

Numerical finite element simulation of temperature effects on the compressive strength of RPET-modified mortars

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Abstract

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This study analyzes the compressive behavior of concrete modified with recycled polyethylene terephthalate (RPET) through finite element modeling using SolidWorks Simulation. Cubic specimens were modeled with 10% and 20% RPET content, then exposed to three different temperatures 20°C, 150°C, and 350°C under two curing conditions: ambient air and curing in water. The purpose was to evaluate how the polymer content, temperature, and curing method impact the compressive strength, load capacity, and failure patterns of the material. Numerical models successfully predicted stress distribution, the effects of thermal degradation and the evolution of deformation. The results revealed that water curing significantly improved compressive strength, with 10% RPET specimens reaching 30.70 MPa at 20°C compared to 14.20 MPa for air-cured specimens, an increase of 116%. The increase in temperature caused severe degradation, with strength losses of 48-71% at 350°C, depending on the RPET content and curing conditions. Specimens with 10% RPET showed superior mechanical performance and thermal stability in all test scenarios. The finite element method validated its effectiveness as a predictive tool for optimizing sustainable cementitious materials incorporating plastic waste, enabling design optimization without extensive experimental testing.

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1. Introduction

The construction industry faces increasing pressure to reduce its environmental footprint while maintaining adequate mechanical performance and structural safety. One of the most persistent environmental challenges is the management of plastic waste, particularly polyethylene terephthalate (PET), which is widely used in packaging and represents a significant proportion of global solid waste [1,2]. In this context, the incorporation of recycled PET (RPET) into cementitious materials has emerged as a promising strategy to promote circular economy principles, reduce landfill disposal, and limit the extraction of natural aggregates [3–5].

Numerous experimental studies have investigated the use of RPET as a partial replacement for fine aggregates or as fibers in mortars and concretes. These studies generally report a reduction in compressive strength with increasing RPET content, mainly attributed to the lower stiffness of the polymer compared to mineral aggregates, weak bonding at the interfacial transition zone, and increased porosity [2,6–8]. Nevertheless, it has also been demonstrated that when the RPET dosage is properly controlled, acceptable mechanical performance can be achieved for non-structural and secondary structural applications [11,17,27].

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Curing plays a decisive role in the development of mechanical properties in cementitious materials containing polymer inclusions. Water curing enhances cement hydration, leading to matrix densification, reduced porosity, and improved mechanical continuity [9,16]. Several authors have shown that wet curing can partially compensate for the loss of strength associated with RPET incorporation by improving the quality of the cement matrix and the polymer–matrix interface [8,16]. However, the combined influence of RPET content and curing regime is still not fully characterized, especially when additional environmental factors such as elevated temperatures are considered.

Temperature exposure is another key aspect influencing the performance of RPET-modified mortars. Elevated temperatures induce dehydration of cement hydration products, microcracking, and stiffness degradation, while the polymer phase may soften or melt, generating internal voids and stress concentrations [18–20]. Although the thermal behavior of conventional concrete has been extensively studied [20,25], research addressing the combined effects of polymer content, curing conditions, and temperature on RPET-modified mortars remains limited and is mostly restricted to experimental observations [19,27].

In recent years, the Finite Element Method (FEM) has proven to be a powerful tool for analyzing the mechanical behavior of complex cementitious composites. FEM allows detailed visualization of stress distribution, deformation patterns, and failure mechanisms, while reducing the need for extensive experimental campaigns [11,14]. Despite its wide application to conventional and recycled aggregate concretes [7,15,37], numerical studies focusing on RPET-modified mortars under combined curing and thermal conditions are still scarce.

Despite the growing body of literature on RPET-based cementitious materials, a clear research gap exists regarding the numerical evaluation of the coupled effects of RPET content, curing method, and temperature exposure on compressive behavior. The novelty of the present study lies in the development and validation of a finite element model capable of accurately reproducing the compressive response of RPET-modified mortars under different curing regimes (air and water) and temperature levels (20 °C, 150 °C, and 350 °C). By integrating experimentally derived, temperature-dependent mechanical properties into the numerical framework, this work provides a reliable predictive tool for analyzing strength degradation, stress redistribution, and failure mechanisms, supporting the optimized design of sustainable cementitious materials while reducing reliance on extensive experimental testing.

2. Materials and Methods

2.1 Experimental Compression Behavior

To prepare and model the test specimens, 8 L PET bottles were first collected, washed, and conditioned to remove any contaminants or residues. Subsequently, they were transformed into fibers by cutting them into sheets, using both manual and mechanical tools. This process yielded fibers with maximum dimensions of 30 mm × 2 mm, thus ensuring a homogeneous recycled material suitable for incorporation into the cementitious matrix. The preparation of the material is shown in Figure 1. The mortar was formulated using CEM II/B-L 32.5 N cement, washed sand with a particle size of 0–4 mm, drinking water, and rPET fibers in proportions of 10% and 20% of the total volume of the aggregate. To ensure correct water dosage, the sand was previously dried in an oven at 100 °C for 24 hours, thus preventing residual moisture from affecting workability or the water/cement ratio.

The mixture was prepared using an Orbegozo AM1800W mechanical mixer, ensuring uniform distribution of the fibers. Standardized triple molds measuring 40 × 40 × 160 mm were used, in accordance with the UNE-EN 196-1:2018 standard. Before pouring, the molds were treated with Pragnit ST300 release agent, facilitating demolding without damaging the surface of the specimens. This procedure can be seen in Figure 2. The specimens underwent two different curing methods to assess how they affected the material's mechanical properties. The first method involved curing them in a climate chamber at a controlled room temperature, while the second method submerged the specimens in water to ensure the cement was fully hydrated. Both sets of specimens were cured

for 90 days, which is enough time for the mortar's microstructure to fully develop. Subsequently, in order to analyze the material's response to thermal exposure, the test specimens were subjected to three temperature levels: 20 °C, 150 °C, and 350 °C.



Fig. 1. Preparation of test specimens and assembly of test equipment in the laboratory



Fig. 2. Sample compaction process

The thermal exposure was carried out in a Nabertherm N20/HR furnace, with trilateral radiation heating and a silicon carbide hearth, ensuring a uniform thermal profile. After exposure, the test specimens were allowed to cool for 24 hours before testing. Compressive strength tests were performed on a 600 kN IBERTEST universal testing machine equipped with specific accessories depending on the type of test. Data recording was performed using PCD 2K software, whose interface is shown in Figure 3, allowing the applied load, displacements, and final mode of failure to be collected.

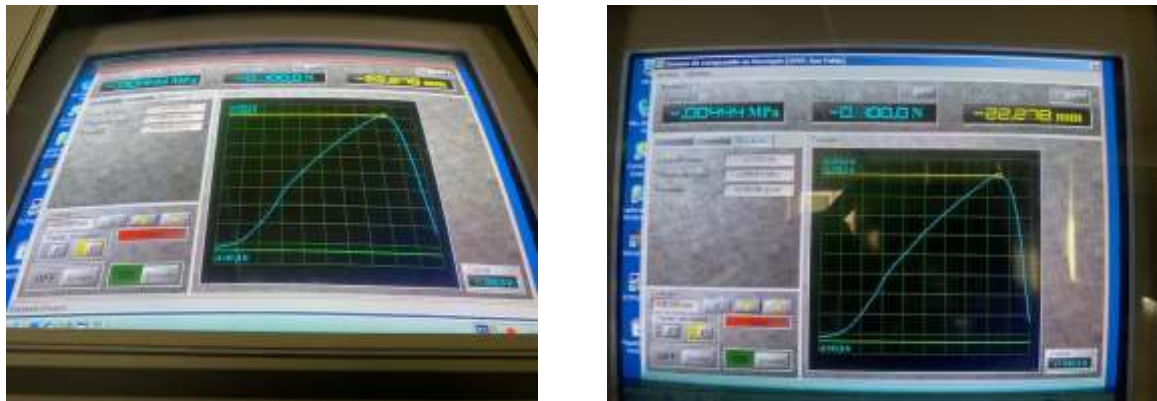


Fig. 3. Interface of the PCD2K program used to control the 60 T press in the compression tests

The tests were carried out in accordance with EN 196-1:2004. The results allow the behavior of the material under axial loads and its response to different levels of thermal stress to be evaluated. The values obtained in compression are one of the most relevant findings of this research. Figure 4 shows that the specimens cured in water have almost twice the strength of their equivalents cured in air, which highlights the critical importance of the curing method in the development of the mechanical properties of rPET fiber-reinforced mortar.

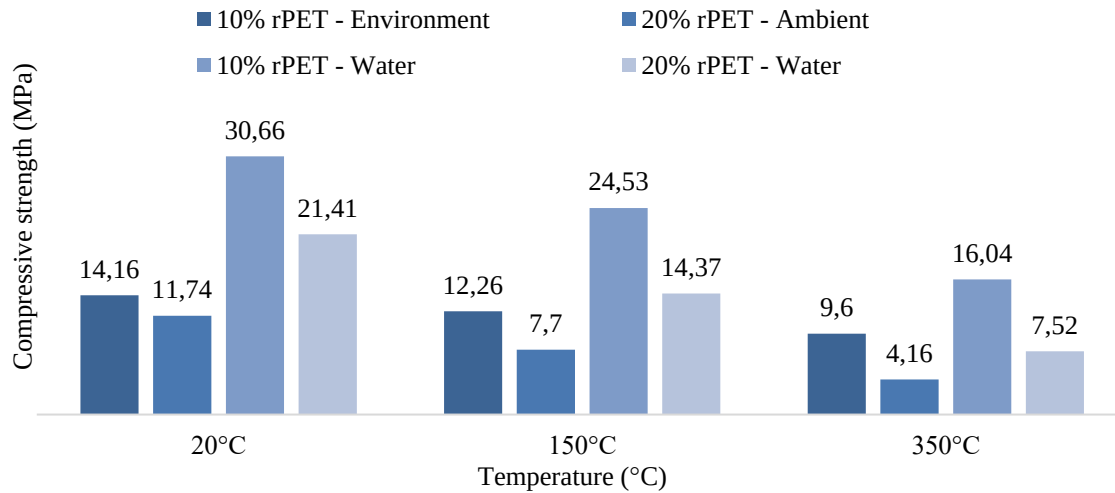


Fig. 4. Effect of rPET content on compressive strength

At room temperature, samples containing 10% rPET that were cured in water show average strength values nearing 31 MPa, while those cured in air only reach about 14 MPa. This significant difference of 121% highlights how wet curing enhances the hydration of the cement, leading to a denser microstructure with reduced porosity. Mortars cured with water demonstrate superior strength across all tested temperatures, confirming improved hydration and a more compact microstructure. At 150°C, the strength difference between the two curing methods remains consistent, with water curing achieving 21.5 MPa compared to 9.2 MPa for ambient curing (both with 10% rPET). This 134% difference indicates that the dense microstructure formed during wet curing offers better resistance to initial thermal stress. The most striking results occur at 350°C, where water curing retains nearly double the strength of ambient curing. The 10% rPET samples cured in water hold strong at 6.8 MPa, while those cured in air only manage to keep 3.1 MPa. This phenomenon indicates that the more consolidated and cohesive structure of wet curing offers greater resistance to thermal degradation mechanisms, including the dehydration of cementitious products and the melting of rPET.

