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Estimation of Elastic Modulus of Concrete in Existing Structures

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Abstract

The accurate estimation of the elastic modulus (E) of existing concrete is a basis for safe, cost-effective tunnel assessment and rehabilitation. Yet mainstream design codes—Eurocode 2 and the CEB-FIP Model Code 2010—were calibrated on laboratory-cured concretes ≤ 90 days old and omit the long-term degradation that centennial-age tunnel linings undergo. This thesis addresses that gap through a combined experimental and analytical programme focused on Italy's extensive network of historical tunnels (1864–1991).

Eleven cylindrical cores extracted from nine representative road and rail tunnels were tested for compressive strength (EN 12504-1) and static secant modulus (EN 13412). Direct comparison showed raw Eurocode 2 and MC-2010 predictions to err by a mean absolute percentage error (MAPE) of ~19 % and exhibit individual over-stiff biases up to +36 %. Era-grouped analysis revealed systematic drift: mid-century linings (H2, 1920–1980) were over-predicted by ~+10 %, whereas post-1980 linings (H3) were under-predicted by ~–8 %.

To reconcile code and reality, a pragmatic calibration scheme was developed, retaining the Eurocode backbone while introducing three easily obtainable calibration factors—construction era (k_{era}), circumferential position (k_{pos}), and portal-distance (k_{PD})—and a global safety factor γ=1.15 to bound residual scatter. The calibrated model reduces MAPE to 17 %, trims the maximum unconservative bias to +25 %, and yields a balanced mean bias (~–2 %). A step-by-step protocol and worked examples demonstrate how the corrected design modulus improves serviceability predictions (convergence, crack width), influencing retrofit sizing and cost by up to 40 %.

This work delivers the first region-specific, code-compatible method for stiffness appraisal of aged tunnel concrete in Italy—and by extension, similar European contexts—bridging laboratory-day formulas and field-aged reality. It provides practitioners with a defensible, immediately implementable tool, while outlining a roadmap for expanding and refining the calibration as additional core data and non-destructive tests become available.

Acknowledgement

All praises are for ALLAH Almighty, the Most Gracious and the Most Merciful, for bestowing me with the strength, patience, and guidance necessary to complete this journey. It is with His blessings that I have been able to conduct this research and emerge with profound learning and growth. I would like to express my extreme gratitude and respect to the Prophet Muhammad (SAW), whose teachings and exemplary life have always been a beacon of guidance towards leading a better, more purposeful life.

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1. Introduction

The performance and safety of Europe's aging infrastructure has become a pressing concern for engineers and public authorities. In particular, the structural assessment of concrete used in historical tunnels poses a unique technical and practical challenge. Unlike newly built structures where standardized design codes and quality controls apply, older tunnels—some over a century in age—often lack detailed construction records, making it difficult to accurately predict their behaviour under current and future loads. Among the various parameters that define concrete performance, the modulus of elasticity plays a critical role. While compressive strength is commonly measured and monitored, the modulus of elasticity governs stiffness, deformation, and serviceability under load, making it a vital parameter that, although increasingly recognized in structural assessments, remains difficult to estimate accurately in aging tunnel infrastructure where original design documentation is often sparse or incomplete.

Italy illustrates the problem vividly. The national inventory lists approximately 1600 railway tunnels and more than 2000 highway/road tunnels, with a combined length about 2600 km for road tunnels alone. Over half were completed before 1950, using materials and workmanship that evolved continuously between the mid-nineteenth and late-twentieth centuries. Continued service therefore hinges on accurately characterising the residual mechanical properties of their concrete linings.

The parameter that most strongly controls serviceability is the secant modulus of elasticity (E), which governs stiffness-driven responses such as deflection, crack width, and lining–ground interaction. Whereas compressive strength can usually be determined with relative ease, E is difficult to quantify for heritage tunnels where coring is restricted, and the concrete has experienced decades of chemical and mechanical ageing. Mis-estimating stiffness—whether by over- or under-prediction—has practical consequences: avoidable retrofit costs at one extreme, unconservative safety assessments at the other. Accurate estimation of elastic modulus is therefore not merely an academic concern but a matter of structural safety, rehabilitation strategy, and resource optimization.

The following sub section provides the geographical and historical development of tunnel infrastructure in Italy to frame the context of this research.

