

Research Project for Sustainable Highway Barriers

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This research project focuses on the application of innovative reinforced concrete (RC) solutions for the development of vehicular safety barriers on motorways. The project integrates hybrid reinforcement systems with low-carbon concrete mixes to drastically reduce the environmental impact while enhancing structural performance and durability.

1 Case description

Italy's road network is among the most extensive in Europe, with the national highway system (Autostrade) spanning approximately 8,000 kilometers and the total road network exceeding 160,000 kilometers. A significant portion of this network is equipped with reinforced concrete safety barriers, which play a critical role in ensuring vehicle containment and roadside safety. Given the ubiquity and structural mass of these barriers across the country, their environmental footprint (primarily stemming from concrete production and steel reinforcement) represents a substantial component of the overall carbon emissions in the transport infrastructure sector.

As the demand for durable and low-maintenance infrastructure increases, and in alignment with European Green Deal targets and the 2050 climate neutrality objectives, the importance of identifying and implementing sustainable alternatives for RC barriers becomes increasingly clear. These elements, due to their volume, repetition, and exposure to harsh environmental conditions, offer a unique opportunity to scale the benefits of green technologies. Enhancing the sustainability of concrete safety barriers through the use of recycled materials, supplementary cementitious materials (SCMs), and corrosion-resistant reinforcements not only contributes to reducing greenhouse gas emissions but also extends the service life of the infrastructure, reduces lifecycle maintenance costs, and supports circular economy principles.

A significant characteristic of this project is its integration of geopolymers and supplementary cementitious material (SCM)-based concretes with hybrid reinforcement solutions, combining steel, FRP bars, and fiber reinforcement to meet structural and sustainability objectives. The research has already included full-scale experimental validation of reinforced concrete members under realistic loading scenarios (Figure 1), providing strong empirical evidence for their reliability. Most notably, the environmental impact of these innovative solutions demonstrates a reduction of more than 60% in greenhouse gas emissions when compared to conventional reinforced concrete structures.

From an environmental, economic, and social standpoint, the project yields multiple benefits. The carbon footprint of reinforced concrete is reduced by up to 70% through the use of optimized binder compositions and recycled aggregates. Durability is significantly improved through the use of corrosion-resistant reinforcements, leading to a substantial decrease in maintenance requirements over the life cycle of the barrier. Furthermore, by incorporating recycled and artificial aggregates, the project contributes meaningfully to the circular economy, promoting resource efficiency and reducing reliance on virgin raw materials.

DETAILED OVERVIEW:

- OBJECTIVES: Design, test, and evaluate sustainable RC solutions for highway safety barriers
- LOCATION: Italy, experimental campaign conducted at University of Brescia with support from Mapei S.p.A. and ANAS S.p.A.
- KEY STAKEHOLDERS: University of Brescia, Mapei S.p.A., ANAS S.p.A.

SCOPE:

- Application of new reinforcement and concrete technologies in RC beams simulating highway barriers
- Validate structural behavior, durability, and environmental performance

DEMANDS:

- Meet regulatory performance standards for impact and durability
- Lower embodied carbon and enable reuse of secondary materials

STRUCTURAL CONFIGURATION AND ENGINEERING CONSIDERATIONS:

- Rectangular RC beams (20 × 30 cm cross-section, 360 cm span)
- Structural response assessments via four-point bending tests (4PBTs)
- Reinforcement strategies:
 - Steel reinforcement only
 - Steel reinforcement and macro-synthetic fibers
 - Hybrid steel reinforcement + GFRP bars + macro-synthetic fibers

2 Suitability enhancement rationale

The suitability of the innovative solution is significantly enhanced by the integration of hybrid reinforcement systems (combining steel, GFRP bars, and FRC and the use of ecofriendly concretes such as those obtained with CEM III and CEM IV cements and geopolymers binder. These reinforcements are embedded longitudinally, while synthetic fibers replace traditional stirrups to resist shear forces. FRP offers a corrosion-resistant and lightweight alternative to steel, while FRC contributes to superior crack control and ductility. Sustainable concretes minimize binder content and utilize recycled aggregates, aligning with sustainability goals. These enhancements collectively yield improved load-bearing capacity, greater deformation capacity (a 125% increase), and notable improvements in durability, including resistance to freeze-thaw cycles, sulfate attacks, and water penetration. These outcomes are validated by full-scale bending tests (Figure 2) and durability results (Figure 3).

3 Environmental impact evaluation including comparison with traditional solutions

The environmental assessment of this project was conducted in accordance with the UNI EN 15804 standard, specifically focusing on stages A1 to A3, which cover the supply of raw materials, transport to the production site, and product manufacturing. The analysis encompasses material volumes, reinforcement types, and logistical factors. Compared to conventional solutions, the reference concrete mix (REF) exhibits a global warming potential (GWP) of 360 kg_{CO2} per cubic meter. In contrast, an ecofriendly mix (ECO3) achieves a GWP of 180 kg_{CO2}/m³, and the geopolymer (GEO) mix goes even further, reducing it to 92 kg_{CO2}/m³. At the structural scale, beams reinforced

with hybrid systems (T8) show an overall embodied carbon value of 153 kg_{CO2}/m³. This equates to a 66% reduction in emissions compared to traditional beams (T1).

