MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

Submitted: December 19, 2025 Revised: February 19, 2026 Accepted: March 11, 2026

# Numerical simulation of flexural breaking load resistance tests in mortars with recycled polyethylene terephthalate

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**ABSTRACT**

This study investigates the flexural behavior of mortars modified with recycled polyethylene terephthalate through numerical simulations developed in SolidWorks Simulation using a linear dynamic approach. Prismatic specimens measuring 40 × 40 × 160 mm$^3$ with recycled polyethylene terephthalate contents of 10 and 20 % were evaluated under three temperature levels (20, 150, and 350 °C) and two curing conditions: ambient and water curing. A linear dynamic finite element model was developed in SolidWorks Simulation to reproduce the bending response and analyze the temporal evolution of Von Mises stresses, principal stresses, and stress distribution patterns. The numerical model incorporated experimentally determined mechanical properties and breaking loads as input parameters. The results indicate that increasing recycled polyethylene terephthalate content reduces the stiffness and load-bearing capacity of the mortar, particularly at elevated temperatures, due to the thermal softening of the polymer and the weakening of the interfacial transition zone. Water curing enhances mechanical performance by promoting matrix hydration and improving the capacity for stress redistribution, thereby mitigating the adverse effects of thermal exposure. The numerical simulations showed strong agreement with experimental observations and successfully captured the evolution of stress localization and failure mechanisms under different thermal and curing conditions. These findings highlight the combined influence of recycled polyethylene terephthalate content, curing regime, and temperature on the structural performance of modified mortars and confirm the suitability of linear dynamic finite element analysis for investigating bending behavior in polymer-modified cementitious materials.

**KEYWORDS**

RPET • bending • finite elements • sustainable mortars • thermal behavior • dynamic simulation

***Funding***. *This work was supported by San Pablo CEU University, Madrid, Spain, through the research project "Analysis of the Structural Behavior of Concrete Subjected to High Temperatures Manufactured with Recycled Materials to Obtain Sustainable Materials (MCP22VEM)", developed within the ARIE Research Group (Registration number: G20/6-06, San Pablo CEU University, Madrid, Spain).*

***Acknowledgements.*** *The authors gratefully acknowledge the technical support provided by the laboratory facilities of the Institute of Technology, San Pablo CEU University, Madrid, Spain. The authors also thank SEVELAR, Spain, for supplying the plastic waste used in this study.*

**Citation:** Maciá Torregrosa ME, Pinilla Hernandez MI, Camacho Diez J, Machín Hamalainen C, González Lezcano RA. Numerical simulation of flexural breaking load resistance tests in mortars with recycled polyethylene terephthalate. *Materials Physics and Mechanics*. 2026;54(2): 111–128.
http://dx.doi.org/10.18149/MPM.5422026_9

## Introduction

The construction sector faces environmental challenges due to its high consumption of natural resources and its contribution to greenhouse gas emissions. The implementation of circular economy strategies, including the reuse of plastic waste as construction materials, represents a promising approach to mitigating these environmental impacts.

Global plastic production has exceeded 380 million tons annually since 2020, generating large amounts of post-consumer waste that require sustainable management solutions [1]. The valorization of plastic residues in cement-based materials offers environmental benefits by reducing landfill disposal and decreasing the demand for natural aggregate extraction. Among plastic wastes, recycled polyethylene terephthalate (RPET) has attracted considerable attention as a potential partial substitute for fine aggregates in cementitious composites. Previous studies have shown that the incorporation of RPET influences the mechanical and fractured behavior of mortars and concretes [2,3]. In addition to modifying mechanical properties, environmental benefits have been reported, including reduced consumption of natural aggregates and lower indirect emissions associated with raw material extraction and processing. The compressive behavior of RPET-modified mortars has been widely investigated; their flexural performance has received comparatively less attention.

Flexural strength is a critical parameter in structural elements subjected to tensile stresses, particularly in slender components or those primarily exposed to bending loads. RPET exhibits a hydrophobic nature and a lower elastic modulus compared with conventional mineral aggregates, which may weaken the interfacial transition zone between the polymer particles and the cementitious matrix. Several studies have reported that increasing the RPET content leads to a reduction in flexural load-bearing capacity, particularly under tensile-dominated structural response conditions [3]. Curing conditions and thermal exposure significantly affect the mechanical performance of polymer-modified cementitious composites. Proper curing promotes cement hydration and matrix densification, whereas inadequate curing may increase porosity and reduce strength. Elevated temperatures affect both the cementitious matrix and the polymer inclusions. At temperatures above approximately 250–300 °C, RPET undergoes thermal softening and partial melting, which may lead to internal void formation, microcracking, and a deterioration of mechanical properties. Despite this known thermal sensitivity, limited research has examined the combined influence of RPET-content, curing conditions, and elevated temperature exposure on flexural behavior.

The finite element method (FEM) provides a numerical framework for simulating stress distribution, deformation patterns, and failure mechanisms in cement-based materials subjected to bending loads. Previous studies have demonstrated that FEM models calibrated and validated with experimental data can accurately reproduce the mechanical response of polymer-modified cementitious composites [3,4]. However, most available studies focus either on experimental characterization under ambient conditions or on numerical simulations without detailed validation under thermal exposure. Despite the growing body of research on RPET-modified mortars, a clear gap remains in the integrated experimental-numerical evaluation of their flexural behavior at elevated temperatures, particularly regarding the temporal evolution of stress distribution up to failure. Furthermore, the influence of curing conditions on post-thermal mechanical response has not yet been quantified using validated dynamic finite element modeling. The object of this research is cement-based mortars incorporating recycled polyethylene terephthalate (RPET) as partial replacement for fine aggregate.

The aim of this study is to quantitatively evaluate the flexural performance and stress evolution of RPET-modified mortars subjected to different curing conditions and elevated temperatures through a combined experimental and linear dynamic finite element approach.

To achieve this aim, the following specific objectives are defined:

1. to experimentally determine the flexural strength, stiffness, and breaking load of mortars containing 10 and 20 % RPET under air and water curing conditions at temperatures of 20, 150, and 350 °C;
2. to analyze the influence of RPET content and curing regime on stiffness degradation and load-bearing capacity;
3. to develop and validate a linear dynamic finite element model using experimentally determined breaking loads as input parameters for defining the load history.
4. to evaluate the temporal evolution of Von Mises and principal stress distributions up to failure;
5. to quantify the agreement between numerical predictions and experimental results to assess the mechanical and thermal sensitivity of RPET-modified mortars.