1.1 Background and Context

Beneath the rolling hills, alpine ridges, and coastal slopes of Italy lies an extensive infrastructure: a vast network of tunnels that have sustained the country's mobility for over a century. From the brick-masonry galleries bored for the inaugural Turin–Genoa railway in the 1850s to the reinforced-concrete motorways driven during the post-war 'Autostrade' boom, these underground arteries mirror shifts in engineering practice as well as in the peninsula's economy and topography.

Yet today, many of these tunnels—once symbols of progress—stand as aging sentinels, whose structural integrity must be reconsidered in the face of time. Figure 1 illustrates the distribution of tunnels across Italy by total length and quantity, offering a snapshot of the country's extensive subterranean infrastructure as of 2018.

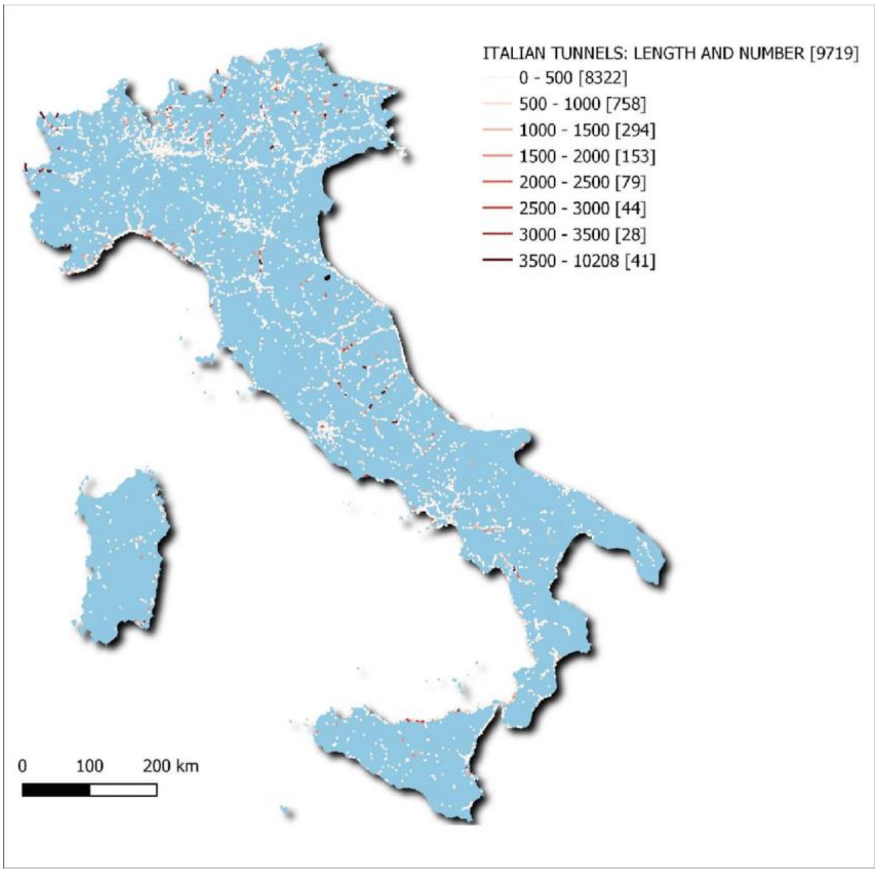

Figure 1 Tunnels in Italy by Length and Number, Source: ISTAT

Inspection campaigns carried out since **2016** have identified concrete deterioration—carbonation fronts up to **40 mm**, leaching, and micro-cracking—in more than **30 %** of sampled linings **(ANAS 2019; RFI 2021)**, triggering a rise in rehabilitation projects across Italy, France, Switzerland, and Germany. Hence, aging infrastructure has risen to the top of the civil engineering agenda across Europe. The increasing frequency of rehabilitation works on road and railway tunnels in countries like France, Switzerland, and Germany highlights a sobering reality: much of the underground infrastructure built in the 19th and 20th centuries is still in operation, often under intensified service demands and deteriorating conditions. In Italy, several tunnel retrofitting programs launched after routine inspections revealed substantial degradation in concrete linings—prompting renewed attention to the mechanical behaviour of historical concrete under in-situ conditions.

