

A systematic method for determining RHT material model parameters for concrete using experimental tests and numerical simulations

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Received: 09/13/2025 Revised: 01/26/2026 Accepted: 08/03/2026

Abstract

This paper presents a systematic and comprehensive method for determining, calibrating, and validating the parameters of the RHT behavioral model for concrete. The proposed method is based on the integration of extensive experimental data including uniaxial, triaxial, Brazilian and dynamic compression tests with advanced numerical simulations developed in LS Dyna software. Important model parameters, especially damage parameters such as D1, D2 and EPM, which are very challenging to determine analytically, were optimized through an iterative and systematic calibration process. Simulations were performed using a Lagrangian solver, with cubic elements and the RHT behavioral model with the obtained parameters. The difference in the results from the tests and simulations showed that there is a good correlation between them, such that the difference in the results in the uniaxial compression test for the axial and lateral stress-strain curves is below 3% and 7%, respectively, in the triaxial compression test it is about 10% and in the Brazilian tensile test it is 3.26%.

Keywords: RHT material model, concrete, calibration, numerical simulation, validation.

1. Introduction

Concrete, as the most widely used construction material, has complex mechanical behavior under various loadings. A detailed understanding of the nonlinear behavior of concrete under such loadings is necessary for the safe design of structures against blast, impact, and penetration. This nonlinear behavior is caused by several factors such as structural heterogeneity, microcrack formation, strain rate effects, and progressive fragility. Concrete behavior models describe the relationship between stress and strain, fragility, cracking, and failure. In recent years, significant progress has been made in the development of concrete behavior models, from classical models such as the elastoplastic model to advanced damage and microstructure-based models. However, the main challenge is to determine the correct parameters for these models, which are usually obtained from experimental tests, numerical methods, or a combination of both. Various factors such as material properties, environmental conditions, and type of loading affect these parameters. To accurately model the behavior of materials, aggregates, and engineering structures, accurate and correct models are needed over a wide range of strain rates [1]. For this purpose, models have been developed for brittle and semi-brittle

materials such as stone, concrete, and ceramics.

In order to accurately simulate the response of concrete under static, dynamic, and impact loads, it is essential to use advanced material models such as Johnson-Holmquist, Karagozian and Case, and Riedel et al. However, the accuracy of these models is highly dependent on the correct determination of the behavioral model parameters through experimental tests and numerical calibration methods.

The RHT behavioral model, by considering the effects of compressibility, fragility, and strain rate effects, is capable of accurately predicting the response of concrete under severe loading conditions. In this research, the aim is to provide a method for determining the parameters of the RHT behavioral model for simulating concrete engineering problems, especially problems involving damage, high strain rates, and high stresses. Determining the parameters of the RHT behavioral model for concrete is a challenging task.

This requires numerous experimental tests. Some parameters are difficult, if not impossible, to determine by experiment alone. This paper presents a complete process based on experimental data, experimental tests, and numerical simulations to minimize assumptions and approximations. In addition, iterative calibration allows the inference of damage parameters. The

accuracy and validity of these parameters are then verified using LS Dyna software under different loading conditions and strain rates.

2. Methodology

2.1. RHT behavioral model

The RHT behavioral model has been developed for brittle and semi-brittle solids such as concrete. This structural model is implemented in software such as LS Dyna and consists of three equations: strength, state, and damage equations. The RHT behavioral model is a strain rate dependent structural model [2].

2.1.1. Strength model

The RHT behavioral model consists of three procedures, namely, the elastic limit procedure, the failure procedure, and the residual strength procedure. These procedures are shown in Figure (1).