## Materials and Methods

### Preparation of the mortar and specimens

The methodology adopted in this study is based on an integrated experimental–numerical approach for analyzing the bending behavior of mortars modified with RPET. The experimental design is supported by previous research on the use of plastic waste in cementitious matrices, where RPET has been identified as a viable partial replacement for fine aggregates. Its incorporation contributes to improved material sustainability, although it may significantly influence mechanical properties [1,2,5,6].

Figure 1 illustrates the experimental setup for the three-point bending test on prismatic mortar specimens, indicating the lower supports and the central loading point. This configuration reproduces the testing conditions established in the UNE-EN 196-1 [7] standard and allows the evaluation of flexural behavior under monotonic load.

The RPET used in this study was obtained from post-consumer plastic bottles that were previously classified, washed and mechanically crushed to produce elongated fibers with irregular geometry. This morphology has been reported to enhance mechanical

**Fig. 1.** Three-point bending test on prismatic mortar specimens

**Fig. 2.** Specimen condition after reaching the breaking load during the bending test

anchorage within the cementitious matrix. However, the hydrophobic nature of the polymer tends to produce a weaker interfacial transition zone (ITZ) compared to conventional mortars [7,8]. The RPET contents were fixed at 10 and 20 % by volume with respect to the fine aggregate. These values are commonly reported in the literature as representative substitution levels before significant reductions in cohesion and workability occur [7].

Figure 2 presents the condition of the specimen after reaching the breaking load during the bending test. The failure mode is governed by tensile stresses in the lower fiber of the specimen, with the main crack located in the central region of the span. This failure pattern is characteristic of the quasi-brittle behavior typically observed in cement-based mortars.

The three-point bending test was conducted on prismatic mortar specimens with dimensions of 40 × 40 × 160 mm$^3$. This configuration enables the evaluation of flexural tensile strength by generating a controlled stress distribution, where maximum tensile stresses develop in the lower fiber while compressive stresses appear in the upper region. Such a setup allows for the study of crack initiation and propagation under monotonic loading conditions. This arrangement facilitates the analysis of crack initiation and propagation under monotonic loading conditions. The experimental procedure follows the European standard UNE-EN 196-1 [7], which specifies methods for determining the mechanical properties of cement mortars, including flexural and compressive strength The standard defines specimen geometry, support span (100 mm), loading rate, and curing procedures to ensure the repeatability and comparability of the results.

The mortar mixtures were mechanically mixed to ensure homogeneous RPET distribution and compacted by vibration to minimize the presence of entrapped air voids. After an initial curing period of 24 h, the specimens were demolded and subjected to two different curing regimes: curing in a controlled environment (20 and 60 % relative humidity) and curing in water for 90 days.

The comparison between these curing regimes enables the evaluation of the influence of cement hydration on microstructural densification and the improvement of the ITZ, aspects that are particularly relevant in mortars containing polymeric inclusions [2,7,8]. After the curing period, the specimens were subjected to thermal exposure at 20, 150 and 350 °C. These temperature levels were selected to represent both in-service conditions and elevated-temperature scenarios associated with polymer softening and melting, as well as the progressive dehydration of the cementitious matrix. At higher temperatures, this process results in the loss of chemically bound water and microstructural deterioration [6,9].

### Definition of mechanical properties and test loads

The mechanical properties used in the numerical simulations were obtained from experimental bending and compression tests conducted on the same mortar formulations. The parameters considered include the elastic modulus, Poisson´s ratio, density, and stress limits. These values fall within the ranges reported in the literature for mortars incorporating plastic particles and polymeric fibers [3,10].

The bending loads were calculated based on the specimen geometry and loading configuration defined in the standard testing method for determining the mechanical strength of cement mortars according to EN 196-1 [6]. The experimentally obtained ultimate loads were used as input parameters in the numerical model to accurately reproduce the three-point bending test and ensure comparability between experimental observations and numerical simulations.

The experimentally determined mechanical and thermal parameters were incorporated into the finite element model. The complete set of input values used in SolidWorks Simulation is summarized in Table 1.

**Table 1.** Input mechanical and thermal parameters used in the numerical model

| Property | Value |
|---|---|
| Elastic modulus, MPa | 25551 |
| Poisson ratio | 0.22 |
| Density, kg/m$^3$ | 2366 |
| Tensile limit, MPa | 3.12 |
| Compression limit, MPa | 14.20 |
| Compression elastic limit, MPa | 7.10 |
| Thermal conductivity, W/m·K | 0.2256 |
| Thermal expansion, K$^{-1}$ | $1\times10^{-5}$ |

These values are consistent with those reported in previous studies on mortars incorporating plastic inclusions, which typically exhibit lower elastic moduli than conventional mortars. This reduction in stiffness is mainly attributed to the lower stiffness of RPET particles and the presence of weaker interfacial transition zones between the polymer inclusions and the cementitious matrix [3,5,11].

RPET replacement levels of 10 and 20 % were chosen to evaluate the effect of moderate incorporation of recycled polymer on the mechanical behavior of the composite material. Previous studies have shown that low to moderate proportions of recycled PET particles can be incorporated into cement-based materials while maintaining acceptable mechanical performance. Replacement levels below approximately 20−30 % are commonly used to study the balance between mechanical properties, workability, and the environmental benefits associated with the use of recycled polymer. Choi et al. reported that moderate contents of PET aggregates allow the production of lightweight cement composites with reasonable strength values [3]. Similarly, Albano et al. observed that the mechanical properties of concrete decrease progressively as the PET content increases, suggesting that moderate replacement levels are preferable for structural performance [4]. Rahmani et al. also indicated that partial replacement ratios of around 10−20 % allow the mechanical behavior to be evaluated without severe degradation of strength [12]. Therefore, the selected RPET contents provide a representative range for analyzing the influence of recycled polymer incorporation on the mechanical response of the material.

### Calculation of bending loads

The experimental flexural strengths used as input for the numerical simulation were obtained through laboratory testing. The flexural strength ($\sigma_f$) was calculated according to the UNE-EN 196-1 standard [6]:

$$\sigma_f = \frac{3FL}{2bd^2}, \quad (1)$$

where $F$ is the applied load (N), $L$ is the span length between supports (100 mm), $b$ is the specimen width (40 mm), and $d$ is the specimen height (40 mm).

The mechanical properties and breaking loads used as input data in the numerical model were obtained from the experimental bending and compression tests performed for each curing condition, RPET content and temperature.

