2\frac{w}{w_c}} - \frac{w}{w_c}(1+c_1{}^3)e^{-c_2}\right\} \tag{5}$$

Where:
w – crack width (mm) according to fracture energy.
$c_1 = 3$ and $c_2 = 6{,}93$ are fixed values (determined by regression analyses with experimental test results) in the tensile stress-crack opening displacement model from Hordijk [9].
$w_c = 5.14 \cdot \frac{G_f}{f_{tm}}$ is the critical crack opening (corresponding to a residual tensile strength equal zero)
$f_{tm} = 0.3 \cdot f_{cm}{}^{2/3}$ is average concrete tensile strength

Next, the calculation of the damage equation proposed by Yu [8] was included, following the traction parameters as outlined in equation (6).

$$d_t = 1 - \frac{\sigma_t}{f_{tm}} \tag{6}$$

σ_t – tensile stress.

2.3 Viscosity values used in the parametric analyses

The simulation of the tensile and compression tests in the numerical model was extrapolated by changing the viscosity parameters of concrete in the CDP. The viscosity values chosen for the analysis were determined based on bibliographical references and are presented in Table 2. These values were compared with a model with a viscosity equal to zero.

Table 4 Viscosity reference used

Reference of values	Viscosity
Value defined by the authors	0
SANTOS et al. [11]	0.00001
SZCZECINA e WINNICKI [3]	0.0001
	0.001
	0.01
WOSATKO et al. [12]	0.002

3 RESULTS AND DISCUSSION

3.1 Numerical simulation of compression test

Based on the simulation conducted in Abaqus, it was able to create a graph illustrating the stress-strain behavior for the various viscosity parameters analyzed in this study (Fig. 2). The maximum compressive stress values obtained were as follows: 28.3 MPa for zero viscosity (equal to the input value), 28.5 MPa for viscosity 0.00001, 29.4 MPa for viscosity 0.0001, 35.0 MPa for viscosity 0.001, 39.2 MPa for viscosity 0.002, and 63.0 MPa for viscosity 0.01.

