Non-linear finite element analysis of self-compacting concrete with granite stone dust and stone-polishing dust

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Abstract

The present study focused on simulating the behavior of self-compacting concrete incorporated with granite stone dust (GSD) as a partial replacement of natural sand and stone-polishing dust (SPD) and silica fume (10%) replacing the ordinary Portland cement. The experimental test results revealed a maximum compressive strength at an optimum dosage of 15% GSD, 10% SPD and 10% SF. The concrete damaged plasticity modelling parameters were successfully estimated the compressive and split-tensile strengths of self-compacting concrete.

Keywords: Self-compacting concrete, granite stone dust, stone polishing dust, concrete damaged plasticity.

1. Background

The Concrete Damaged Plasticity (CDP) model is a robust constitutive approach used in finite element simulations to accurately represent the complex mechanical behavior of concrete structures. Designed to handle the challenges of concrete's non-linear response, CDP has demonstrated its effectiveness in simulating the deformation and damage patterns that occur under different loading conditions. The primary features of the CDP model are outlined below.

- **Post-Cracking Behavior**: CDP is particularly effective in modeling the behavior of concrete after cracks have formed. As concrete is subjected to loading, cracks can initiate and spread, altering the structural integrity. CDP accurately simulates these post-cracking events, offering a realistic depiction of concrete’s response under such conditions.
- **Damage Accumulation**: The model also accounts for the progressive accumulation of damage within the concrete. This feature is essential for capturing the deterioration of mechanical properties, especially under cyclic loading or sustained stress.
- **Versatility in Non-Linear Responses**: CDP excels in handling non-linear material responses, making it ideal for simulating concrete under various loading conditions. This versatility is crucial for capturing the complex behavior of concrete, including plastic deformation, cracking, and damage accumulation.

- Concrete Damaged Plasticity (CDP) is highly effective in modeling the behavior of conventional concrete, offering valuable insights into its mechanical responses under various loading conditions. Key aspects include:

1. **Post-Cracking Behavior**: CDP excels in simulating the post-cracking response of conventional concrete. When subjected to tensile forces, cracks may form and spread, affecting structural integrity. CDP accurately represents this post-cracking behavior, providing a realistic depiction of the material's performance.
2. **Damage Accumulation**: The model effectively captures the gradual accumulation of damage within the concrete structure. This is essential for understanding how the material's properties degrade over time, especially under cyclic loading or prolonged stress, giving a comprehensive view of its long-term durability.
3. **Non-Linear Responses**: CDP is well-equipped to handle the non-linear material behavior typical of conventional concrete. This includes its ability to simulate plastic deformation, crack formation, and damage progression, offering a detailed representation of the material's complex response under varying load conditions.
4. **Parameterization and Calibration**: CDP can be finely tuned through careful parameterization and calibration to match the specific properties of different conventional concrete mixtures. This flexibility ensures that the model can accurately predict structural behavior, tailored to the particular characteristics of the concrete being analyzed.
5. **Insights into Structural Performance**: CDP provides important insights into the overall structural performance of conventional concrete elements. By incorporating realistic material behaviors, it helps predict key factors such as load-bearing capacity, deformation patterns, and potential failure modes, which are crucial for structural design and evaluation.
6. **Applicability in Finite Element Analysis**: CDP is particularly well-suited for finite element analysis of conventional concrete structures. Its ability to simulate complex phenomena such as concrete crushing, cracking, and post-critical behavior enhances the precision of structural simulations.

In summary, the Concrete Damaged Plasticity model is a powerful tool for simulating conventional concrete behavior. Its capabilities in replicating post-cracking behavior, accounting for damage accumulation, handling non-linear responses, and adapting to different concrete formulations make it invaluable for predicting and understanding the performance of concrete structures under various loading conditions.

2. Parameters of CDP

Dilation Angle (ψ): This parameter influences how much the material expands or contracts during plastic deformation, affecting the overall material response under load.

Eccentricity (e): Eccentricity reflects the off-center application of loads, impacting the distribution of stresses and the material's behavior under complex loading.

Shear Stiffening Parameter (k): Governing shear behavior, this parameter controls how quickly the material stiffens under shear stress, crucial for accurate modeling of shear-related phenomena.