In particular, the experimentally determined breaking load was used to define the load history applied in the linear dynamic analysis, allowing the temporal evolution of the equivalent Von Mises stress to be reproduced up to failure. The boundary conditions included the restriction of vertical displacement at the supports and the progressive application of the load at the center point. The load history was defined using the experimentally determined breaking loads presented in Table 2.

**Table 2.** Experimental values of breaking load of RPET content, type of curing and temperature

| Material | T, °C | Flexural strength, MPa | Compression strength, MPa | Elastic limit, MPa | Breaking load, kN | Breaking, MPa |
|---|---|---|---|---|---|---|
| Air 10 % rpet 20 °C | 20 | 3.12 | 14.20 | 7.10 | 22.63 | 14.14 |
| Air 10 % rpet 150 °C | 150 | 1.20 | 12.30 | 6.15 | 19.55 | 12.21 |
| Air 10 % rpet 350 °C | 350 | 0.50 | 9.60 | 4.80 | 15.08 | 9.42 |
| Air 20 % rpet 20 °C | 20 | 4.34 | 11.80 | 5.90 | 18.80 | 11.75 |
| Air 20 % rpet 150 °C | 150 | 0.70 | 7.70 | 3.85 | 11.75 | 7.34 |
| Air 20 % rpet 350 °C | 350 | 0.49 | 4.16 | 2.08 | 6.70 | 4.18 |
| Water 10 % rpet 20 °C | 20 | 4.41 | 30.70 | 15.35 | 49.07 | 30.66 |
| Water 10 % rpet 150 °C | 150 | 3.50 | 24.50 | 12.25 | 39.30 | 24.56 |
| Water 10 % rpet 350 °C | 350 | 1.60 | 16.00 | 8.00 | 25.66 | 16.04 |
| Water 20 % rpet 20 °C | 20 | 3.48 | 21.40 | 10.70 | 34.26 | 21.41 |
| Water 20 % rpet 150 °C | 150 | 2.03 | 14.40 | 7.20 | 23.01 | 14.38 |
| Water 20  pet 350 °C | 350 | 0.52 | 7.52 | 3.76 | 11.60 | 7.25 |

## Numerical modeling in SolidWorks simulation

The selected output variables evaluated included Von Mises stress, principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$), maximum strains, and neutral axis position. These variables are commonly used indicators for interpreting the flexural behavior of cementitious materials using FEM analysis [12,13]. Table 3 summarizes the main parameters of the numerical model, including geometry, mesh characteristics, boundary conditions, and evaluated variables.

This set of variables coincides with those used in previous studies of bending of mortars modified with polymers by FEM [3,9]. The numerical modeling was performed using SolidWorks Simulation through a linear dynamic analysis aimed at reproducing the three-point bending test applied to the mortar specimens. The geometry of the specimen, as well as the supports and the loading point, was explicitly defined to accurately represent the experimental configuration. Meshing was performed using second-order parabolic tetrahedral elements, which provide a more accurate approximation of the stress gradients compared with linear elements. Aditionally, local mesh refinement was applied in critical contact areas and in the central region subjected to maximum bending. This approach follows commonly accepted recommendations for FEM simulations of cementitious materials and fiber-reinforced composites [11,12,14,15].

**Table 3.** Parameters of the FEM numerical model for the three-point bending test

| **Category** | **Description** |
|---|---|
| Model geometry | Prismatic specimen of 40 × 40 × 160 $mm^3$<br>Cylindrical supports of 10 mm in diameter<br>Cylindrical load pointer of 10 mm in diameter |
| Meshing | Parabolic tetrahedral elements of 10 nodes<br>Global element size: 2.5 mm<br>Local mesh refinement: 1 mm in critical contact areas<br>Total number of elements: 45,000–52,000 |
| Boundary conditions | Supports restricted in vertical translation<br>Load applied as equivalent pressure $F/A$ in the contact area of the pointer<br>Transient analysis with linear increase of load until reaching $F$ |
| Evaluated variables | Equivalent Von Mises stresses<br>Main stresses $\sigma_1$, $\sigma_2$, $\sigma_3$<br>Position of the neutral line and curvature<br>Maximum deformations<br>Triaxial stress state in the tensioned zone |

The boundary conditions included the restriction of vertical displacements at the lower supports, while the load was progressively applied at the central point through a pressure-equivalent formulation reproducing the standardized three-point bending configuration. The temporal evolution of the load was defined until reaching the experimentally determined ultimate load corresponding to each test condition, enabling a direct analysis of the stress response as a function of time. This approach is particularly suitable for evaluating the quasi-fragile behavior of the mortar and for identifying the instant of failure, as has been pointed out in previous studies on fracture and crack propagation in cementitious materials [16–20].

The equivalent Von Mises stress was used to analyze the global evolution of the stress state up to the breaking load, while the principal stresses allowed the identification of the regions dominated by tensile or compressive stresses and the potential initiation zones of structural damage. This set of variables has proven particularly effective for correlating numerical and experimental results in cementitious materials modified with recycled polymers [14,15,21,22].

The numerical approach adopted in this study enables a detailed analysis of the combined influence of RPET content, curing regime, and temperature on the mechanical response of the material. The inclusion of thermally degraded models is consistent with previous research demonstrating that the strength of cementitious materials significantly decreases at elevated temperatures due to matrix dehydration and the loss of stiffness in polymeric inclusions [23,24]. Furthermore, the finite element method has been widely recognized as a robust tool for evaluating the structural behavior of mortars with RPET, complementing standardized bending tests defined by ASTM and EN standards. FEM analysis provides additional insight into internal stress distribution and failure mechanisms that cannot be obtained solely from global experimental measurements [24,25].

The thermal-mechanical analysis conducted in this work is supported by well-established studies on the behavior of lightweight and composite cementitious materials subjected to elevated temperatures. Previous investigations have shown that increasing temperature leads to a gradual reduction in stiffness and load-bearing capacity due to dehydration of the cement matrix and internal redistribution of strains [26,27]. In this context, linear dynamic simulation allow accurate representation of the evolution of stress states up to the breaking load, providing valuable information about thermal degradation mechanisms that are difficult to capture experimentally.

From the perspective of numerical analysis, FEM is particularly suitable for evaluating damage tolerance and crack localization in quasi-brittle composite materials. Previous research has demonstrated the ability of FEM to identify critical stress concentration zones and predict the loss of structural integrity in polymer-modified mortars under mechanical loading conditions [28]. In the RPET-modified mortars analyzed in this study, the evaluation of Von Mises and the principal stresses allows identification of damage iniciation in tensiled zones and its evolution until global failure.