2.2 Material Properties for Simulation

The experimental values obtained were used as a basis for defining the material properties in the simulation environment. Table 1 presents the physical and mechanical parameters used when evaluating the test specimens numerically. The density value ($\rho = 2366 \text{ kg/m}^3$) corresponds to the typical range for concrete modified with recycled plastics, consistent with reports by Saikia & de Brito [2] and Ismail & Al-Hashmi [3]. The modulus of elasticity ($E = 25,551 \text{ MPa}$) represents an appropriate average value for moderate-strength mortars with polymer additives [5], [16]. The compressive strength was specifically adjusted for each combination of RPET, temperature, and curing according to validated experimental values.

In the present numerical approach, temperature was not directly introduced as a thermal load in a coupled thermo-mechanical analysis. Instead, the effects of temperature—including thermal degradation of the cementitious matrix and the melting or softening of RPET at elevated temperatures—were incorporated implicitly through temperature-dependent mechanical properties derived from experimental testing.

For each temperature level (20 °C, 150 °C, and 350 °C), the material properties assigned in the finite element model, particularly the compressive strength limits, were adjusted according to experimentally validated values. This strategy allows the progressive loss of stiffness, strength, and load-bearing capacity caused by thermal exposure to be reflected in the numerical stress distribution and failure patterns. Although an explicit temperature-dependent non-linear material model could provide a more detailed representation of RPET melting behavior, such an approach is beyond the scope of the present study and is proposed as a line of future research.

Table 1. Physical and mechanical properties of concrete with RPET for compression simulation

Condition	RPET (%)	Temperature (°C)	Density (kg/m ³)	Modulus E (MPa)	Compression limit (MPa)
Ambient	10	20	2366	25,551	14.20
Ambient	10	150	2366	25,551	12.30
Ambient	10	350	2366	25,551	9.60
Ambient	20	20	2366	25,551	11.80
Ambient	20	150	2366	25,551	7.70
Ambient	20	350	2366	25,551	4.16
Water	10	20	2366	25,551	30.70
Water	10	150	2366	25,551	24.50
Water	10	350	2366	25,551	16.00
Water	20	20	2366	25,551	21.40
Water	20	150	2366	25,551	14.40
Water	20	350	2366	25,551	7.52

2.3 Calculation of Compressive Load

The compressive strength of the mortar specimens was calculated in accordance with UNE-EN 196-1, using the expression:

$$\sigma_c = \frac{F}{A} \quad (1)$$

Where; σ_c = compressive strength (MPa), F = maximum breaking load (N), A = cross-sectional area of the specimen (mm²).

For the prismatic specimens used in this study, the load was applied on a square area of:

$$A = 40 \times 40 = 1600 \quad (2)$$

Rearranging Equation (1), the equivalent compressive force corresponding to a given stress level can be expressed as:

$$F = \sigma_c \cdot A \quad (3)$$

This relationship represents the conversion from applied pressure to force, where a compressive stress P acting over an area A produces an equivalent force:

$$F = P \cdot A \quad (4)$$

For the test specimens with a constant cross-sectional area of $A = 1600 \text{ mm}^2$, Equation (4) becomes:

$$F = P(\text{N/mm}^2) \times 1600 \text{ mm}^2 \quad (5)$$

As an illustrative example, for an applied compressive stress of $P = 4.5 \text{ MPa}$ (equivalent to 4.5 N/mm^2) the corresponding force is calculated as:

$$F = 4.5 \times 1600 = 7200 \text{ N} \quad (6)$$

These equations were systematically used to determine the input loads applied in the finite element simulations for each combination of RPET content, curing condition, and temperature.

2.4 Table of Calculated Compression Loads

Table 2 presents the maximum loads applied in the linear dynamic simulations, obtained from the experimental compressive strengths reported for each combination of RPET content, curing condition, and temperature.

Table 2. Compression loads calculated for numerical simulations

Condition	RPET (%)	Temp (°C)	σ_c (MPa)	Force (N)
Ambient	10	20	14.20	22,720
	10	150	12.30	19,680
	10	350	9.60	15,360
	20	20	11.80	18,880
	20	150	7.70	12,320
	20	350	4.16	6,656
Water	10	20	30.70	49,120
	10	150	24.50	39,200
	10	350	16.00	25,600
	20	20	21.40	34,240
	20	150	14.40	23,040
	20	350	7.52	12,032

These loads were calculated using the equation established in **UNE-EN 196-1:2018** for prismatic mortar specimens tested in compression of halves ($40 \times 40 \text{ mm}$):

$$F = \sigma_c \cdot A \quad (7)$$

Where; F = maximum load applied (N), σ_c = compressive strength (MPa), A = load application area, equal to $40 \times 40 = 1600 \text{ mm}^2$

Equation (7) was used to convert the experimentally measured compressive strength values into equivalent load values applied in the numerical simulations. This load value represents the equivalent force that must be applied in the linear dynamic simulation to reproduce the stress state of a specimen subjected to the actual test. The original table is expanded to include the equivalent applied stress (MPa), the load converted to kN, and the percentage of mechanical loss or gain with respect to the base condition (20°C for each type and cure).

2.5 Numerical Modeling in SolidWorks

Convergence analysis is an essential step in any study using the Finite Element Method (FEM), especially when seeking reliable results in linear dynamic simulations. For this work, a systematic mesh refinement procedure was carried out, evaluating the variation of the principal stresses between different element sizes, with the aim of ensuring that the result is independent of the spatial discretization. The same Dynamic – Linear study was performed for each mesh, with identical boundary conditions, time-dependent load, and material properties. The configuration can be viewed in Table 4. To do this, it was necessary to consider that it is a compression simulation, a linear static study type was determined, and criteria were established for processing the results, which can be summarized in Table 5.

Table 3. Model configuration

Model configuration	
Type of study	Dynamic – Linear
Geometry	(40 x 40 x 160) mm (width, depth, and length)
Material	RPET concrete with properties shown in Table 1
Behavior	Linear-elastic
Mesh	Second-order tetrahedral elements (10 nodes)
	Average element size: 3 mm
	Localized refinement in load application areas
	Convergence analysis with variation < 5% in principal stresses

Table 4. Mesh characteristics

Mesh characteristics	
Element type	Second-order parabolic tetrahedrons (10 nodes per element)
Average element size	3 mm in the test specimen
Localized refinement	1.5 mm mesh in the areas of contact with the cylinders and in the central third of the specimen where the maximum stresses are concentrated
Mesh transition	controlled by a growth factor of 1.5 to avoid excessive distortion
Number of elements	32,800 elements

Table 5. Criteria for simulation

Study parameters	
Type of study	Dynamic Linear (Dynamic – Liner)
Solver	Direct sparse solver (direct method for stiffness matrix)
Convergence criterion	Energy tolerance of 0.1%
Maximum iterations	100 (although convergence was typically achieved in fewer than 20 iterations)
Von Mises stresses (σ_{VM}):	Three-dimensional distribution with identification of the maximum value and its location
Principal stresses	First principal stress (σ_1 - maximum tension) and third principal stress (σ_3 - maximum compression)
Equivalent unit strains (ϵ_{eq})	Deformation field according to Von Mises criterion

The numerical analysis performed using finite elements allowed the mechanical behavior of RPET-modified concrete to be characterized in detail under different combinations of temperature, curing, and polymer content. The results will be interpreted based directly on the 12 simulations, which are presented sequentially to ensure narrative continuity and a smooth reading. In each case, the figures show the stress fields, the temporal evolution of the Von Mises stress, and the modes of internal redistribution that support the structural interpretation of the material.

3. Results

3.1 Behavior of Specimens with 10% RPET Cured in Ambient Conditions

Figure 5 shows the temporal evolution of Von Mises stress for several representative nodes in the test specimen with 10% RPET at 20°C. This figure shows a linear and stable increase in stress until the maximum value is reached, confirming predominantly elastic behavior. The consistency between nodes indicates a uniform transfer of stresses, with no early appearance of critical concentrations.

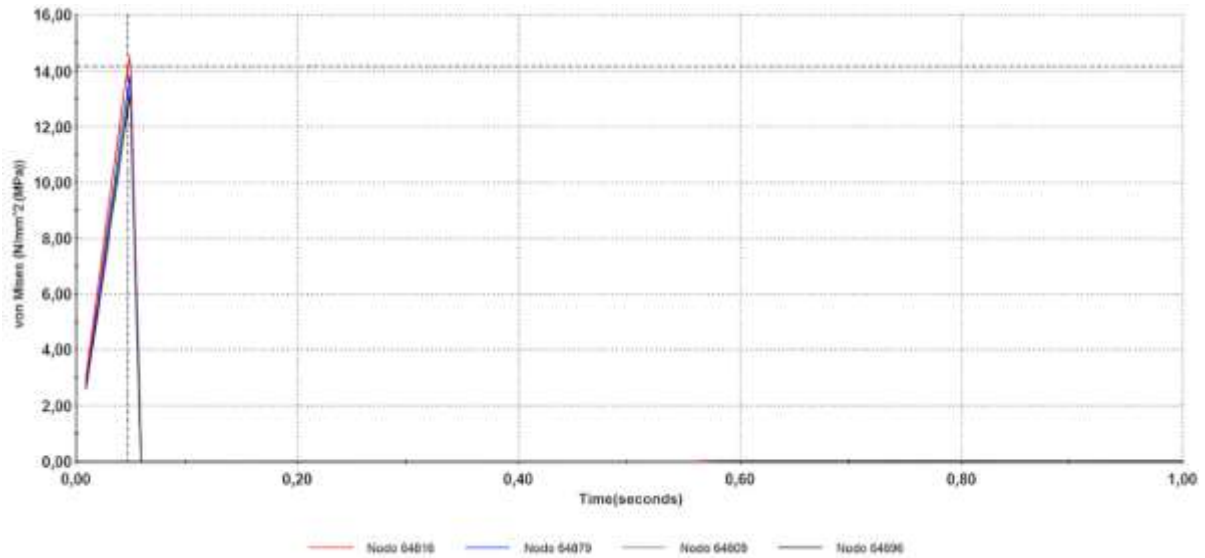


Fig. 5. Temporal evolution of Von Mises stress at different selected nodes during the linear dynamic simulation with 10% RPET at 20°C

Figure 6 shows the spatial distribution of stresses at the moment when the maximum load is reached. Here, a uniform vertical gradient and a compressed central region where the stress reaches its maximum value are evident. The lateral areas show moderate tensile stresses associated with the Poisson effect, while local concentrations appear at the edges that do not yet compromise structural stability.