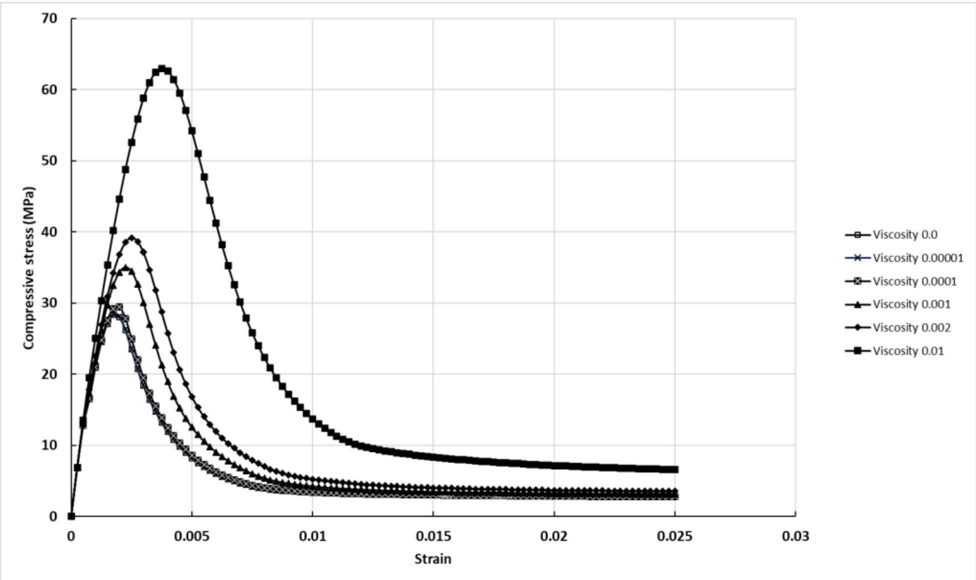


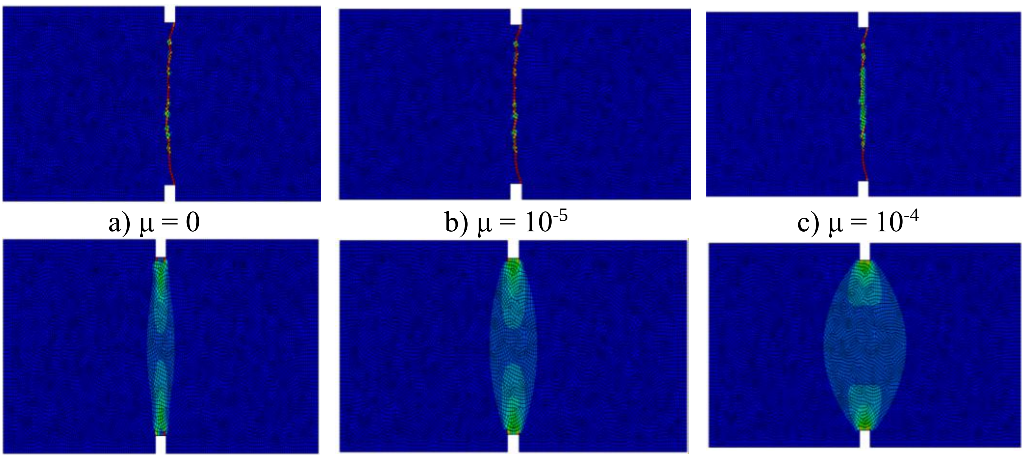
Fig. 2 Measured compressive stress-strain behavior in the numerical models according to the viscosity value.

According to the results obtained, it is possible to verify that the changes observed in the damage distribution for values starting from 0.001 are also noticeable in the stress × deformation behavior since from a viscosity of 0.001, it is possible to notice a more significant difference in the maximum stress value. Therefore, a significant increase in compressive strength was observed when the viscosity parameter increased from 0.0001 to 0.001 and, even more noticeable when this value increased from 0.002 to 0.01. In addition, for all viscosity values, a higher residual compressive strength was observed by increasing the viscosity value. Therefore, the viscosity parameter influences the stress-strain behavior of the CDP in the case of compression, with an increase in compressive strength and increased post-peak residual compressive strength for viscosity values higher than 0.0001.

3.2 Numerical simulation of tensile test

The results presented for the tensile study refer to the calibration of the model considering the CDP, according to the study's parameters used as reference [3]. Therefore, the distribution of tensile damage, the distribution of tensile plastic strains in the specimen and the stress-strain behavior were evaluated for each viscosity value studied. According to Fig. 3, it is possible to observe that, as the viscosity value increases, the area of influence of the damage is more significant. When analyzing Fig. 3-a and 3-b, it is impossible to point out a substantial difference in the damage area. This perception appears in Fig. 3-c, but becomes noticeable from Fig. 3-d onwards. In Fig. 3-d, it can be seen that the damaged area begins to spread in the middle of the simulated beam, while its ends remain with significant damage, with a width of 1 to 5 mm. Furthermore, for Fig. 3-d, 3-e, and 3-f, it is noted that the dispersion of the damage area increases as the viscosity value increases.

Another point to highlight is that by observing the results obtained for the initial modeling, one can see the evident presence of a crack along the entire section of the notch of the model.



a) $\mu = 0$ b) $\mu = 10^{-5}$ c) $\mu = 10^{-4}$

d) $\mu = 10^{-3}$ e) $\mu = 2 \cdot 10^{-3}$ f) $\mu = 10^{-2}$

Fig. 3 Representation of tensile damage of the numerical model.

Based on the simulation performed in Abaqus, it was possible to create a graph showing the stress-strain behavior for the viscosity parameters analyzed in the present study, reaching maximum stress (tensile) values of 3.52 MPa (zero viscosity), 3.53 MPa (viscosity 0.00001), 3.56 MPa (viscosity 0.0001), 3.67 MPa (viscosity 0.001), 3.76 MPa (viscosity 0.002) and 4.19 MPa (viscosity 0.01). In addition, to compare the results, the curves obtained for the stress-strain behavior in the case of the numerical tensile model were plotted on the same graph for the viscosity values studied in the present work, as shown in Fig. 4.

According to the results obtained, it is possible to verify that the changes observed in the distribution of damage and tensile plastic strains for viscosities above 0.001 are also noticeable in the tensile stress-strain behaviour (Fig. 4).