The dynamic nature of the analysis adopted in this work is supported by previous studies highlighting the importance of considering the temporal evolution of stresses and strains in materials exhibiting viscoelastic or temperature-dependent behavior [29,30].

Overall, the application of FEM to the study of RPET-modified mortars contributes to a better understanding of their structural performance and reinforces their potential as sustainable construction materials within more resilient and resource-efficient building strategies.

It should be noted that the present FEM model is based on a linear dynamic formulation and therefore does not explicitly simulate crack propagation or nonlinear damage evolution. However, it provides a reliable approximation of the stress evolution and failure onset up to the experimentally observed breaking load.

The numerical model was validated through comparison with the experimentally measured breaking loads obtained from the three-point bending tests. The consistency between the simulated stress distributions and the experimental failure loads confirms the reliability of the proposed FEM approach for analyzing the flexural behavior of RPET-modified mortars.

## Results

### Specimens with 10 % RPET cured under ambient conditions

At temperature of 20°C, specimens containing 10 % RPET hit a breaking load of 22.63 kN, corresponding to a flexural strength of 3.12 MPa. Figure 3(a) presents the temporal evolution of the Von Mises stress, which increases almost linearly until peak load. This behavior indicates predominantly elastic mechanical response prior to failure. After reaching a peak load, a sudden drop in stress occurs, indicating brittle collapse governed by tensile stresses.

The stress distribution at the peak load, illustrated in Fig. 3(b), shows a typical bending pattern with maximum tensile stresses located in the lower fiber of the specimen and compressive stress concentrated in the upper region. No significant stress concentrations are observed, suggesting relatively uniform stress transfer between the cementitious matrix and the RPET inclusions under ambient temperature conditions.

When the temperature increases to 150 °C the breaking load decreases to 19.55 kN, representing a reduction of approximately 13.6 % compared with the 20 °C condition.

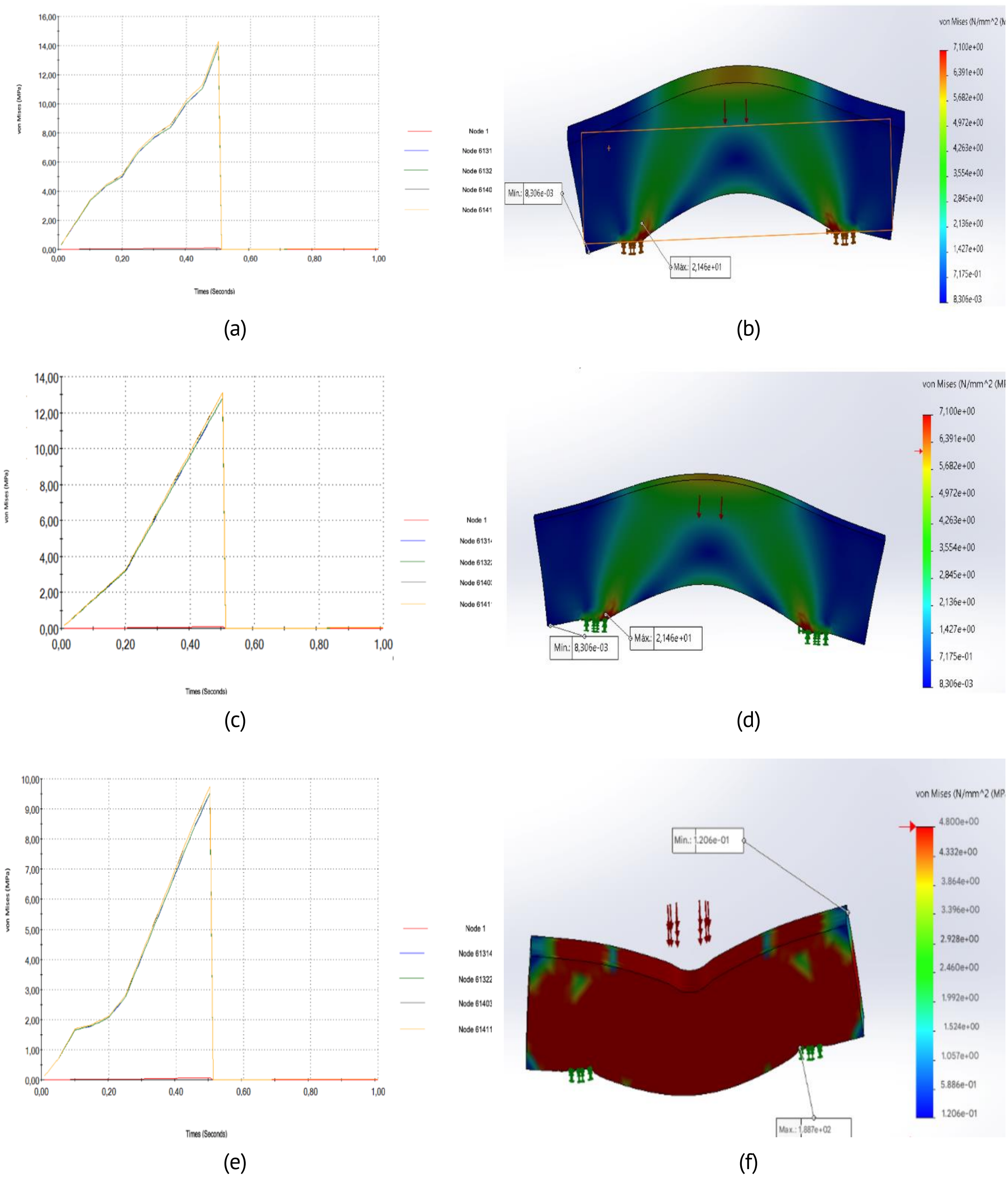


**Fig. 3.** Temporal evolution (a,c,e) and spatial distribution of Von Mises stress (b,c,f) in specimens containing 10 % RPET cured under ambient conditions at different temperatures: (a,b) 20 °C, (c,d) 150 °C, (e,f) 350 °C

As shown in Fig. 3(c), stress-time curves exhibit a lower steep gradient plus experience peak stress onset sooner thereby signaling reduced global stiffness.