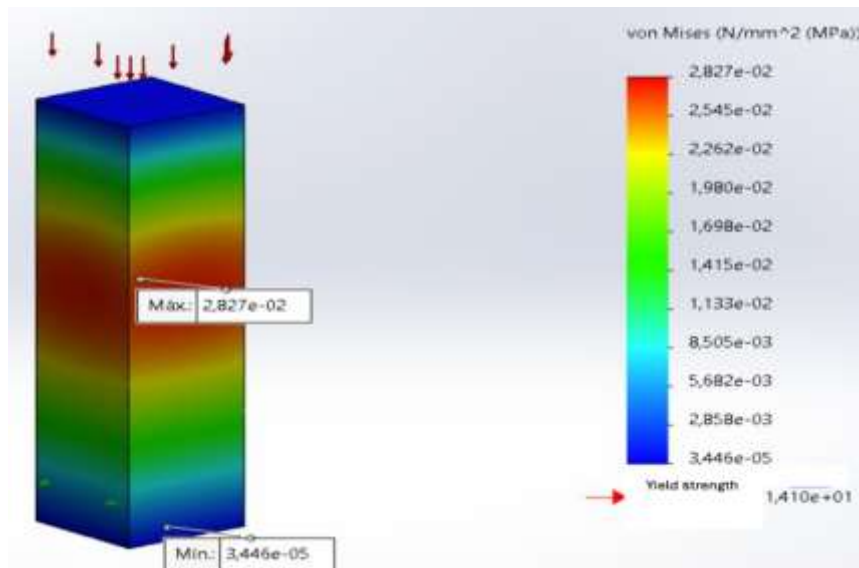


Fig. 6. Von Mises stress distribution in the specimen under dynamic linear loading applied to the upper face 10%RPET 20°C

When the temperature is increased to 150°C, Figure 7 reveals a less uniform temporal evolution, with a slight separation between the curves of the different nodes, reflecting the onset of thermal degradation and loss of stiffness. Figure 8 corresponding to the stress distribution, shows a greater localization in the central region and an increase in lateral tensile stresses, which rise to approximately 3.12 MPa. This behavior confirms the presence of micro discontinuities at the RPET–matrix interface.

Exposure to 350°C leads to much more pronounced deterioration. In Figure 9 the time evolution shows an evident loss of linearity and a substantial reduction in maximum stress. Figure 10 illustrates a highly concentrated stress distribution in a small volume, accompanied by extensive unloaded areas. This configuration reflects the onset of structural collapse due to RPET melting and dehydration of cement hydration products. Together, Figures 1 to 6 show progressively how the mechanical integrity of the material decreases with increasing temperature, confirming that the combination of thermal degradation of the matrix and softening of the RPET radically modifies the stress distribution.

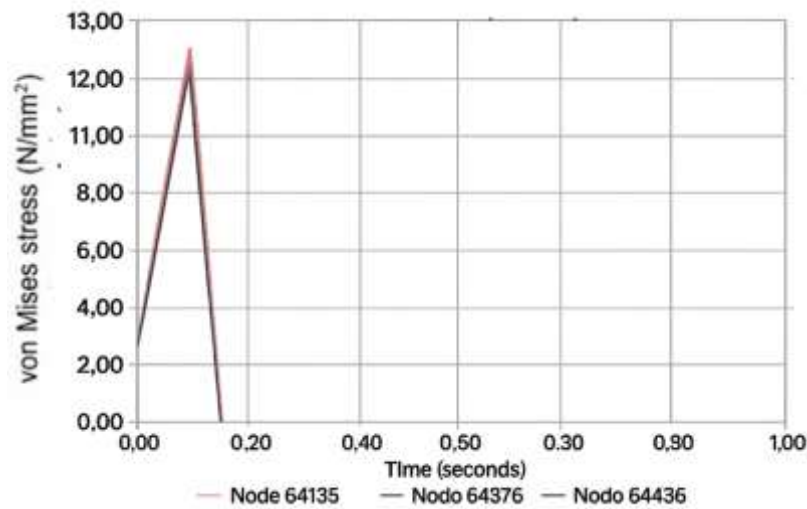


Fig. 7. Temporal evolution of Von Mises stress at different selected nodes during the linear dynamic simulation with 10%RPET at 150°C.

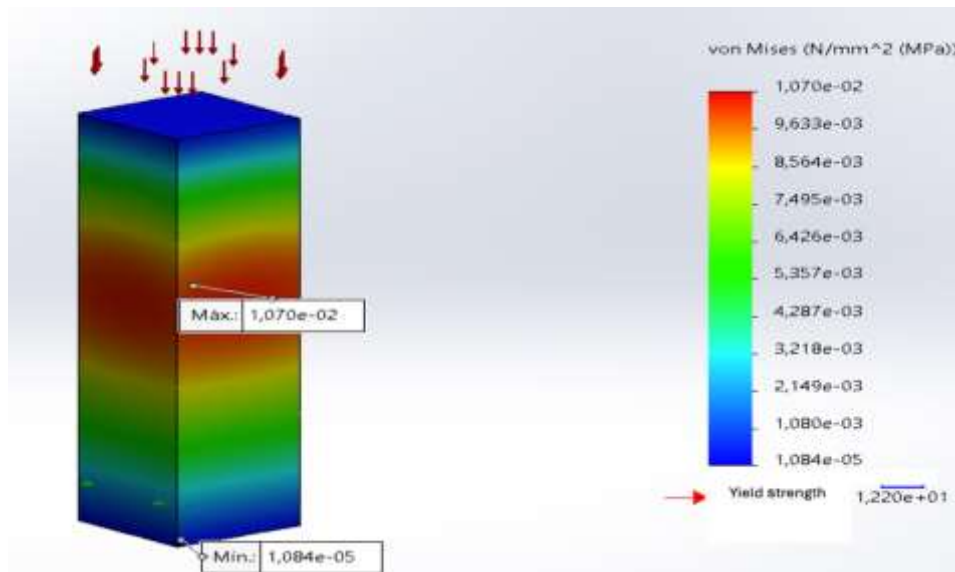


Fig. 8. Von Mises stress distribution in the specimen under dynamic linear loading applied to the upper face 10%RPET at 150°C

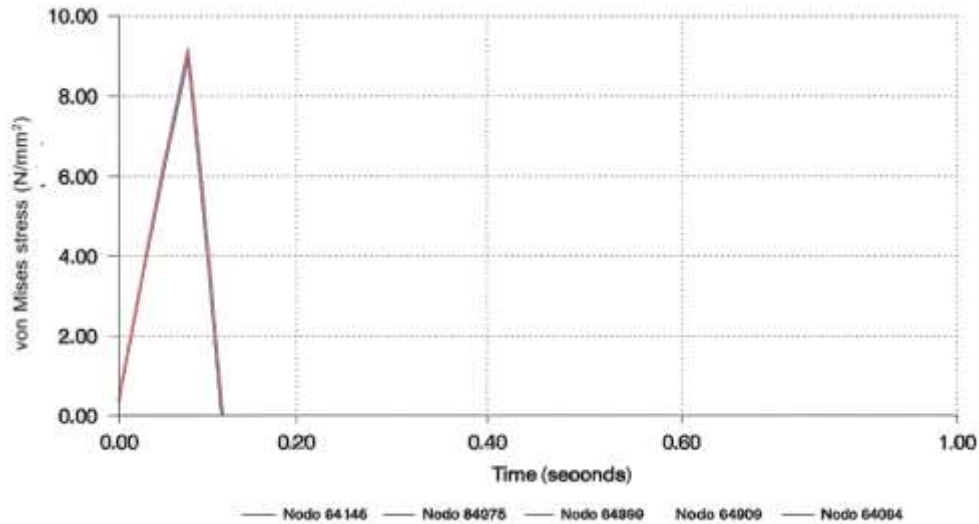


Fig. 9. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 10% RPET at 350°C.

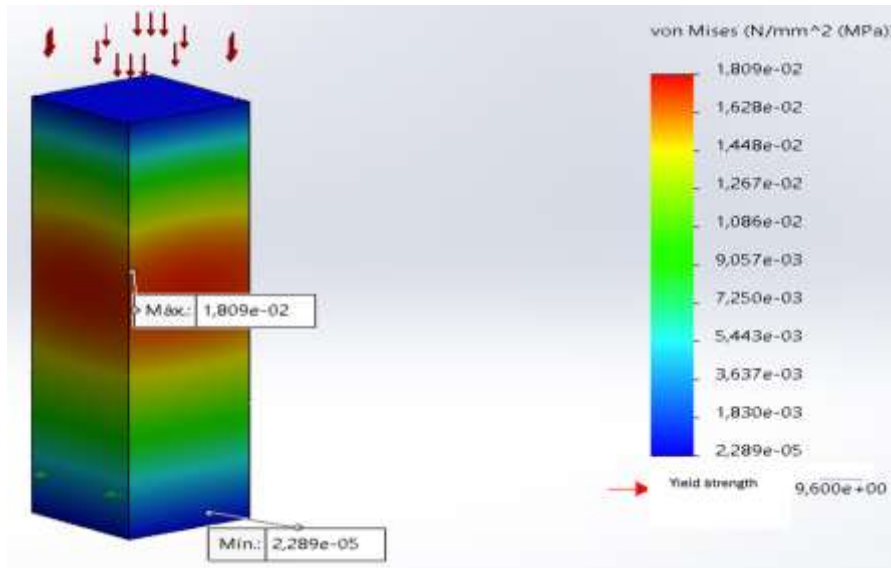


Fig.10. Distribution of Von Mises stresses in the test piece under dynamic linear loading applied to the upper face 10%RPET at 350°C

3.2 Behavior of Specimens with 10% RPET Cured in Water

Water curing generates a notable change in mechanical performance. Figure 11 shows a much higher and more stable temporary increase in stress compared to specimens cured in air. Figure 12 visually confirms this improvement, showing a uniformly distributed stress distribution and a compressed central zone of large amplitude, indicating a more efficient use of the resistant material. At 150°C, the trend continues. Figure 13 shows a moderate drop in the stress evolution over time, although without any sudden interruptions.

Figure 14 shows a still relatively homogeneous distribution, with a controlled increase in lateral stresses, which shows that thermal damage progresses less aggressively than in ambient curing. Deterioration at 350°C is inevitable but less severe. Figures 15 and 16 show a more stable response than their air-cured counterparts. Although localized areas of high stress are observed, there is still a significant proportion of the structural volume that actively participates in stress transmission, reflecting superior residual strength.