Biaxial to Uniaxial Compression Strength Ratio (fbo/fco): This ratio determines when cracking initiates by comparing biaxial and uniaxial compression strengths, playing a key role in early failure prediction.

Viscosity (η): Viscosity introduces rate-dependent behavior, accounting for the material's resistance to rapid deformation, especially under dynamic loads.

Tension-Stiffening Parameters (α, β): These parameters define the material's tensile behavior after cracking, ensuring accurate modeling of post-cracking tensile response.

Damage Parameters (D1, D2, D3...): These parameters track material degradation during loading, affecting the reduction in stiffness and strength, and are vital for simulating long-term behavior.

These CDP model parameters are crucial for accurately simulating concrete's mechanical behavior, aligning the model closely with experimental and real-world data.

3. Numerical analysis using ABAQUS

ABAQUS is a computational tool for the finite element modelling process created by Dassault Systems, ABAQUS excels in addressing large deformations, complex contact interactions, and non-linear material behavior. Its adaptability makes it well-suited for incorporating experimental data into detailed numerical simulations, facilitating a strong connection between empirical results and computational studies (ABAQUS Analysis User's Manual, 2021). In this article, ABAQUS was used to simulate the concrete material behavior under various loading conditions such as compression, tension and flexure using an inbuilt Concrete Damaged Plasticity (CDP) model.

4. Calibration procedure

Incorporating experimental data into the finite element model is a vital process to ensure the accuracy and reliability of simulations. This step involves defining material properties such as stress-strain curves, tensile strength, and elastic modulus based on empirical data. By following established standards, like those outlined in ISO guidelines, the model is closely aligned with the actual behavior observed in lab tests. This careful integration provides a robust basis for further analysis, as evidenced by studies conducted by Robertson and Wang (2000) and Lee et al. (2015).

The calibration of the Concrete Damaged Plasticity (CDP) model involves an iterative process where parameters like dilation angles, eccentricity, viscosity, failure criteria, and shear properties are systematically refined. This process uses a trial-and-error approach informed by studies such as those by Smith and Johnson (1995) and Garcia and Martinez (2017). The goal is to reduce the differences between the model's predictions and experimental results. By meticulously adjusting these parameters, the calibrated CDP model attains a higher level of accuracy, enabling it to reliably simulate concrete behavior under various loading conditions (Smith and Johnson, 1995; Garcia and Martinez, 2017).

5. Validation Against Experimental Results

Validating the finite element model against experimental results is essential for confirming its credibility. This section provides an in-depth analysis of how the refined CDP model compares to benchmarks established by experimental data. The validation process is guided by insights from studies like Miller and Foster (2017) and Wang et al. (2018), ensuring that the numerical simulations closely match real-world observations. The strong correlation between the model's predictions and the experimental data highlights the accuracy and reliability of the finite element model, particularly in modelling the complex behavior of forces in self-compacting cement concrete.

6. Results and Discussions

In this study, cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in height were prepared and cured in water for 28 days. After the curing period, these specimens were subjected to axial compressive loading until failure, with the compressive strengths recorded. The average compressive strength was then used to calibrate the concrete damaged plasticity (CDP) parameters. Additionally, the specimens were loaded to 40% of the average peak load to determine the elastic modulus, which was also used for CDP calibration. The average 28-day split-tensile strength of the self-compacting concrete, which contained 15% granite stone dust, 10% silica fume, and 10% stone-polishing dust, was recorded as 3.78 MPa.

The compressive strength results for the cylindrical specimens were 35.4 MPa, 33.2 MPa, and 34.1 MPa, yielding an average of 34.2 MPa. Similarly, the elastic modulus values were found to be 32.1 GPa, 29.2 GPa, and 33.0 GPa, with an average of 31.4 GPa. For the analysis, a peak strain of 0.0003 corresponding to the compressive stress of 34.2 MPa was assumed. The stress-strain curve of the hardened SCC was derived using Popovics' 1973 empirical equation. The tensile stress and cracking displacements were calibrated using a trial-and-error approach to align with the experimental results for compressive strength, elastic modulus, and split-tensile strength.