The stress distribution shown in Fig. 3(d) becomes more heterogeneous, with localized tensile stress concentrations appearing in the lower fiber and beneath the loading point. These patterns suggest thermal softening of the RPET particles and progressive weakening of the interfacial transition zone (ITZ), which reduces the efficiency of stress redistribution.

At temperature of 350 °C, severe mechanical degradation is observed. The ultimate load decreases to 15.08 kN, corresponding to an overall reduction of approximately 33.4 % relative to the 20 °C condition. The stress evolution presented in Fig. 3(e) indicates limited stress development followed by abrupt collapse, which is characteristic of brittle failure associated with advanced thermal damage.

The stress distribution at failure (Fig. 3(f)) reveals strong stress localization in the tensile zone. This behavior is likely associated with internal discontinuities generated by the partial melting of RPET particles. The combined effect of reduced matrix cohesion and weakened interfacial bonding significantly decreases stiffness and load-bearing capacity.

Overall, temperature emerges as a primary factor governing the mechanical behavior of mortars containing 10 % RPET under ambient curing conditions. Although the fundamental bending mechanism remains unchanged, increasing thermal exposure progressively reduces stiffness, peak load, and the capacity for stress redistribution, ultimately leading to brittle tensile failure.

A comparative analysis of the three temperature levels under ambient curing conditions indicates that mechanical degradation occurs progressively as temperature increases. This degradation is primarily controlled by thermal effects rather than polymer content at the dosage considered. While the bending mechanism remains dominated by tensile stress, the stiffness and ability to redistribute stress decrease steadily with increasing temperature.

**Specimens with 10 % RPET cured under water**

At temperature of 20 °C, water curing significantly enhanced flexural performance of the mortar specimens. The Von Mises stress curves demonstrate a continuous increase until reaching a peak load of 49.07 kN, which is more than twice the value obtained for specimens cured under ambient conditions (22.63 kN). Figure 4(a) illustrates a steeper stress-time gradient and a clear peak, suggesting increased stiffness and load-bearing capacity. The stress distribution at the maximum load (Fig. 4(b)) appears more uniform compared with the ambient-cured specimens. Tensile stresses remain concentrated in the lower fiber, but without pronounced localization. The neutral axis remains stable along the span, indicating improved matrix densification and more effective stress transfer across the interfacial transition zone (ITZ).

At temperature of 150 °C, the breaking load decreases to 39.3 kN, corresponding to a reduction of approximately 19.9 % compared with the value measured at 20 °C. However, this value still exceeds the strength of specimens cured under ambient conditions at the same temperature (19.55 kN). According to Fig. 4(c), the stress–time response maintains a relatively steep gradient, suggesting that water curing mitigates the initial effects of thermal softening.

The stress distribution at peak load (Fig. 4(d)) shows moderate tensile concentrations while preserving a relatively uniform stress field. Compared with ambient curing at the same temperature, stress localization is less pronounced, reflecting improved resistance to microstructural degradation induced by thermal exposure.

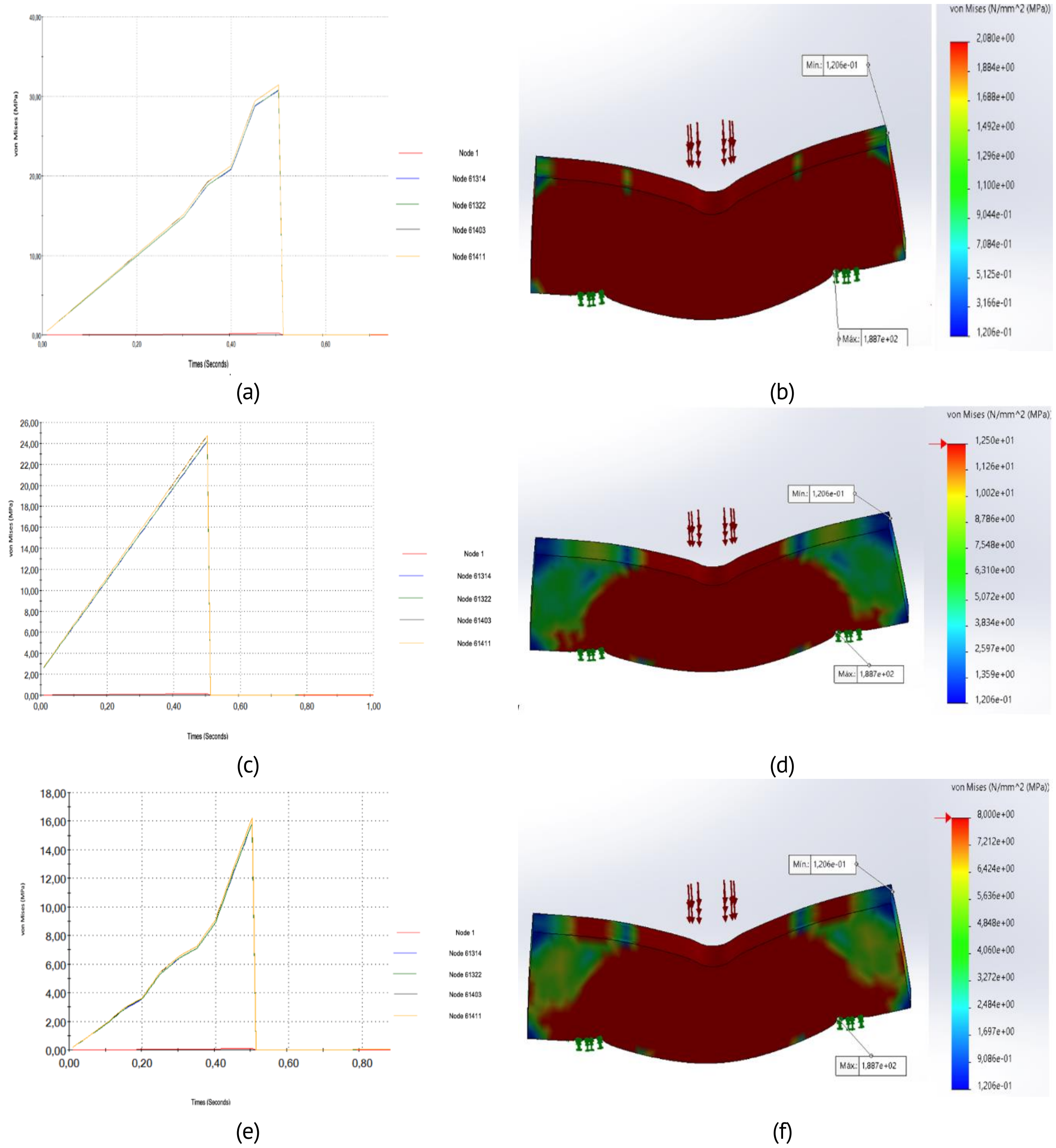


**Fig. 4.** Temporal evolution (a,c,e) and spatial distribution of Von Mises stress (b,d,f) in specimens containing 10% RPET cured under water at different temperatures: (a,b) 20 °C, (c,d) 150 °C, (e,f) 350 °C

At temperature of 350 °C, significant mechanical degradation occurs; however, water-cured specimens still maintain a breaking load of 25.66 kN, which is approximately 70 % higher than that of the specimens cured under ambient conditions (15.08 kN). Figure 4(e) shows the stress evolution, which exhibits a more gradual increase before failure compared with ambient curing, indicating partial preservation of structural integrity.