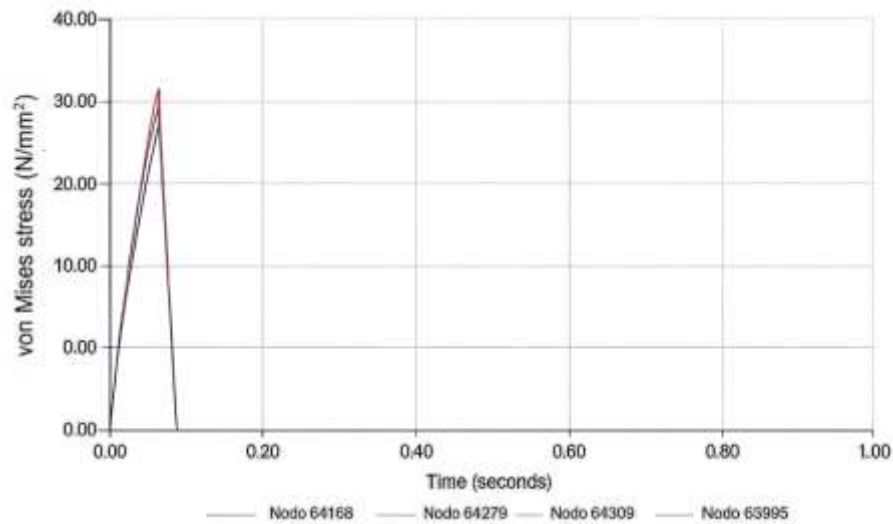


Fig. 11. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 10% RPET at 20°C (water-cured)

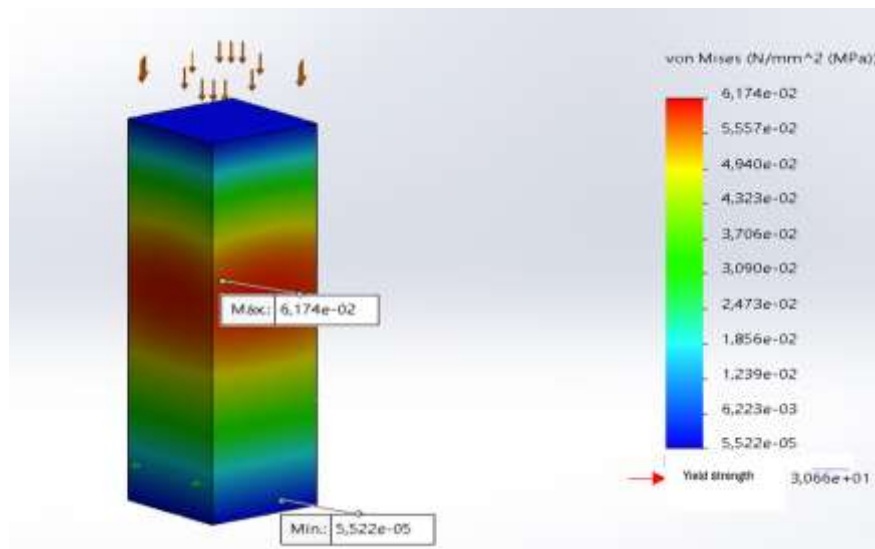


Fig. 12. Distribution of Von Mises stresses in the test piece under dynamic linear load applied to the upper face 10%RPET at 20°C (water-cured)

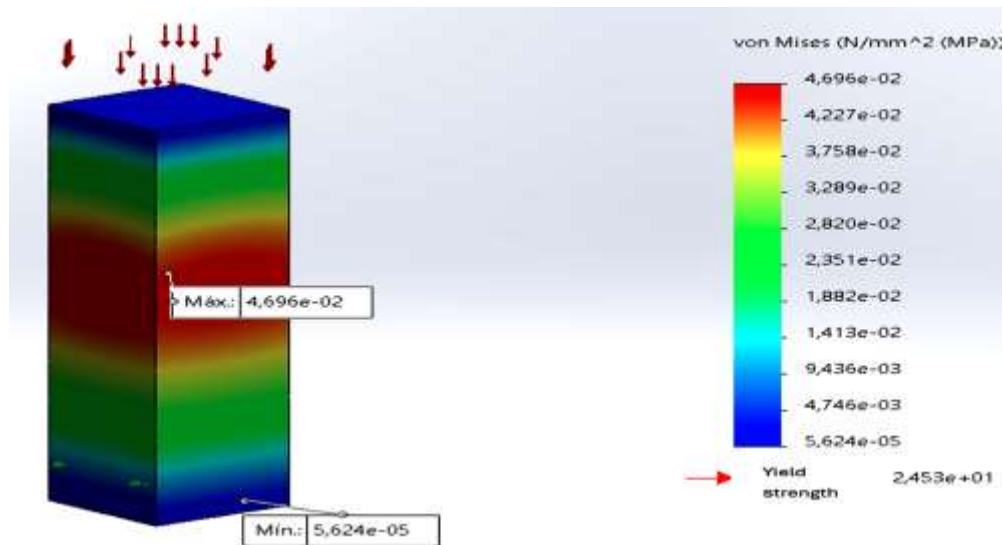


Fig. 13. Temporal evolution of Von Mises stress at different nodes selected during the linear dynamic simulation with 10% RPET at 150°C (water-cured)

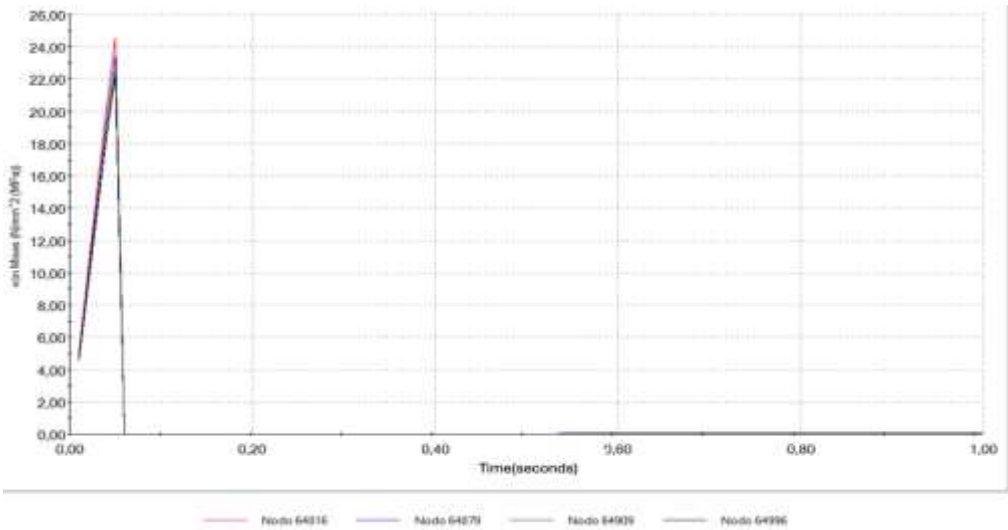


Fig. 14. Distribution of Von Mises stresses in the specimen under dynamic linear loading applied to the upper face 10%RPET at 150°C (water-cured)

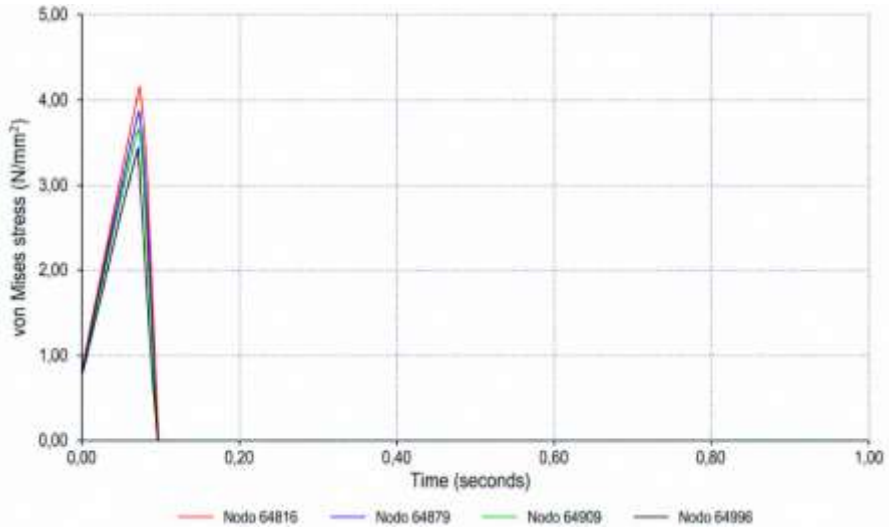


Figure 15. Temporal evolution of Von Mises stress at different nodes selected during the linear dynamic simulation with 10% RPET at 3 50°C (water-cured)

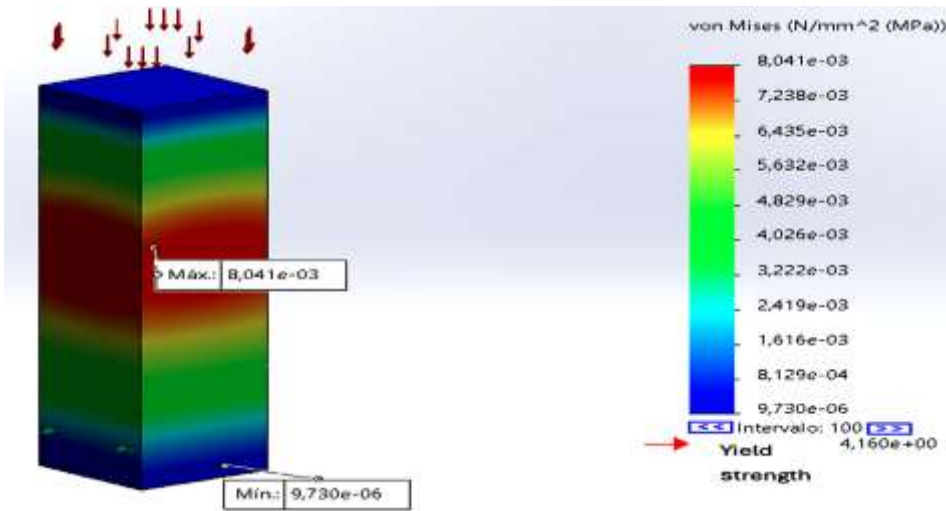


Fig. 16. Distribution of Von Mises stresses in the specimen under dynamic linear loading applied to the upper face 10%RPET at 350°C (water-cured)

Taken together, these figures confirm that complete cement hydration, resulting from water curing, generates a dense microstructure that limits the propagation of thermal cracks and improves the retention of mechanical properties even under extreme exposure.

3.3 Behavior of Specimens with 20% RPET Cured in the Environment

Increasing the RPET content reduces internal cohesion. Figure 17, corresponding to the time evolution at 20°C, shows lower maximum stress and greater dispersion between nodes. Figure 18 confirms this observation with a significantly less uniform stress distribution, with multiple areas of secondary concentration.

At 150°C, Figures 19 and 20 show accelerated deterioration. The time curve shows a significant reduction in resistance and greater separation between nodes, while the stress map shows a pattern of "islands" of concentrated stress surrounded by virtually inactive regions. This phenomenon is attributed to the abundance of RPET–matrix interfaces, which act as triggers for thermal microcracks.