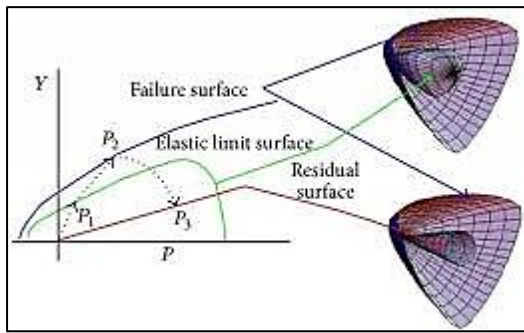


Figure 1. RHT Strength Model

The general formulation of the failure surface of the RHT material model is given in Eq. 1 [2]:

$$\sigma_f = \sigma_f(p, \theta, \dot{\epsilon}_p) = f_c \sigma_f^* \left(p^*, F_R(\dot{\epsilon}_p, p^*) \right) R_3(\theta, p^*) \quad (1)$$

where σ_f represents the maximum strength of material at different effective plastic strain rates $\dot{\epsilon}_p$ lode angles θ and pressures p . p^* is the pressure normalized with uniaxial compressive strength f_c . σ_f^* is the failure surface obtained from the triaxial compressive stress. F_R is the strain rate-dependent factor. $R_3(\theta, p^*)$ which depends on lode angle and pressure and can be calculated using the William-Warnke formulation.

The strength value is interpolated between the initial elastic limit surface and the failure surface as given Eq. 2 [2]:

$$\sigma_y(p, \theta, \dot{\epsilon}_p) = f_c \sigma_f^* \left(\frac{p^*}{\gamma}, F_R(\dot{\epsilon}_p, p^*) \right) R_3(\theta, p^*) \gamma \quad (2)$$

where σ_y is the yield surface and γ is a factor to interpolate the yield surface between the initial elastic limit surface and the failure surface.

The residual surface is the last RHT strength model surface. Residual surface does not depend on strain rate and lode angle, despite failure and elastic limit surfaces.

The formulation of the residual surface is given by Eq. 3 [2]:

$$\sigma_r^*(p^*) = \begin{cases} A_f p^{*n_f} \rightarrow (p^* > 0) \\ 0 \rightarrow (p \leq 0) \end{cases} \quad (3)$$

Where σ_r^* expresses the residual failure surface, which depends only on pressure. A_f and n_f are the RHT material parameters to manifest the residual surface.

2.1.2. Damage model

Damage parameter D has been defined in order to interpolate the strength value between the residual and failure surfaces. The damage parameter is calculated by Eq. 4 [2]:

$$D = \sum \frac{\Delta \epsilon_p}{\epsilon_p^f} \quad (4)$$

where $\Delta \epsilon_p$ is the plastic strain during a cycle of integration and ϵ_p^f is the pressure-dependent allowable plastic strain according to Eq. 5 [2]:

$$\epsilon_p^f = \max(D_1(p^* - (1 - D)p_t^*)^{D_2}, \epsilon_p^m) \quad (5)$$

where ϵ_p^m is a minimum allowable plastic strain and p_t^* is Huguenot Tensile Limit (HTL). D_1 and D_2 are damage parameters. According to Eq. 5, damage has been defined as normalized accumulated strains, and it varies from 0 to 1, which are for failure and residual surface, respectively.

2.1.3. Equation of state model

Equation of state of the RHT material model is plotted in Fig. 2. This EOS comprises two general formulations to describe the behavior of rocklike materials in tension and compression over a huge range of pressure values, as given by Eqs. 6 and 7, respectively [2]:

$$p = \frac{1}{\alpha} [B_0 \alpha \rho e + T_1 \mu + T_2 \mu^2] \quad (6)$$

$$= \frac{1}{\alpha} [(B_0 + B_1 \mu) \alpha \rho e + A_1 \mu + A_2 \mu^2 + A_3 \mu^3] \quad (7)$$

where $\mu(\rho) = \frac{\alpha \rho}{(\alpha_0 \rho_0)} - 1$ and $A_1, A_2, A_3, B_0, B_1, T_1$ and T_2 are the material parameters and polynomial coefficients of the equation of state in the RHT material model.

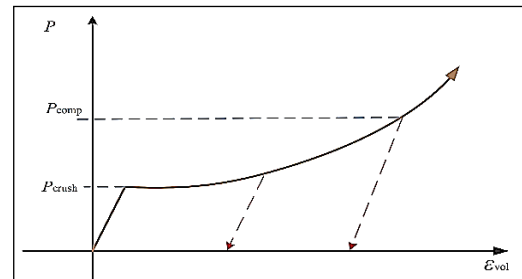


Figure 2. EOS of RHT material model

2.2. Tests performed in this study

2.2.1. Determine of Physical properties of produced concrete

The samples were cored from a large block of manufactured concrete and then prepared according to the ISRM recommended methods and ASTM standards. The samples for uniaxial compressive strength (UCS), triaxial compressive strength (TCS) and Brazilian tensile strength (BTS) tests were 54 mm in diameter and had slenderness ratios (L/D) of 2.5, 2 and 0.5 respectively [3]. Concrete samples were prepared at the Faculty of Civil Engineering, Imam Hussein University (AS) with a strength of 35 MPa. These samples were stored for 28 days in water at a temperature above 4°C. The physical properties of the produced concrete are listed in Table (1).