The stress distribution at failure (Fig. 4(f)) reveals localized tensile regions associated with the partial melting of RPET particles, while the cementitious matrix retains a certain degree of cohesion. Although the final collapse is primarily due to brittle tensile failure, the enhanced hydration from water curing delays stiffness degradation and improves the residual load-bearing capacity.

Overall, water curing improves the mechanical performance of mortars containing 10 % RPET across all temperature ranges. Although thermal exposure progressively reduces strength and stiffness, the beneficial effect of improved matrix hydration remains evident even under severe thermal conditions. These results indicate that curing conditions play a critical role in mitigating the adverse mechanical impacts associated with polymer inclusions and high-temperature exposure.

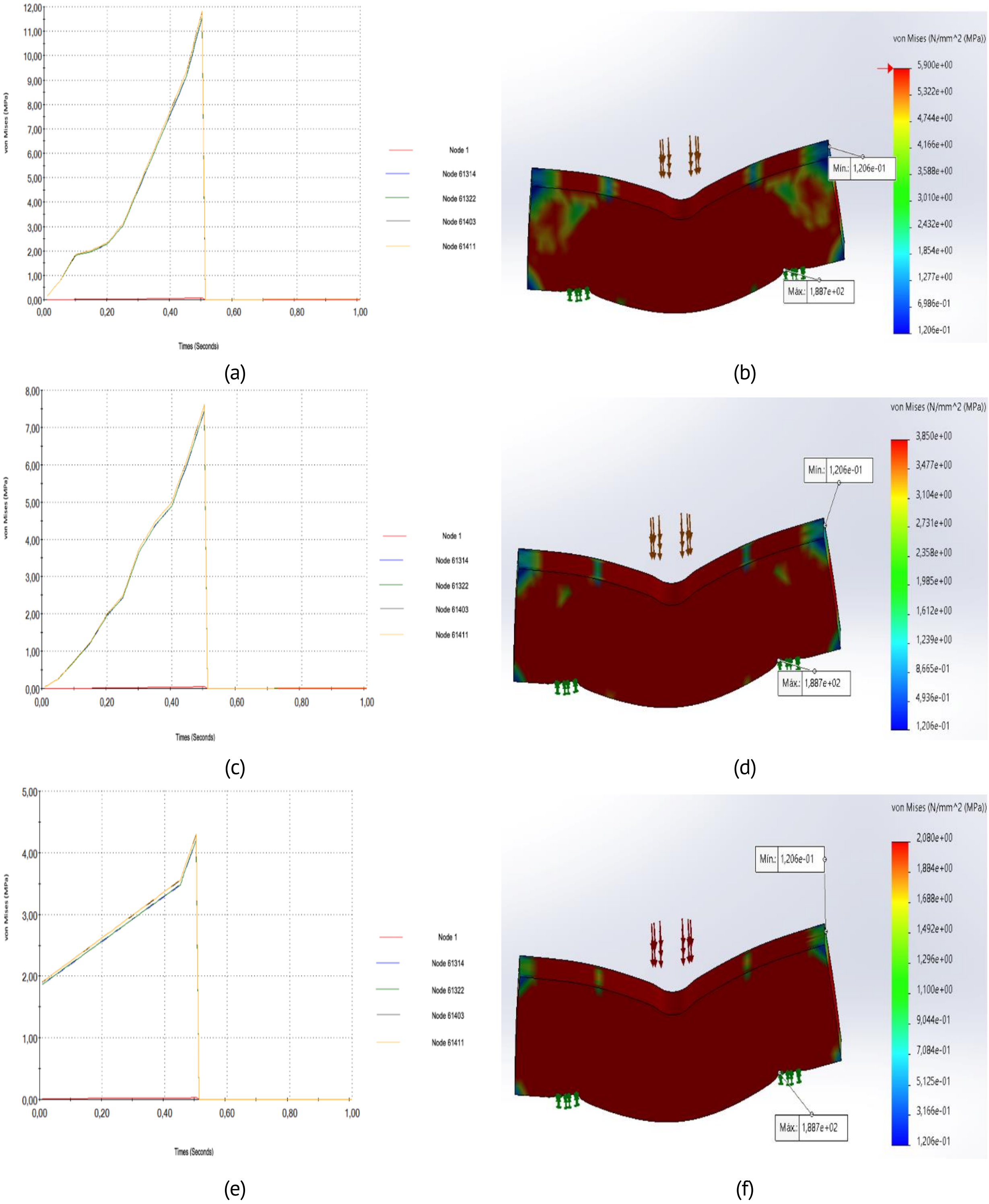


**Fig. 5.** Temporal evolution (a,c,e) and spatial distribution of Von Mises stress (b,d,f) in specimens containing 20 % RPET cured under ambient conditions at different temperatures: (a,b) 20 °C, (c,d) 150 °C, (e,f) 350 °C

## Specimens with 20 % RPET cured at 20 °C

At temperature of 20 °C, increasing the RPET content from 10 to 20 % results in a noticeable reduction in mechanical performance. The breaking load decreases to 18.8 kN**,** accompanied by less steep stress-time curves and greater stress dispersion across the nodes. The stress−time curves shown in Fig. 5(a) present a lower initial slope, indicating reduced global stiffness. The stress distribution at peak load (Fig. 5(b)) reveals localized tensile concentrations in the lower fiber and beneath the loading point. Compared with the 10 % RPET mixture, the stress field is less uniform, indicating weaker interfacial bonding and reduced stress transfer efficiency due to the higher polymer content.