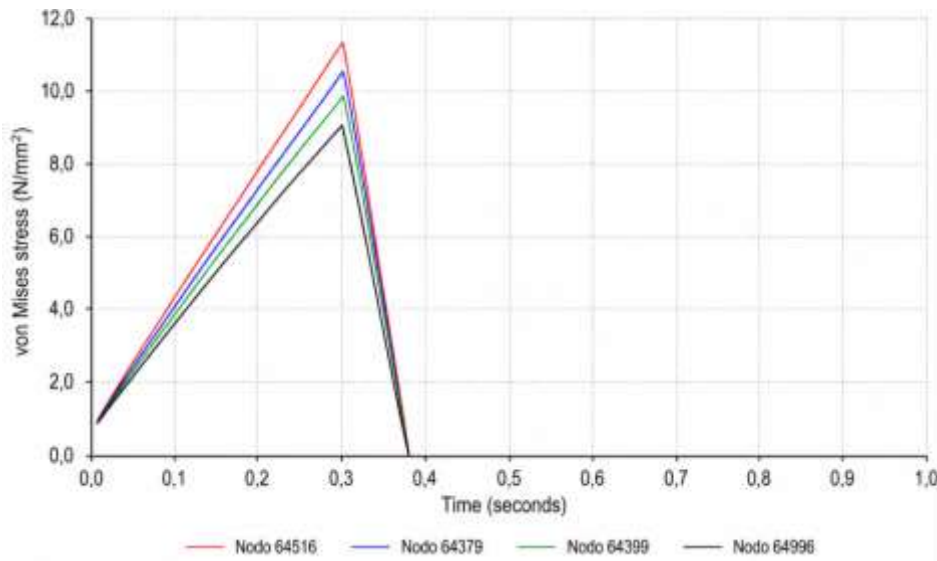


Fig. 17. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20% RPET and at 20°C.

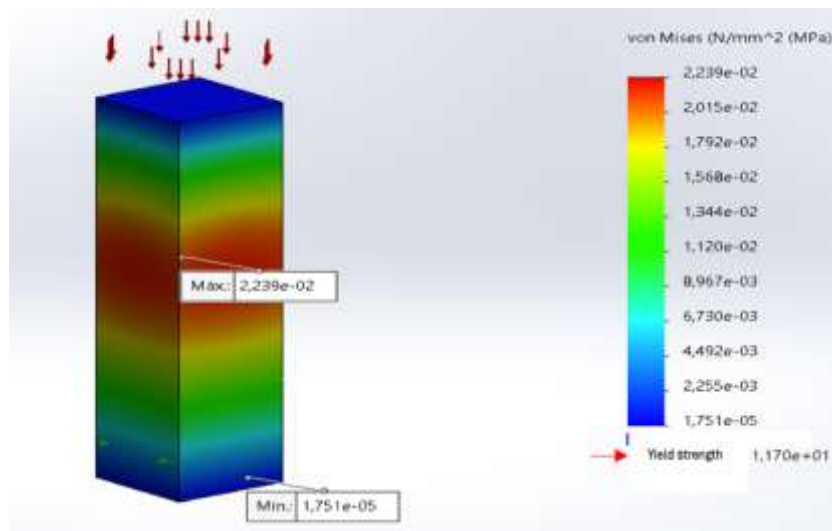


Fig. 18. Distribution of Von Mises stresses in the specimen under dynamic linear loading applied to the upper face 20%RPET20°C

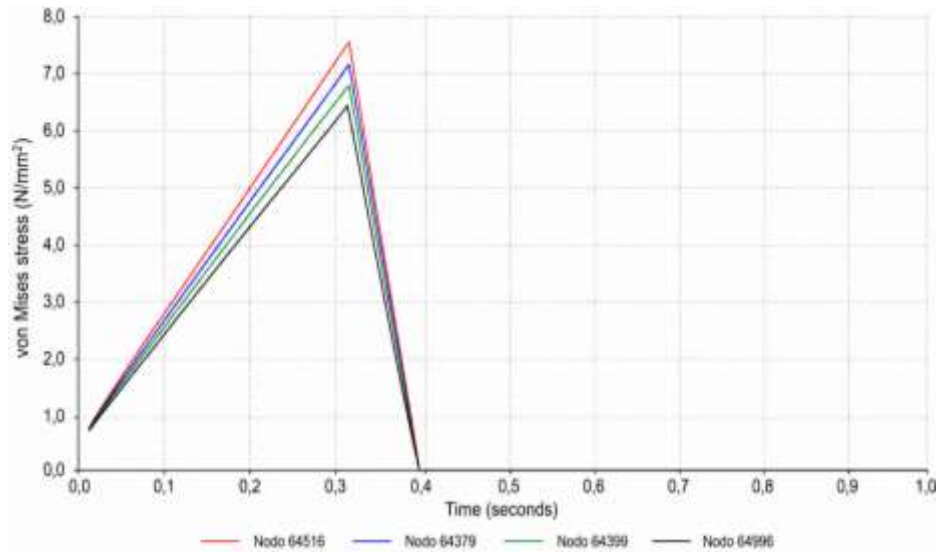


Fig. 19. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20%RPET150°C

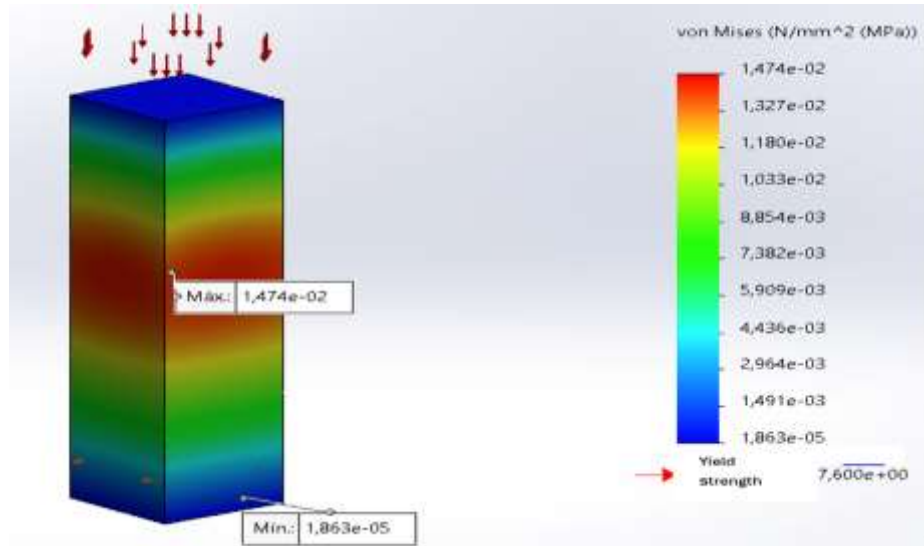


Fig. 20. Distribution of Von Mises stresses in the specimen under dynamic linear loading applied to the upper face 20%RPET150°C

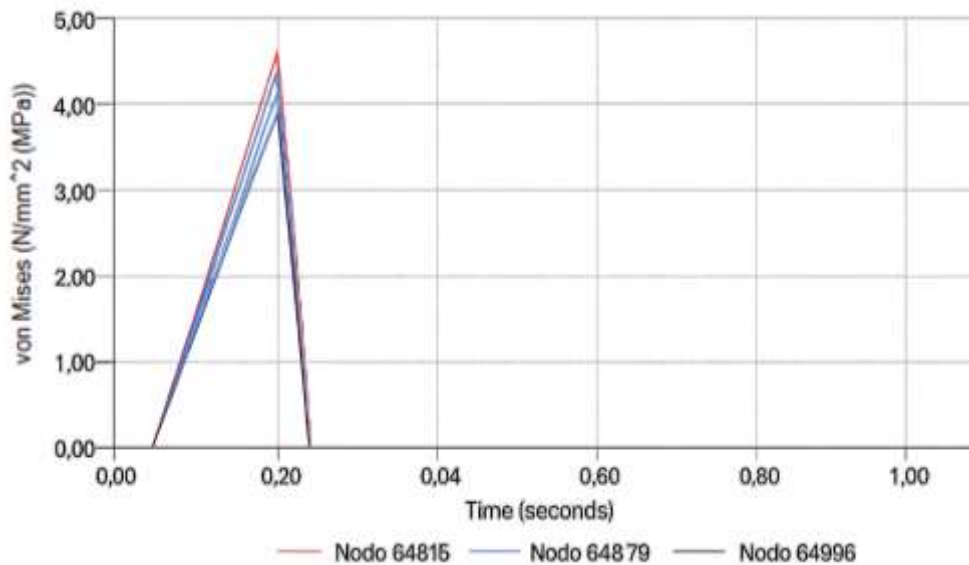


Fig. 21. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20% RPET at 350°C

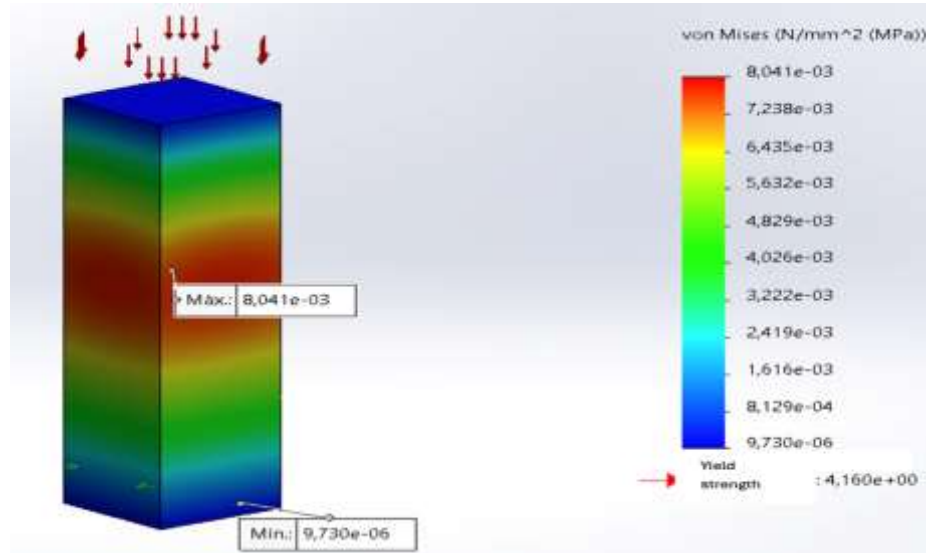


Fig. 22. Distribution of Von Mises stresses in the specimen under dynamic linear loading applied to the upper face 20%RPET at 350°C

Finally, at 350°C, Figures 21 and 22 show an almost total loss of resistance capacity. The stress distribution becomes extremely localized, with lateral stresses close to typical uniaxial tensile levels, which anticipates the brittle collapse of the specimen. The deformation is concentrated at a critical point, and the behavior is no longer recoverable.