Table 1. Physical properties of produced concrete

Physical properties	amount
Density (gr/cm ³)	2.32
Dry density (gr/cm ³)	2.30
Pressure wave speed (m/s)	4122.1
Shear wave speed (m/s)	2400.8
Average compressive strength (MPa)	35.33

2.2.2. Uniaxial and triaxial compressive strength tests

They were used for uniaxial and triaxial compressive strength tests under different confining pressure values. The produced concrete has an elastic modulus of 22.8 GPa and a Poisson's ratio of 0.14. The stress-strain curve of the uniaxial strength test is plotted in Figure (3). The results of the triaxial strength test apparatus under four confining pressures are presented in Table (2).

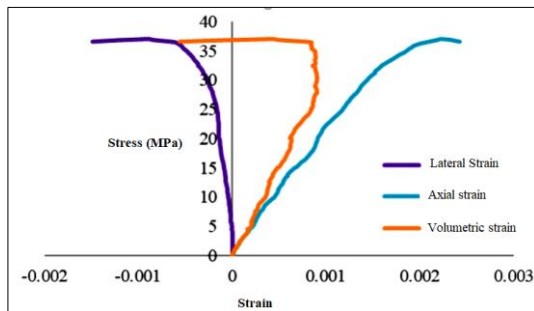


Figure 3. Stress-strain curve of uniaxial and triaxial tests

Table 2. results of the triaxial strength test

Sample	σ_1 (MPa)	σ_3 (MPa)	Strain Rate (10 ⁻⁶ s ⁻¹)
1	0	36.2	2.1
2	5	68.3	2.5
3	10	82.2	2.9
4	15	102.3	3.5
5	20	122.7	4.5

In this study, three Brazilian tests were conducted using disc-shaped concrete specimens (NX core size).

2.2.3. Brazilian tensile strength test

In this study, three Brazilian tests were conducted using disc-shaped concrete specimens (NX core size).

2.2.4. Brazilian dynamic test with Hopkinson pressure bar

The Hopkinson pressure bar is a system for measuring the dynamic behavior of materials. The ISRM recommends that the dynamic tensile strength of minerals be obtained using the Brazilian method with the Hopkinson apparatus. In this study, three Brazilian Hopkinson experiments were performed with three cylindrical specimens with a diameter of 37 mm and a thickness of 18 mm. Copper disk pulse shapers were used to reduce the slope of the incident wave and increase the impact time. The prepared specimen is shown in Figure (4). By using the pulse shaping method, a rectangular pulse wave can be transformed into a ramp pulse.



Figure 4. Brazilian Hopkinson test sample

The results of three Brazilian dynamic tests on manufactured concrete are listed in Table (3).

Table 3. Brazilian Hopkinson test results

Sample	Impact speed (m/s)	Stress rate (GPa/s)	Tension (GPa)	Increase Factor
1	13.378	478.67	3.8	3.47
2	9.996	402.11	3.6	2.39
3	9.06	388.30	3.3	2.22

2.2.5. Numerical simulations on concrete samples

In this study, LS-Dyna software with explicit and Lagrangian solution methods was used in the simulations. Figure (5) shows the modeling, meshing, and application of initial and boundary conditions in concrete specimens with a strength of 35 MPa with dimensions of 150 mm diameter and 300 mm height for simulating uniaxial and triaxial tests. It should be noted that concrete specimens with a diameter of 37 mm and a thickness of 18 mm were used for simulating the Brazilian test.