At 150 °C, mechanical degradation becomes more pronounced. Table 6c shows the breaking load decreases to 11.75 kN, which corresponds to a reduction of approximately 37.5 % relative to 20 °C. The stress−time response reaches its maximum at an earlier stage, reflecting accelerated stiffness loss. The stress field shown in Fig. 5(d) exhibits clear localization in the tensile zone and instability of the neutral axis. The combined effect of increased polymer content and thermal softening leads to higher stress concentrations, promoting early crack initiation and propagation.

At temperature of 350 °C, the structural response shows severe deterioration. The breaking load decreases to 6.70 kN, representing an overall reduction of approximately 64.4 % compared with the 20 °C condition. The temporal stress evolution (Fig. 5(e)) shows minimal stress development prior to sudden collapse, indicating highly brittle behavior.

Figure 5(f) depicts the stress distribution and confirms extreme localization in the lower tensile region and a generalized loss of stress continuity. The combined effect of high RPET content and elevated temperature reduces matrix cohesion, leading to rapid failure under tensile stresses. Overall, increasing the RPET-content to 20 % reduces stiffness, peak load, and thermal stability under ambient curing conditions.

The material becomes considerably more sensitive to temperature increases, and the combined effects of polymer softening and reduced matrix cohesion accelerate structural degradation.

### Specimens with 20% RPET cured under water 20 °C

At temperature of 20 °C, water curing significantly improves the mechanical response compared with ambient curing conditions. The breaking load reaches 34.26 kN, representing an increase of approximately 82 % compared with ambient-cured specimens with the same RPET content 18.8 kN. The stress−time curves presented in Fig. 6(a) exhibit a steeper slope and a well-defined peak, indicating improved stiffness and load-bearing capacity.

The stress distribution at peak load (Fig. 6(b)) appears more balanced than ambient curing, with reduced tensile localization in the lower fiber. However, compared with specimens containing 10 % RPET, the stress field shows moderate heterogeneity, suggesting that the increased polymer content limits stress transfer efficiency.

At 150 °C, the breaking load decreases to 23.01 kN, corresponding to a reduction of approximately 32.8 % relative to the value measured at 20 °C. Nevertheless, this value remains significantly higher than that observed in specimens cured under ambient conditions at the same temperature (11.75 kN). The stress−time evolution (Fig. 6(c))

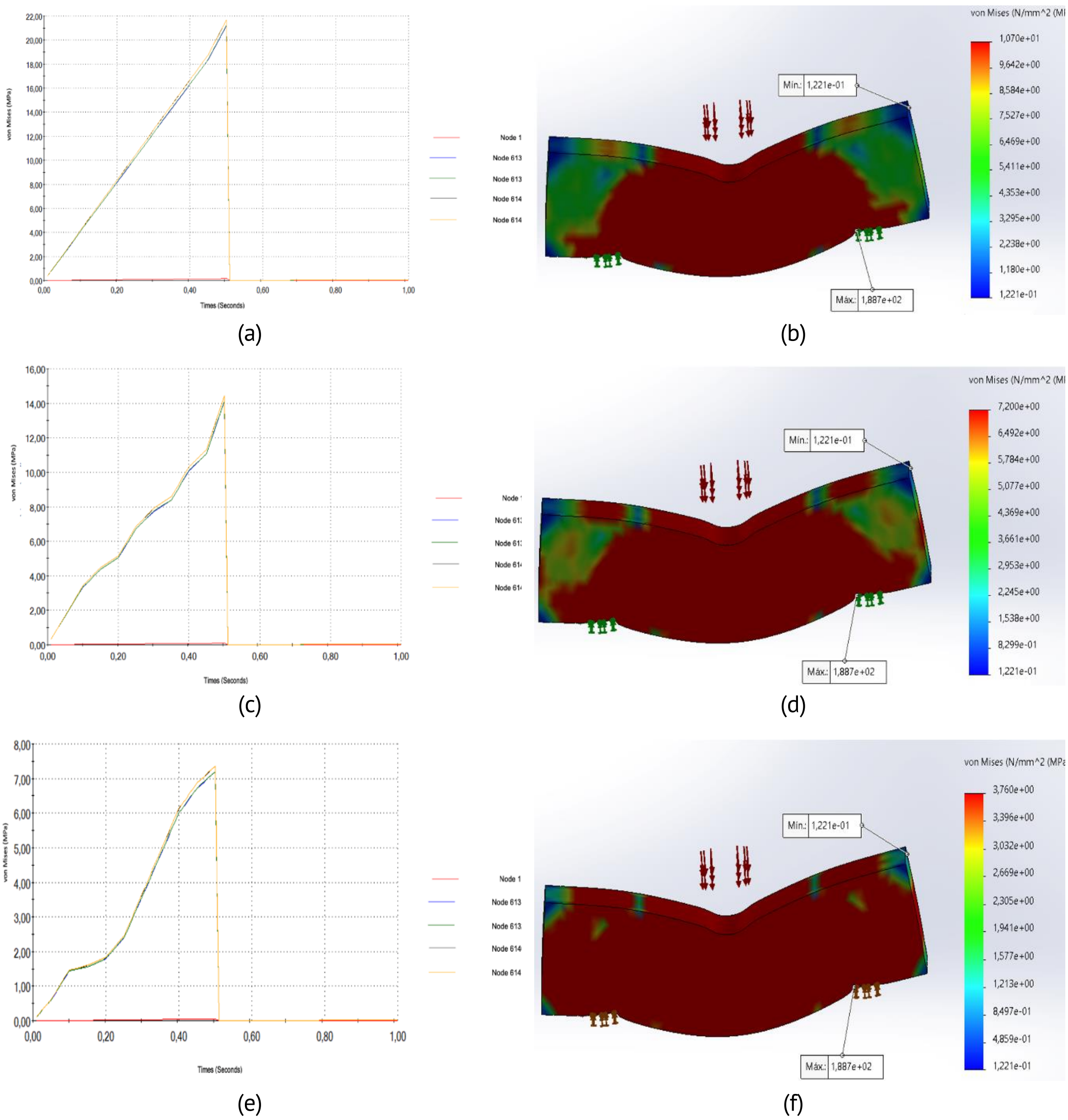


**Fig. 6.** Temporal evolution (a,c,e) and spatial distribution of Von Mises stress (b,d,f) in specimens containing 20% RPET cured under water at different temperatures: (a,b) 20 °C, (c,d) 150 °C, (e,f) 350 °C

shows a progressive increase until failure, while the stress distribution (Fig. 6(d)) indicates localized tensile concentrations that are less severe than those observed in the ambient-cured specimens. Water curing helps mitigate stiffness degradation by improving matrix hydration and strengthening the interfacial bonding, which slows the development of thermally induced damage.