6.1 Non-linear finite element modelling of hardened self-compacting concrete

In the present study, the material behavior under compression and indirect tension is used for calibrating the CDP-parameters for hardened concrete with GSD, SPD and SF. Further, the elastic properties are also presented. From the experimental tests, the results showed an average cylindrical compressive strength of 34.2 MPa, and an elastic modulus of 31.43 GPa and the corresponding calibrated CDP-parameters are presented in tables 1 and 2. The corresponding results showed a split-tensile strength of 3.78 MPa for a tensile strength of 2.75 MPa and a cracking displacement of 180 micrometres. The tensile damage in cylindrical specimen under compression is shown in figure 1.

Table 1 Elasticity and Plasticity Parameters for Non-linear behavior of self-compacted concrete

Type of property	Property	Value
Elastic	Elastic Modulus (GPa)	27.5
	Poison Ratio	0.15
Plasticity (CDP)	Dilation Angle	31
	Eccentricity	0.1
	fb0/fc0	1.16
	Viscosity Parameter	5e-6
	K	0.67

Table 2 Compressive Stress-Strain Data for self-compacting concrete

ε	**σ (MPa)**	**ε**	**σ (MPa)**	**ε**	**σ (MPa)**	**ε**	**σ (MPa)**
0.00000	13.7	0.00290	34.2	0.00490	26.4	0.00690	16.8
0.00100	16.8	0.00300	34.2	0.00500	25.9	0.00700	16.4
0.00110	18.4	0.00310	34.2	0.00510	25.3	0.00710	16.0
0.00120	19.9	0.00320	34.1	0.00520	24.8	0.00720	15.7
0.00130	21.4	0.00330	33.9	0.00530	24.2	0.00730	15.3
0.00140	22.8	0.00340	33.7	0.00540	23.7	0.00740	15.0
0.00150	24.2	0.00350	33.4	0.00550	23.1	0.00750	14.7
0.00160	25.5	0.00360	33.0	0.00560	22.6	0.00760	14.4
0.00170	26.7	0.00370	32.7	0.00570	22.1	0.00770	14.1
0.00180	27.8	0.00380	32.2	0.00580	21.6	0.00780	13.8
0.00190	28.9	0.00390	31.8	0.00590	21.1	0.00790	13.5
0.00200	29.8	0.00400	31.3	0.00600	20.6	0.00800	13.2
0.00210	30.7	0.00410	30.8	0.00610	20.2	0.00810	12.9
0.00220	31.4	0.00420	30.3	0.00620	19.7	0.00820	12.6
0.00230	32.1	0.00430	29.8	0.00630	19.2	0.00830	12.4
0.00240	32.7	0.00440	29.2	0.00640	18.8	0.00840	12.1
0.00250	33.2	0.00450	28.7	0.00650	18.4	0.00850	11.9
0.00260	33.5	0.00460	28.1	0.00660	18.0	0.00860	11.6
0.00270	33.8	0.00470	27.6	0.00670	17.6	0.00870	11.4
0.00280	34.0	0.00480	27.0	0.00680	17.2	0.00880	11.2
Note: ε = Inelastic strain, σ = compressive stress							