4 Economic and societal considerations including comparison with traditional solutions

While the adoption of FRP bars and FRC in the construction of RC barriers introduces higher upfront material costs, the overall economic viability improves due to several offsetting benefits. Corrosion-resistant materials can significantly lower long-term maintenance expenses and extend the functional lifespan of structures (potentially up to 100 years when geopolymer concrete is used). Enhanced material efficiency, due to better mechanical performance, allows for reduced overdesign, resulting in cost savings over the project lifecycle. From a societal perspective, these sustainable barriers provide safer infrastructure through improved ductility and post-cracking behavior, and they reduce installation time and on-site disruptions by simplifying construction practices (e.g., using fibers instead of stirrups). The project also supports the local circular economy by utilizing construction and demolition (C&D) waste as aggregate. When compared to traditional alternatives, the innovative barrier systems perform on par or better in terms of strength and deformation behavior. Additionally, indicators like Concrete Sustainability Potential (CSP) show that the advanced barrier systems can deliver up to five times the structural efficiency per unit of CO₂ emitted (Figure 4).

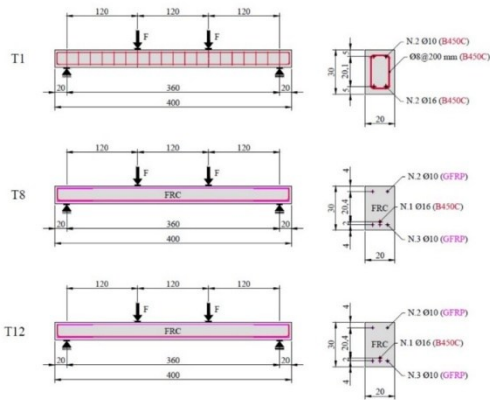


Figure 1: Four point bending test

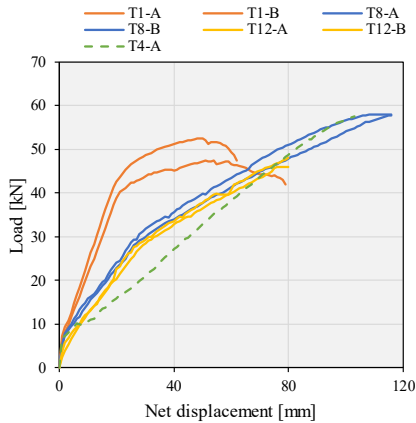


Figure 2: Structural response of beams

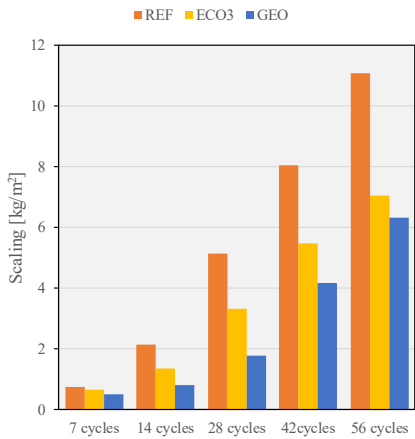


Figure 3: Freeze-thaw cycles resistance test results

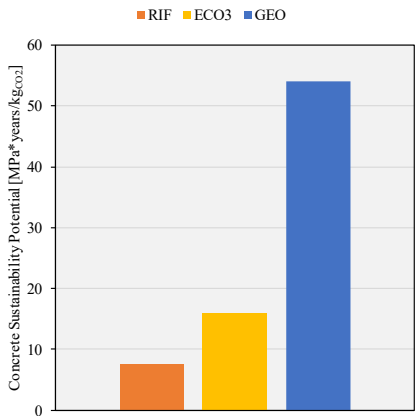


Figure 4: Concrete Sustainability Potential

5 Regulatory compliance and standards in the project

The project adheres to all relevant Italian and European technical standards. Concrete mix design and production comply with UNI EN 206:2021 and UNI 11104:2016, while structural performance and modeling conform to the NTC 2018 (Italian Structural Code). Specific guidelines from CNR-DT 203 and 204 are followed for FRP and FRC applications, respectively. Although innovative materials like FRP require specific design considerations (particularly for crack-width control and stiffness) the project has successfully navigated these challenges through experimental calibration and the application of the CSLLPP Guidelines for FRC issued in 2021 and 2022. This comprehensive regulatory approach ensures that the innovative solutions meet both structural reliability and safety standards.

6 Potential for upscaling innovation

The technologies tested in this research show strong potential for replication across a variety of infrastructure contexts beyond safety barriers. The systems developed can be adapted for use in bridges, tunnels, retaining walls, and noise barriers. The main advantages of upscaling include a considerable reduction in life-cycle costs and enhanced durability in aggressive environmental conditions. Nevertheless, challenges remain, such as market acceptance, limited familiarity among designers, and a lack of standardization in some design methods for hybrid materials. These barriers can be overcome through broader pilot applications, targeted policy incentives promoting low-carbon construction, and the development of digital design tools tailored to hybrid reinforcement systems. The scalability of these innovations supports their role in a broader strategy for achieving carbon-neutral infrastructure.

7 References and background documents

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