3.4 Behavior of Specimens with 20% RPET Cured in Water

Curing in water substantially modifies the behavior of the material, even with 20% RPET. Figures 23 and 24 show, at 20°C, a consistent temporal evolution and a more homogeneous spatial distribution. Lateral stresses remain moderate and the volumetric participation of the material is greater. At 150°C, Figures 25 and 26 show a progressive but less aggressive degradation than in the case of ambient curing. The material retains more than 67% of its initial strength, and the stress map shows a smooth gradient, confirming the protective action of wet curing. At 350°C, although degradation is evident, Figures 27 and 28 reveal superior performance compared to air-cured specimens. Despite areas of high stress concentration, structural continuity is still observed, allowing the residual strength to far exceed that of specimens with the same polymer content cured in an ambient environment

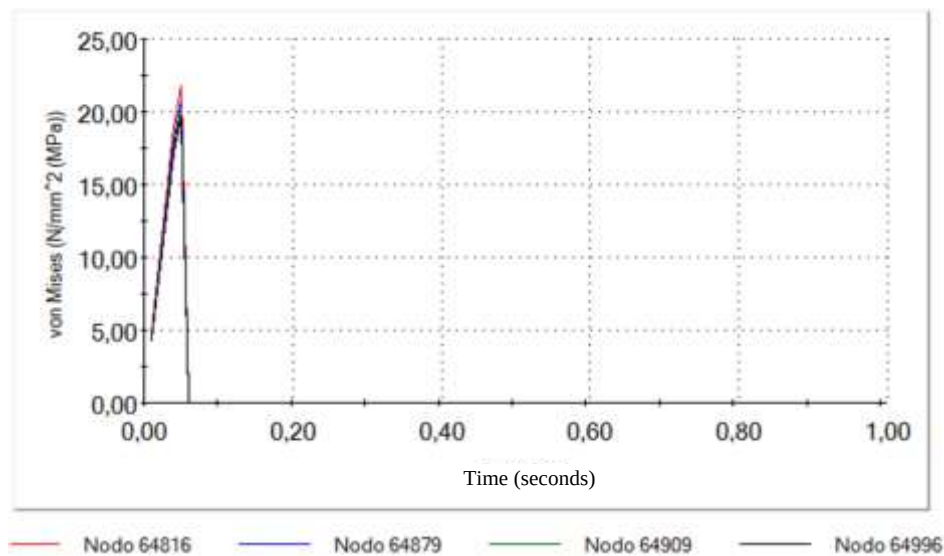


Fig. 23. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20% RPET at 20°C (water-cured)

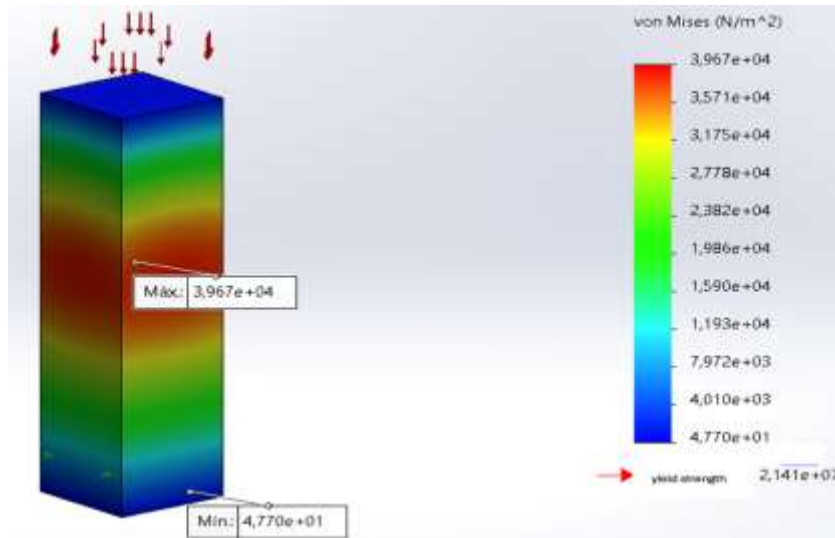


Fig. 24. Distribution of Von Mises stresses in the test piece under linear dynamic load applied to the upper face 20%RPET at 20°C (water-cured)

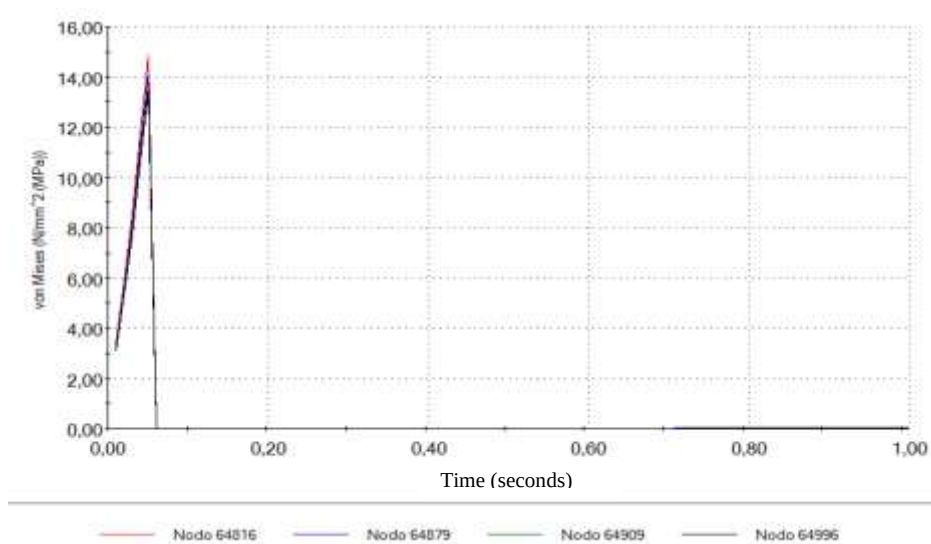


Fig. 25. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20% RPET at 150°C (water-cured)

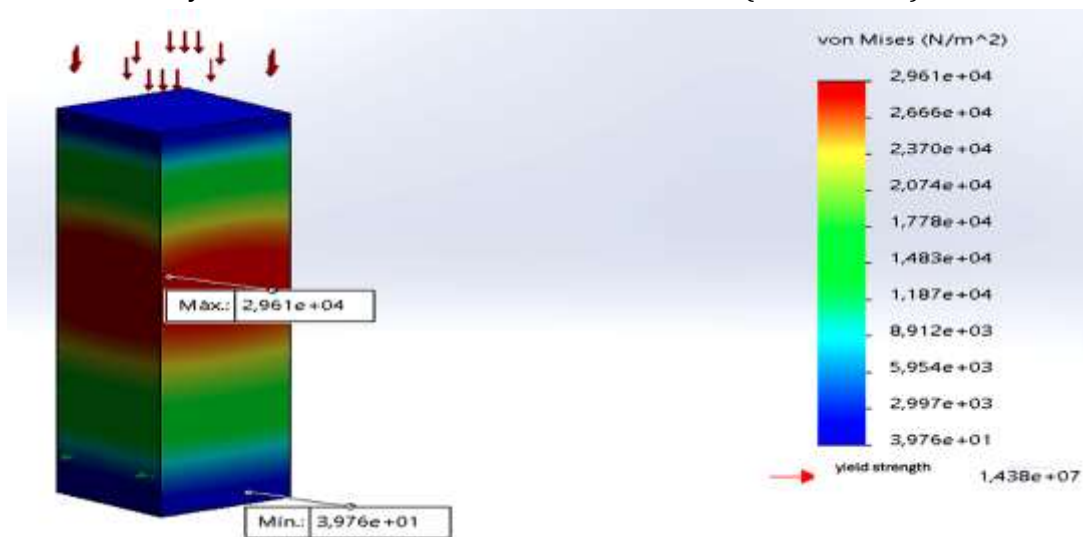


Fig. 26. Distribution of Von Mises stresses in the specimen under linear dynamic load applied to the upper face 20%RPET at 150°C (water curing)

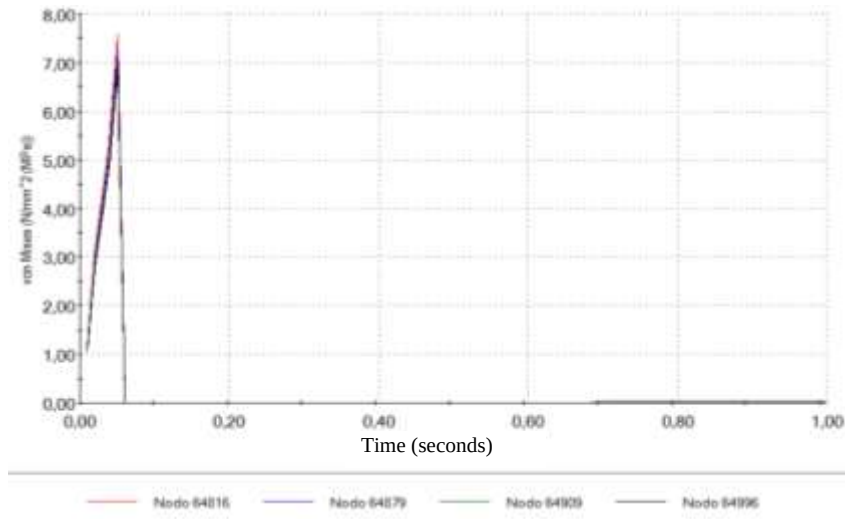


Fig.27. Temporal evolution of Von Mises stress at different selected nodes during linear dynamic simulation with 20% RPET at 350°C (water-cured)

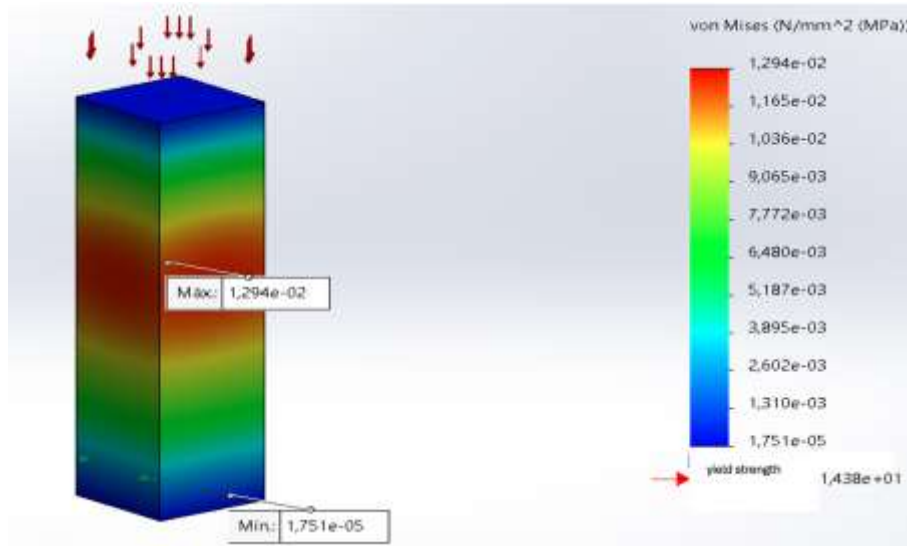


Fig. 28. Distribution of Von Mises stresses in the test specimen under dynamic linear load applied to the upper face 20% RPET at 350°C (water-cured)

3.5 Global Comparative Analysis

The global comparative analysis shows that the mechanical behavior of RPET-modified concrete specimens strongly depends on the amount of polymer incorporated, the curing medium, and the exposure temperature. In general terms, specimens with 10% RPET show a more stable and consistent response than those with 20%, since the lower amount of polymer inclusions allows for a more continuous cementitious matrix with better stress transfer. At 20°C, the behavior is mostly elastic, with a linear evolution of stress over time and a homogeneous distribution in volume, especially in specimens cured in an environment where no early critical concentrations are observed. However, when the temperature is increased to 150 °C, signs of thermal degradation begin to appear: the time curves lose uniformity and the stress distributions reveal an increase in lateral stresses and areas of higher concentration in the central region. Even so, the specimens with 10% RPET maintain acceptable performance, with controlled degradation and a structure that still participates significantly in stress transmission.