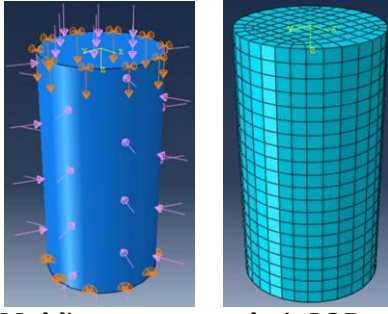


Figure 5. Modeling concrete samples in LS Dyna software

In this study, three Brazilian tests were conducted using disc-shaped concrete specimens (NX core size).

3. Results and Discussion

3.1. Determination of strain rate coefficients of RHT model parameters for concrete

Hopkinson compressive strength data from various papers have been collected to investigate the strain rate dependent parameters of the RHT behavioral model with respect to the dynamic compressive and tensile to static compressive strength of concrete, Figures (6) and (7). By fitting the curve to these data, from Figure (6) the compressive strain rate coefficients $\beta_c=0.01696$ and $\gamma_c=0.3213$ and from Figure (7) the tensile strain rate coefficients $\beta_t=0.0379$ and $\gamma_t=1.551$ are obtained.

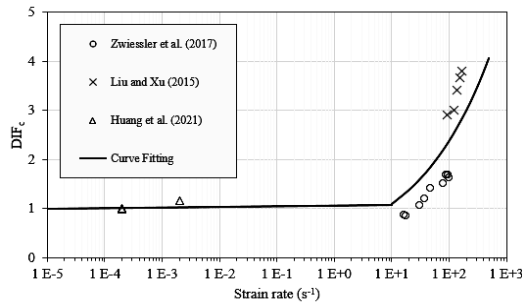


Figure 6. Determination of DIF_c quantities of concrete by the curve crossing method and using data from Papers [4, 5 and 6]

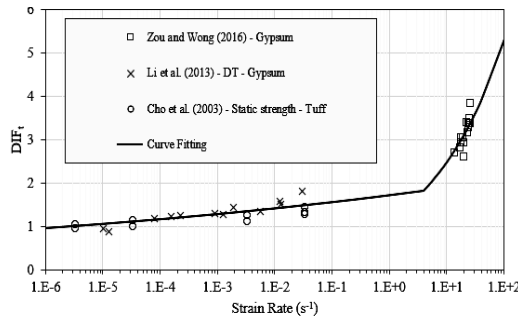


Figure 7. Determination of DIF_t quantities of concrete by the curve crossing method and using data from articles [7, 8 and 9]

3.2. Strength equation parameters

The strength parameters of the RHT behavioral model can be extracted from the results of the triaxial compressive strength test. The results of the triaxial compressive strength test with different measured strain rates can be used to determine the coefficients dependent on the load angle quantity in the RHT behavioral model damage surface equation. The RHT behavioral model considers the transition behavior from brittle to ductile state of concrete using Equation. Therefore, according to the results of the triaxial test of concrete, the compressive and tensile meridian ratio of the failure surface for concrete for different stress values has been calculated in Figure (8) to determine the values $Q_0 = 0.5436$ and $B = 0.0488$.

The RHT behavioral model uses equation (3) to determine the failure mode constants (A and n) at different pressures. These constants are obtained from triaxial compression tests, but in this paper, these constants are obtained from data from various papers and curve fitting on these data. These parameters are determined based on the data obtained from the triaxial compression tests of concrete, which are shown in Figure (9) as $A = 2.236$ and $n = 0.481$, respectively. Figure (10) shows how to obtain the residual surface coefficients (A_f and n_f) by the calibration method using numerical simulations. In this method, by keeping one of these parameters constant and changing the other, a failure pattern can be qualitatively achieved that is consistent with the laboratory tests.