At 350 °C, significant degradation occurs. Figure 6(e) shows the breaking load decreases to 11.6 kN, representing a total reduction of approximately 66 % compared to 20 °C. The spatial stress distribution shows localized tensile concentrations in the lower fiber.

The stress distribution (Fig. 6(f)) shows pronounced tensile localization in the lower fiber and reduced stress continuity across the specimen. This behavior is consistent with the melting of RPET particles and the formation of internal voids within the cementitious matrix.

Although water curing preserves some residual cohesion, it cannot fully compensate for the combined effects of high polymer content and severe thermal exposure.

Overall, water curing improves the flexural behavior of mortars containing 20 % RPET at all temperature levels. However, increasing polymer content significantly enhances thermal sensitivity of the material. Temperature remains the primary factor controlling mechanical degradation, although improved hydration delays stiffness loss and increases residual strength.

## Discussion

### Influence of RPET-content

Increasing the RPET content from 10 to 20 % led to a noticeable reduction in flexural strength and, consequently, a decrease in breaking load from approximately 22.6 kN to 18.80 kN under ambient curing conditions at 20 °C. This behavior is consistent with previous experimental studies reporting that higher PET aggregate contents reduce stiffness and load-bearing capacity due to the lower elastic modulus of polymer particles and weaker bonding within the interfacial transition zone (ITZ) [3,4]. Similar reductions in both flexural and compressive strength have been reported for cement-based composites incorporating recycled PET aggregates, where increasing polymer fractions promote stress concentration and disrupt matrix continuity [12].

### Effect of temperature on polymer-modified mortars

Thermal exposure significantly affects the mechanical performance of the mortars investigated in this study. When the temperature increased from 20 to 150 °C, the breaking load decreased by approximately 13–38 %, depending on the RPET content. This reduction agrees the previous studies indicating that moderate thermal exposure progressively degrades cementitious materials due to matrix dehydration and the onset of polymer softening [26,27]. The temperature range between 150 and 300 °C has been identified as particularly critical for polymer-modified cementitious composites. Within this range, polymer inclusions begin to lose stiffness and their bond with the cement matrix weakens, resulting in a reduction in load-bearing capacity.

### Influence of high temperature on mechanical performance

At temperature of 350 °C, severe mechanical degradation was observed, with reductions in breaking load exceeding 60 % in specimens containing 20 % RPET. Numerical simulations revealed strong stress localization in the tensile zone and abrupt failure following limited stress development. Similar failure mechanisms have been described in previous studies on polymers exposed to high temperatures, where polymer melting generates internal voids and microcracks that disrupt matrix continuity and accelerate brittle collapse [27,30]. These findings confirm that the thermal stability of polymer inclusions plays a decisive role in determining the residual mechanical capacity of cementitious composites subjected to high temperatures.

The numerical predictions showed good agreement with the experimentally measured breaking loads and reproduced the main stress distribution patterns observed during the three-point bending tests.

### Influence of water curing

The curing regime was found to significantly influence the flexural behavior of the mortars. Specimens cured in water exhibited substantially higher breaking loads than those cured under ambient conditions. For instance, at 20 °C, specimens containing 10 % RPET and cured in water reached breaking loads of approximately 49 kN, more than twice the value measured for ambient-cured specimens. This improvement can be attributed to enhanced hydration of the cement matrix, leading to a denser microstructure that strengthens the interfacial transition zone and improves stress transfer between the matrix and the polymer inclusions. Comparable improvements associated with enhanced curing conditions have been reported for polymer-modified cementitious materials, where increased matrix densification contributes to both improved strength and durability [30].

Overall, the present results confirm previously reported trends regarding the influence of polymer aggregates in cementitious composites while providing additional insight into the combined effects of RPET content, curing regime, and thermal exposure on the stress redistribution and failure mechanisms.

## Conclusions

Following the integrated experimental and numerical analysis, the subsequent scientific conclusions are established:

1. RPET incorporation changes flexural stiffness and load-bearing capacity. Increasing RPET-content from 10 to 20 % by volume reduces both the breaking load and stiffness under all curing conditions. This behavior suggests that higher polymer content weakens the interfacial transition zone (ITZ), thereby reducing stress transfer efficiency within the composite.
2. Temperature is the governing parameter for mechanical degradation. Exposure to 150 °C and particularly 350 °C causes progressive reductions in breaking load, stiffness, and stress redistribution capacity. At 350 °C, brittle tensile-controlled failure dominates due to RPET softening and matrix dehydration.
3. Water curing improves mechanical performance. Specimens cured in water exhibit greater breaking loads and more homogeneous stress distributions across all temperatures. Improved cement hydration leads to matrix densification and strengthens the ITZ, which mitigates the detrimental effects of thermal degradation.
4. The combined effect of high RPET-content and elevated temperature is critical. Mortars containing 20 % RPET and cured under ambient temperature exhibit the highest thermal sensitivity, experiencing severe stress localization and rapid brittle failure at 350 °C.
5. The numerical model reproduces experimental behavior with accuracy. Finite element simulations successfully capture the temporal evolution of Von Mises stresses and the spatial stress redistribution patterns up to failure, thereby validating the proposed experimental–numerical methods.

Overall, a balance between sustainability and mechanical performance can be achieved by limiting RPET content to moderate levels and applying appropriate curing conditions, especially in applications involving elevated temperature exposure.

Finite element simulations successfully capture the temporal evolution of Von Mises stresses and the spatial stress redistribution patterns up to failure. The numerical predictions showed good agreement with the experimentally measured breaking loads and the stress distribution patterns observed during the bending tests.

## CRediT authorship contribution statement

**M.E. Maciá Torregrosa** conceived and designed the study and supervised the overall research process; **M.I. Pinilla Hernandez** carried out the experimental work, including specimen preparation, curing procedures, and mechanical testing, and was responsible for data collection; **J. Camacho Diez** contributed to the definition of the experimental methods and supported the analysis of mechanical test results; **C. Machín Hamalainen** participated in the interpretation of results and contributed to the preparation and revision of figures and tables; **R.A. González Lezcano** contributed to data interpretation, critical revision of the manuscript, and overall scientific supervision. All authors critically reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

## Conflict of interest

The authors declare that they have no conflict of interest.

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