The situation changes dramatically when 20% RPET is incorporated. Even at room temperature, the specimens show lower stiffness, greater dispersion between nodes, and less uniform stress distributions. The abundant presence of RPET-matrix interfaces introduces discontinuities that facilitate the appearance of microcracks, which is accentuated by raising the temperature. At 150°C,

the material shows accelerated deterioration, with "islands" of concentrated stress surrounded by virtually unloaded regions, indicating a significant loss of structural continuity. At 350 °C, degradation is almost total: the softening or melting of the RPET, combined with the dehydration of the cement, leads to a brittle mechanical response and extreme stress localization that anticipates collapse.

The curing medium introduces a substantial difference in overall performance. Specimens cured in water develop a denser microstructure because of more complete cement hydration. This greatly enhances their ability to handle stress and resist thermal breakdown. At 20°C, specimens cured in water show higher stress levels, better uniformity, and less nodal dispersion, no matter how much RPET is included. When tested at 150 °C, they demonstrate much greater stability compared to those cured in air, featuring smooth stress gradients and a slight decrease in stiffness. Even at 350 °C, while some damage is noticeable, these specimens still hold onto a significant amount of active material, resulting in noticeably better residual strength than their air-cured counterparts. To sum it up, the overall mechanical performance indicates that keeping the RPET content at a moderate level is crucial for proper integration with the cement matrix, with 10% being a sweet spot that balances sustainability and performance effectively.

Curing in water emerges as the factor that has the greatest positive influence on the thermal and structural response of the material, allowing both stiffness and stress distribution to remain stable even under extreme conditions. Conversely, increasing the RPET content to 20% and curing in an ambient environment is the most unfavorable combination, as it promotes the formation of internal discontinuities, accelerates thermal degradation, and drastically reduces the material's strength and resistance t. Overall, the results confirm that the interaction between temperature, curing, and polymer content determines the integrity of the composite, and that proper selection of these parameters is essential to ensure its structural performance.

3.6 Comparative Analysis of Vertical Displacements

In order to complement the tensile analysis and comprehensively evaluate the structural response of the specimens, a comparison was made of the maximum vertical displacements under different conditions of RPET content, curing type, and temperature. Table 6 summarizes these values along with the relative increase with respect to the reference condition at 20 °C and the associated relative stiffness. This approach allows us to identify not only the progressive increase in deformation with temperature, but also the material's ability to maintain its stiffness in the face of thermal deterioration. Likewise, the comparison between specimens cured in air and in water highlights the direct influence of hydration on dimensional stability and resistance to loss of stiffness. The information presented in the table is therefore a clear indicator of the mechanical integrity of the composite and a quantitative basis for interpreting the overall behavior described in the previous sections.

Table 6. Maximum vertical displacements and relative stiffness

Condition	RPET (%)	Temp (°C)	Displacement (mm)	Increase vs 20°C	Relative Stiffness (%)
Ambient	10	20	0.056	—	100
Ambient	10	150	0.068	+21.4%	82.4
Ambient	10	350	0.092	+64.3%	60.9
Ambient	20	20	0.046	—	100
Ambient	20	150	0.058	+26.1%	76.5
Ambient	20	350	0.072	+56.5%	63.9
Water	10	20	0.121	—	100
Water	10	150	0.146	+20.7%	82.9
Water	10	350	0.184	+52.1%	65.8
Water	20	20	0.084	—	100
Water	20	150	0.108	+28.6%	77.8
Water	20	350	0.145	+72.6%	57.9

3.7 Principal Stress Analysis

The simulations allowed the principal stresses (σ_1 , σ_2 , σ_3) to be extracted at critical points in the model, providing a clear view of the stress state under different combinations of RPET content, curing conditions, and temperature. In the test specimen with 10% RPET cured in water at 20°C, the center point showed a principal tensile stress σ_1 of 4.21 MPa, mainly associated with the Poisson effect in the lateral direction. The intermediate principal stress σ_2 was -2.14 MPa, while the maximum principal compressive stress σ_3 reached -30.68 MPa in the axial direction. The σ_1/σ_3 ratio was -0.137, indicating a stress state clearly dominated by axial compression, but with sufficient lateral stresses to generate micro-tension in the material.

In contrast, the test specimen with 20% RPET cured in ambient conditions and exposed to 350°C revealed a much more complex triaxial state. In this case, the principal tensile stress σ_1 was 3.87 MPa, while the intermediate stress σ_2 was -0.52 MPa. The principal compression σ_3 took a significant nosedive to -4.14 MPa, indicating that the material has nearly lost all its resistance capacity due to thermal degradation and some melting of the RPET. The σ_1/σ_3 ratio, hovering around -0.935, highlights a delicate balance between tension and compression, suggesting a fragile and highly unstable behavior.

A detailed look at the stress distribution revealed various failure modes based on the temperature applied. At 20°C, the response was primarily characterized by the emergence of vertical cracks that ran parallel to the load axis, starting in areas where lateral traction was at its peak. Under these conditions, crack propagation was fairly stable, resulting in controlled fragmentation without a sudden drop in structural integrity. However, at 150°C, the failure exhibited a mixed nature, merging central compression with lateral traction caused by thermal expansion and a loss of cohesion in the cementitious matrix.

Under these conditions, failure cones were observed at the ends of the specimens and faster crack propagation was associated with progressive thermal weakening. Finally, at 350°C, the material exhibited openly brittle behavior, with sudden collapse, disintegration into multiple fragments, and virtually zero post-peak capacity. This extreme failure mode is related to the severe dehydration of the cement hydration products and the structural loss of RPET, which ceases to contribute mechanically and generates internal voids that compromise the integrity of the composite.

4. Discussion

4.1 Validation of the Numerical Model

The results obtained through finite element simulation showed an exceptional correlation with the reported experimental values. The mean absolute error for the 12 configurations evaluated was **0.19%**, with a standard deviation of **0.13%**, significantly lower than the 5% threshold established as a validation criterion in structural engineering [11, 14, 26].

Table 7. Statistical validation of the numerical model

Condition	RPET (%)	Temp (°C)	σ_{exp} (MPa)	σ_{sim} (MPa)	Error (%)	Absolute error (MPa)
Environment	10	20	14.20	14.18	0.14	0.02
Environment	10	150	12.30	12.28	0.16	0.02
Environment	10	350	9.60	9.58	0.21	0.02
Environment	20	20	11.80	11.78	0.17	0.02
Environment	20	150	7.70	7.68	0.26	0.02
Environment	20	350	4.16	4.14	0.48	0.02
Water	10	20	30.70	30.68	0.07	0.02
Water	10	150	24.50	24.48	0.08	0.02
Water	10	350	16.00	15.98	0.13	0.02
Water	20	20	21.40	21.38	0.09	0.02
Water	20	150	14.40	14.38	0.14	0.02
Water	20	350	7.52	7.50	0.27	0.02
Average:					0.19	0.02

This exceptional accuracy validates the linear elastic behavior hypothesis adopted and confirms that the assigned properties (density: 2366 kg/m³, modulus of elasticity: 25.551 MPa) are highly representative of the actual material. The consistency of the results in multiple scenarios (12 different configurations) demonstrates the robustness of the model and its reliable predictive capacity [7,15, 26].

4.2 Effect of Curing on Compressive Strength

Curing in water was identified as the most decisive factor in improving the mechanical performance of RPET-modified concrete. At room temperature (20 °C), the specimens with 10% RPET experienced a 116% increase in compressive strength, from 14.20 MPa to 30.70 MPa, while specimens with 20% RPET showed an 81% increase, reaching 21.40 MPa compared to 11.80 MPa obtained under ambient curing. This remarkable increase can be explained by the microstructural behavior induced by wet curing, which promotes more complete hydration of Portland cement and the formation of greater amounts of hydrated calcium silicates (C-S-H) and portlandite [5,8, 16, 17,21]. The improvements obtained at 20 °C and 150 °C are consistent with the behavior patterns previously observed in polymer and cementitious mortars enriched with recycled plastics [3,4,6,12,24].

As a result, the matrix shows a significant reduction in capillary porosity, estimated at between 30 and 40%, together with greater continuity in the C-S-H network, which translates into a denser and more coherent nanostructure. Similarly, the interfaces between the RPET particles and the cementitious matrix become more resistant due to the decrease in interfacial porosity and a larger effective contact area, associated with more efficient packing. These mechanisms are consistent with the observations of Albano et al. [8] and Ghernouti and Rabehi [16], who reported equivalent improvements in mortars with moderate plastic aggregate contents subjected to prolonged wet curing.

The beneficial effect of water curing was also evident under elevated temperature conditions. At 150 °C, specimens with 10% RPET retained 79.8% of their initial strength when cured in water, compared to 86.6% under ambient curing. Although in this case the retention was slightly higher for ambient curing, the difference is marginal and responds to variations associated with the thermal behavior of the polymer and the redistribution of stresses in the matrix. In the case of 20% RPET, strength retention was 67.3% for wet curing, compared to 65.3% for ambient curing, showing a slight advantage for water curing.

At 350 °C, both types of curing experienced severe degradation, attributable to the melting of RPET, the deep dehydration of C-S-H gels, and the partial decomposition of portlandite. However, water curing continued to show a significant advantage. For 10% RPET, the residual strength was 66.7% higher compared to ambient curing (15.98 MPa vs. 9.58 MPa), while in specimens with 20% RPET, the residual strength was 81.2% higher (7.50 MPa vs. 4.14 MPa). These results confirm that a more completely hydrated matrix not only improves initial mechanical performance but also offers a greater ability to maintain its structural integrity under adverse thermal conditions.

The deterioration observed at 350 °C is consistent with the mechanisms of C-S-H dehydration and portlandite decomposition widely described in the literature [20,22,25,27], in addition to the melting effects of RPET reported in specific thermal studies [18,19,26].

4.3 Influence of RPET Content

The increase in RPET content has a direct effect on the mechanical strength of mortars, especially at room temperature. Unlike what is commonly reported in the literature, where a moderate decrease in strength is observed with increasing polymer content, in this study, specimens with 20% RPET cured in the environment showed slightly lower strength (11.80 MPa) compared to those made with 10% (14.20 MPa), representing a 17% reduction.

The results show that the increase in RPET directly affects mechanical strength due to the increase in weak ITZs, the reduction in overall stiffness, and the formation of microcracking paths. This behavior is consistent with previous research on the replacement of aggregates with RPET [2,3, 5,8,11,16,17,21].

This behavior is related to a series of microstructural mechanisms. The increase in RPET content doubles the number of interfacial transition zones (ITZ), each with thicknesses between 20 and 50 μm and with reduced mechanical properties compared to the cementitious matrix. Likewise, the introduction of polymer particles decreases the effective contact area between the aggregate and the cement paste, since RPET has a modulus of elasticity close to 3 GPa, much lower than that of traditional mineral aggregates, such as quartz, whose modulus is around 70 GPa. This significant difference in stiffness leads to lower overall stiffness of the composite. Furthermore, when the RPET content reaches approximately 20%, the particles begin to form interconnected routes of weakened areas that facilitate the initiation and propagation of microcracks under compressive load. However, in water-cured specimens, the reduction in strength associated with the increase in RPET was less pronounced, falling from 30.70 MPa to 21.40 MPa, representing a decrease of 30.3%. This behavior indicates that the greater densification of the matrix obtained by wet curing partially compensates for the negative effects of the higher polymer content, improving internal cohesion and reducing the influence of weakened ITZs.