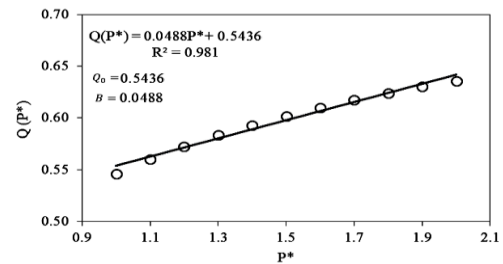


Figure 8. Compressive meridian of the failure surface of the concrete RHT model

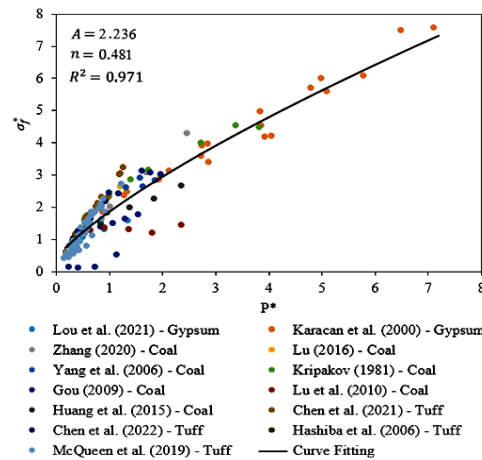


Figure 9. Determination of failure mode constants by the curve crossing method and using data from articles [10 to 17]

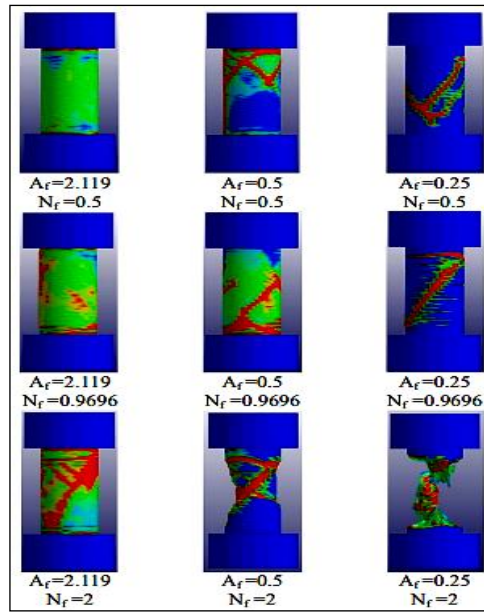


Figure 10. Residual resistance calibration

3.3. Parameters of the equation of state

According to Figure (11), the values of C_0 and S for concrete were determined by fitting a curve between the shock data. In the present study, the values of the fitted curve for the manufactured concrete are $C_0 = 4.770$ km/s and $S = 2.81$.

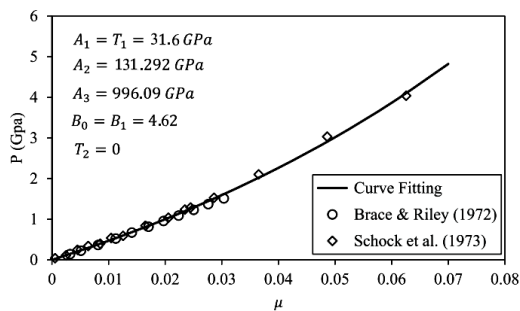


Figure 11. Curve fitted for concrete shock data

4. Conclusions

This paper presents a comprehensive method for determining the parameters of the RHT behavior model for concrete. This method involves conducting experimental tests, using data available in scientific literature, and numerical calibration to determine the physical properties, compressive and shear strengths, and load angle-dependent parameters, strain rate parameters, and failure mode coefficients, and equation of state parameters. The residual strength and damage parameters of the model are also calibrated through an iterative process using numerical simulations. This calibration ensures the accuracy of the model by comparing simulation results with experimental data. To validate the model, a comparison is made between the measured data from various tests, including uniaxial compressive strength, triaxial compressive strength, Brazilian tensile strength and Brazilian dynamic tests, and the numerical

simulation data generated using the LS Dyna code. The results of these comparisons confirm the ability of the model to accurately predict the behavior of concrete under compression and tension, for both dynamic and static loading conditions. The findings also highlight the effectiveness of the RHT behavioral model in predicting the behavior of concrete under different loading conditions and demonstrate its versatility in practical applications. The axial and lateral stress-strain curves obtained from numerical and experimental results in uniaxial compression test are in good agreement with the numerical results, so that the maximum difference in the results in the axial and lateral stress-strain curves is 3 and 7 percent, respectively. The maximum difference between the results of the triaxial compression test and the results of numerical simulations is about 10 percent. On the other hand, it was determined that the tensile strength of concrete was measured experimentally as 3.05 MPa and simulated as 15.3 MPa in the numerical model. Therefore, the difference between the numerical and experimental results is 2.3 percent.

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