In practice, the results indicate that increasing the viscosity parameter above 0.001 may increase the concrete tensile strength effectively considered in the numerical model and overestimates the residual post-peak tensile strength compared to the correct value (related to a viscosity equal 0). Besides, as the residual concrete tensile strength may have a significant influence on problems where the concrete tensile strength play a key influence (for example, the shear capacity of reinforced concrete members without stirrups), in practice, values of viscosity above 0.00001 could also be considered inappropriate.

In other words, it shall be noted that the tensile stress-strain behaviour inputed in the numerical model would be the one with the viscosity equal zero. Therefore, the results from viscosity zero is the one that may be considered as the correct ones. Any changes observed in the residual tensile stress-strain behaviour or concrete tensile strength due to an increased viscosity value may be considered errors included in material behaviour that may impact the structural behaviour of the simulations.

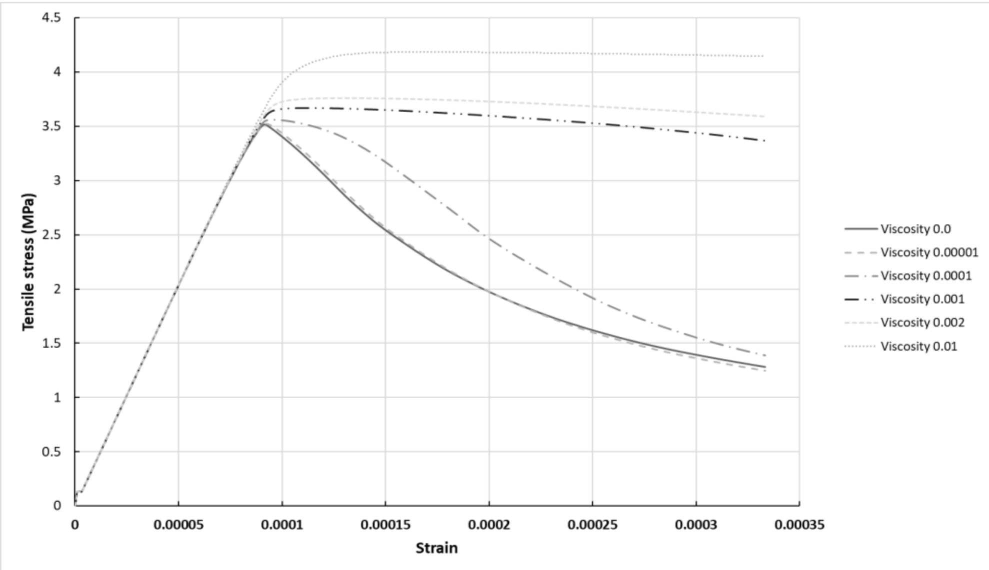


Fig. 4 Tensile stress-strain behavior measured in the simulations varying the viscosity parameter.

4 CONCLUSIONS

The results of this research enabled valuable insights into the behavior of the analyzed model, highlighting the following conclusions:

- The viscosity parameter significantly influenced the stress-strain behavior in compression and tension. Viscosity values above 0.001 are associated with increased compressive and tensile strength, indicating a sensitivity of the CDP model to this parameter.
- Significant differences between the input data (informed) and output (measured in the numerical results) may appear according to the viscosity parameter value in tensile test simulations. This behavior was noted when viscosity values started at 0.001, suggesting a potential inconsistency in the numerical model for these viscosity values.
- A correlation was observed between the viscosity value and the concrete damaged area in the tensile test simulation. Specifically, the damaged area increased as viscosity increased. Additionally, it was noted that higher viscosity led to more diffuse damage zones. For a viscosity value of 0.01, the damage zone began to take on a circular shape. However, this pattern of

cracks and damage does not accurately reflect real behavior and using values greater than 0.0001 is not recommended.

- Therefore, we recommend using values of viscosity below 0.0001 to limit the influence of viscosity in the compressive and tensile behavior effectively considered in the simulations. In other words, the use of higher values of viscosity may introduce changes in the effective compressive and tensile strengths and residual post-peak strength. Besides that, using low viscosity values is also recommended to improve the accuracy in predicting the cracking pattern, as higher viscosity values also influence the concrete damaged area in the simulations.

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