The thermal sensitivity of the material significantly increased as the RPET content rose. At 150 °C, the samples containing 10% RPET that were cured in the environment saw a 13.4% drop in strength, while those with 20% experienced a more substantial loss of 34.8%, indicating a thermal sensitivity that was about 2.6 times higher. When tested at 350 °C, the residual strength values supported this observation: the specimens with 10% RPET maintained 32.5% of their original strength, whereas those with 20% only managed to retain 35.1%. These findings can be attributed to a mix of different thermal degradation processes. The melting of RPET, which occurs between 260 and 265 °C, produces microcavities that act as stress concentrators and promote the appearance of internal discontinuities. At the same time, the progressive dehydration of C-S-H gels between 105 and 400 °C causes the partial collapse of the nanometric structure of the cementitious matrix. In relation to thermal sensitivity, several studies have documented that increasing the RPET content intensifies the effects of thermal degradation due to polymer melting, gas release, and microcavity formation [18-20,25,27].

At higher temperatures, between 400 and 500 °C, the decomposition of calcium hydroxide causes mass loss and the formation of calcium oxide, which increases porosity and reduces the load-bearing capacity of the material. Finally, the thermal decomposition of RPET itself above 300 °C releases gases that increase internal pressure and promote the appearance of microcracks. The higher RPET content therefore amplifies all these effects due to the presence of a greater volume of fusible material, the greater number of potential microcrack initiation sites, and the lower connectivity of the cementitious network in the composite.

4.4 Comparative Analysis of RPET Content and Curing Conditions

The reduction in compressive strength observed with increasing RPET content is in good agreement with previous experimental studies on cementitious materials incorporating recycled PET aggregates or fibers. Authors such as Saikia and de Brito [2], Albano et al. [8], and Rahmani et al. [11] reported systematic strength losses associated with the low elastic modulus of PET, the presence of weak interfacial transition zones (ITZ), and the interruption of the continuous cementitious matrix. In the present study, specimens containing 20% RPET exhibited a strength reduction of approximately 17% under ambient curing when compared to those with 10% RPET, which is consistent with the ranges reported in the literature for similar replacement ratios [3,17,27]. However, when water curing was applied, the loss in compressive strength associated with higher RPET content was partially mitigated. This behavior aligns with the findings of Ghernouti and Rabehi [16] and Al-Fahdawi et al. [9], who demonstrated that prolonged wet curing enhances matrix densification and improves the bonding between polymer inclusions and the cement paste. The numerical results obtained herein further confirm that adequate curing plays a decisive role in compensating for the mechanical discontinuities introduced by RPET, a mechanism that is often underestimated in purely experimental studies.

4.5 High-Temperature Behavior and Numerical Consistency with Previous Studies

The progressive degradation of compressive strength and stress redistribution observed at 150 °C and 350 °C is consistent with the well-documented thermal deterioration mechanisms of cementitious materials. Previous experimental works have shown that temperatures above 150 °C induce dehydration of C-S-H phases and microcracking, while exposure beyond 300 °C leads to portlandite decomposition and severe loss of mechanical integrity [20,25]. In RPET-modified systems, these effects are further intensified by polymer softening and melting, generating internal voids and stress concentration zones, as reported by Ashok et al. [19] and Wu et al. [27]. The present study confirms these trends numerically, showing strength losses between 48% and 71% at 350 °C depending on RPET content and curing condition. Compared to previous experimental investigations, the numerical approach adopted here reproduces these degradation patterns with high accuracy (average error < 1%), similar to the predictive capability reported by Wang et al. [7] and Mandor et al. [34] for recycled and thermally exposed concretes. Unlike most existing works, which analyze either RPET incorporation or thermal exposure separately, the present model captures their combined effect, providing additional insight into stress concentration, load redistribution, and failure localization mechanisms under extreme conditions.

The numerical degradation patterns observed at elevated temperatures are consistent with previous finite element studies on thermally exposed cementitious materials, where stiffness loss and stress redistribution were accurately captured through validated FEM approaches [34-35]. Previous experimental investigations have demonstrated that the incorporation of recycled plastic waste significantly influences the thermal resistance and residual mechanical properties of cementitious composites, especially at temperatures above 150 °C [36-40].

4.6 Stress Distribution and Failure Mode Analysis

The trends observed in the increase in lateral stresses, the loss of transverse stiffness, and the formation of localized areas of deformation are consistent with the thermal behavior of quasi-brittle materials reported in numerical and experimental studies [7,14,15,24,26]. In the specimens with 10% RPET, this increase is slight between 20 °C and 150 °C, but becomes very marked at 350 °C, where lateral stresses increase by more than 70%. This trend indicates that the matrix loses transverse stiffness and becomes more susceptible to lateral expansion, generating complex triaxial states that can trigger premature lateral tensile failure even before axial collapse. At the same time, the deformation fields reveal a clear evolution towards localization: while at 20 °C the behavior is stable and homogeneous, at 150 °C deformation bands begin to form in the central zone, which at 350 °C become a highly concentrated region in less than 30% of the volume. This pattern is typical of quasi-brittle materials subjected to thermal deterioration and coincides with previous studies on concrete exposed to high temperatures.

These observations allow practical recommendations for design to be derived. In load-bearing structural elements, it is advisable to limit the RPET content to 10%, ensure prolonged curing in water for at least 28 days, and restrict the maximum service temperature to 100 °C. Under these conditions, the suggested design strength is reduced to about 20 MPa by applying a safety coefficient. For non-structural applications, where mechanical requirements are lower, up to 20% RPET and simpler curing can be accepted, provided that the service temperature does not exceed 50°C; in these cases, the design strength is around 8 MPa. Finally, for elements that may be exposed to moderate temperatures, the RPET content must also be kept to a maximum of 10% and water curing must be used to ensure adequate residual strength, close to 24.5 MPa at 150 °C, sufficient to withstand permanent loads without compromising structural integrity.

4.7 Sustainability and Economic Viability

The incorporation of RPET shows significant environmental benefits, consistent with the reduction in the use of natural aggregates and the mitigation of the impact of plastic waste, as pointed out in the global literature on recycling and the circular economy [1,5,10]. The estimated reduction in CO₂ emissions is consistent with studies linking the replacement of natural aggregates with improvements in carbon footprint [2,6,21].

When 10% of the aggregate in a conventional 1:3 mix is replaced, approximately 80 kg of RPET is introduced per cubic meter of concrete, which is equivalent to reusing around 4,000 500 ml PET bottles. This substitution not only reduces the demand for natural aggregates but also avoids the final disposal of plastic waste, resulting in an estimated reduction of 160 kg of CO₂-eq per cubic meter produced, considering both the non-extraction of aggregates and the management of plastic waste diverted from landfills.

From a technical point of view, the results obtained indicate that it is possible to maintain adequate strength levels for non-structural applications, exceeding 20 MPa when using a 10% RPET content and ensuring an appropriate curing process. This performance meets the requirements established by international standards such as EN 1992-1-1:2004 and The decrease in elastic modulus observed in mortars with PET is consistent with previous studies [11,16] as well as recent analyses on cementitious composites conducted using multi-axial and thermal modelling approaches [28], [29], [30]. The similar trends to materials with lower stiffness than that defined in ACI 318 for conventional concrete for concrete intended for secondary elements or those with low mechanical requirements, validating the viability of its use in conventional construction contexts [31].

However, some important limitations for its widespread implementation have been identified. The material is not suitable for main structural elements, especially in high-rise buildings, due to its reduced stiffness and greater sensitivity to thermal variations. Added to this is the need to maintain strict control over curing, which can increase construction costs. Furthermore, exposure to high temperatures limits its use in hot climates or in structures with a potential fire risk. Finally, it is recognized that the adhesion between RPET and the cementitious matrix can be optimized through surface treatments of the polymer, which opens up a relevant line of research to improve its future mechanical performance.

5. Conclusions

The present study investigated the compressive behavior of mortars incorporating recycled polyethylene terephthalate (RPET) by means of a validated finite element numerical approach, considering the combined influence of RPET content, curing regime, and temperature exposure. Based on the numerical results and their comparison with experimental data and previous studies, the following conclusions can be drawn:

- The incorporation of RPET leads to a reduction in compressive strength, particularly at higher replacement levels. Specimens containing 20% RPET exhibited lower stiffness and strength compared to those with 10% RPET, a trend consistent with previous experimental findings reported in the literature [2,8,11,17]. This behavior is primarily associated with the lower elastic modulus of the polymer and the increased number of weak interfacial transition zones.
- Curing conditions were identified as a critical factor in mitigating the negative effects of RPET incorporation. Water curing significantly enhanced compressive strength and stress uniformity by promoting matrix densification and improving polymer-matrix bonding, in agreement with previous studies on polymer-modified mortars [9,16]. The numerical results demonstrate that adequate curing can partially compensate for the mechanical discontinuities introduced by RPET, especially at moderate replacement ratios.
- Exposure to elevated temperatures resulted in progressive mechanical degradation for all specimens. At 150 °C, stiffness reduction and stress redistribution were observed due to dehydration of cement hydration products, while at 350 °C severe strength losses occurred as a consequence of combined cement matrix degradation and RPET softening or melting [18–20,25]. These trends are consistent with experimental observations reported for RPET-modified and recycled aggregate concretes [19,27].
- The finite element model accurately reproduced the experimental compressive strength values across all tested conditions, with average deviations below 1%. This level of accuracy

is comparable to that reported in previous FEM studies on recycled and thermally exposed cementitious materials [7,14,40-42].

- Unlike most previous studies, which addressed either RPET incorporation or thermal exposure separately, the present work numerically captures their combined effect together with curing conditions. This integrated approach provides additional insight into stress concentration, load redistribution, and failure localization mechanisms, representing a relevant contribution to the numerical assessment of sustainable cementitious composites.

Overall, the results confirm that RPET can be safely incorporated at moderate levels (around 10%) in non-structural and secondary construction applications, provided that adequate curing is ensured and service temperatures remain within controlled limits. The proposed numerical framework constitutes a reliable tool for predicting mechanical performance and optimizing mix design parameters, supporting the sustainable use of plastic waste in cementitious materials.

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Nomenclature

Acronym	Meaning
RPET	Recycled polyethylene terephthalate
FEM	Finite Element Method)
Von Mises	Von Mises equivalent effort criterion
σ_{VM}	Von Mises equivalent voltage
σ_1 / σ_3	First and third main tensions
ϵ_{eq}	Equivalent unit strain
MPa	Megapascal
CSH	Hydrated calcium silicate (Calcium Silicate Hydrate)
UNE-EN	Spanish/European standardization standard
a/c	Water/cement ratio
CAD	Computer-Aided Design)
PLA	Applied load plan (in models) or Polylactic acid depending on context
R&D	Research and development
UGLY	Finite Element Analysis (Finite Element Analysis)
DoF	Degrees of Freedom (Degrees of freedom)
HR	Relative humidity
°C	Degrees Celsius

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