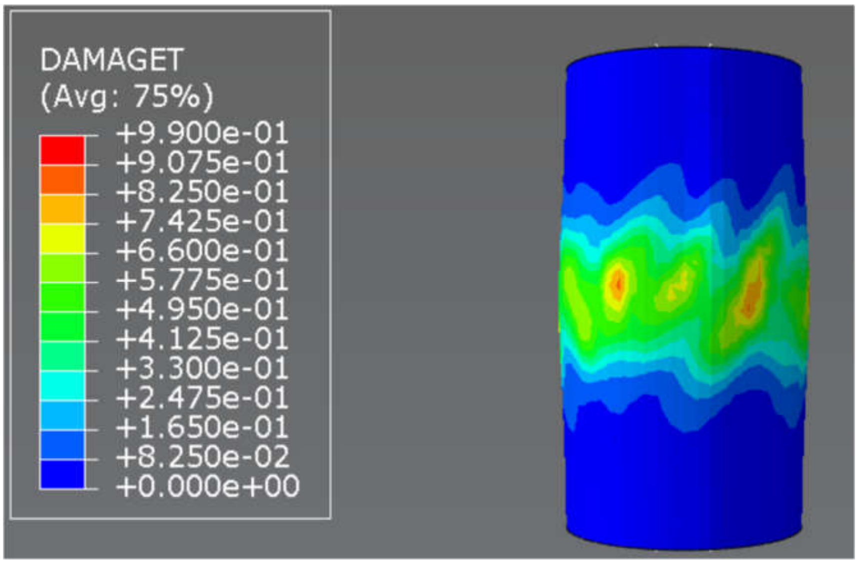

Figure 1 Tensile damage in concrete under uniaxial compression

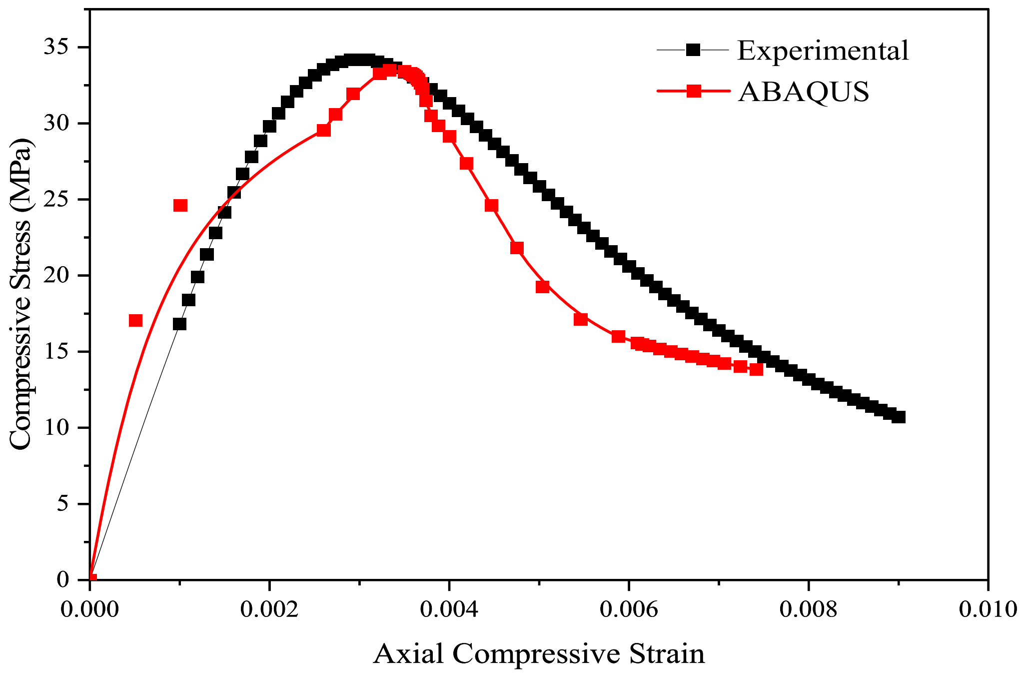

Figure 2 Stress-strain curves of cylindrical specimen under compression

The numerical simulations indicated a compressive strength of 33.5 MPa, with a deviation of 2.05% compared to the average compressive strength observed in the experimental study. Figure 2 illustrates the stress-strain curves derived from both ABAQUS simulations and the Popovics equation based on the experimental data. Additionally, the simulations revealed a split-tensile strength of 3.56 MPa, showing a 5.8% deviation from the experimentally measured value of 3.78 MPa. Given the close agreement between the numerical and experimental strength results, the corresponding CDP parameters are recommended for accurately predicting the behavior of reinforced self-compacting concrete that includes a 15% replacement of fine aggregates with granite stone dust, 10% stone-polishing dust, and 10% silica fume as a substitute for Portland cement.

7. Conclusions

In conclusion, the numerical simulations closely matched the experimental results, demonstrating the accuracy of the calibrated CDP parameters for predicting the behavior of reinforced self-compacting concrete. The compressive strength from simulations showed a minor deviation of 2.05% from the experimental average, while the split-tensile strength had a 5.8% deviation, indicating a strong correlation between the numerical and experimental findings. The calibrated CDP parameters effectively capture the material behavior under both compression and indirect tension, as evidenced by the stress-strain curves and tensile damage data. The use of granite stone dust, stone-polishing dust, and silica fume in the concrete mix was successfully modeled, with the results supporting the recommended CDP parameters. The presented data, including the elastic properties and tensile damage observations, confirm the model's reliability in simulating the mechanical performance of hardened concrete. Overall, this study provides a robust foundation for further analyses and the practical application of the CDP model in predicting concrete behavior.

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