Concrete, the world's most widely used construction material, forms the foundation of modern infrastructure—bridges, buildings, dams, and tunnels—providing the rigidity and longevity required for load-bearing elements. However, as infrastructure networks age, a growing engineering challenge arises on how to accurately evaluate the residual mechanical properties of concrete in existing structures. These properties are essential for assessing structural performance, verifying serviceability, and making informed decisions regarding maintenance, rehabilitation, or replacement. Concrete, while robust and economical, is not immutable. Over time, its stiffness, strength, and durability evolve in response to chemical, mechanical, and climatic factors. These observations expose a broader engineering dilemma: how to quantify the residual mechanical properties of concrete that has already endured decades of chemical, mechanical, and climatic actions. Laboratory-derived prediction models, calibrated on young, factory-cured specimens, rarely capture the in-situ behaviour of linings. With original mix designs often undocumented, the key question becomes how engineers can determine the stiffness of concrete that is 40, 80, or even 150 years old—quickly, safely, and with defensible accuracy.

This challenge is far from theoretical. In Italy alone, hundreds of tunnels constructed between the 1860s and 1990s are still operational. These structures vary dramatically in terms of geometry, material composition, construction techniques, and maintenance history. Engineers tasked with evaluating their safety often work with partial information, and an urgent need for data that reflects actual in-situ conditions, not theoretical assumptions.

Among the parameters that govern the mechanical response of concrete, the modulus of elasticity (E) plays a decisive role. It defines the stiffness of the material and influences deformation behaviour under service loads. Whether in seismic vulnerability assessments, crack control design, or numerical simulations using FEM, E is fundamental to predicting how a structure will perform. In structural engineering, concrete's mechanical properties directly influence the integrity, durability, and longevity of infrastructure. Among these properties, the modulus of elasticity, also known as the elastic modulus or Young’s modulus, plays a crucial role. It defines the relationship between stress and strain within the elastic limit of the material, thereby characterizing the stiffness of concrete. Precise knowledge of concrete stiffness is essential for analysing structural behaviour, predicting deflections, assessing load-bearing capacity, and ensuring overall serviceability and safety (Neville, 2011). For newly constructed concrete structures, standardized testing procedures and prediction models typically offer reliable assessments. However, existing structures, particularly tunnels and other infrastructural elements subjected to decades of service conditions, introduce unique complexities and uncertainties into the estimation process (ACI Committee 228, 2019). Empirical models commonly used to estimate E from compressive strength—such as those found in Eurocode 2 or ACI 318—are typically based on data from laboratory-cured, modern concrete. Their reliability for decades-old concrete, exposed to field conditions for generations, is uncertain and often questionable.

In this context, experimental campaigns involving core extraction and laboratory testing become not just beneficial but essential. By physically sampling the concrete from tunnel linings and measuring both compressive strength and static modulus under standardized protocols (EN 12504-1 and EN 13412), engineers can obtain the mechanical fingerprints of historical concrete. This enables the creation of region-specific, age-adjusted correlations, tailored to real-world conditions found across Italian infrastructure.

This thesis builds upon such an initiative. Using core samples extracted from Italian tunnels constructed between 1864 and 1991, it aims to explore the relationship between compressive strength and elastic modulus in concrete that has endured generations of use. The objective is twofold: first, to generate empirical data on the mechanical behaviour of historical concrete from tunnels; and second, to evaluate the adequacy of established estimation models (Eurocode, ACI, CEB-FIP) when applied to aged European structures.

Far from being a purely academic exercise, this study contributes to a pressing national and continental need: equipping engineers with the tools and understanding necessary to preserve, retrofit, and responsibly manage the underground infrastructure that continues to serve Europe’s transport lifelines.

1.2 Concrete Aging in Tunnels

The behaviour of concrete over time is governed by a complex interplay of chemical, physical, and environmental factors that gradually alter its mechanical properties. In tunnel structures—often located in persistently high-humidity, low-light, or geologically active environments—these aging processes can be particularly pronounced and unpredictable. Unlike exposed infrastructure, tunnels age in more stable but moisture-rich conditions, which can accelerate internal deterioration mechanisms such as carbonation, leaching, alkali–silica reaction (ASR), and microcracking. Long-term monitoring shows that carbonation depths can reach 20–40 mm in 80- to 100-year-old Italian linings (Fantilli et al. 2023). Field surveys along Alpine highway tunnels have recorded mean carbonation fronts of 11–12 mm, with peaks up to 40 mm in 40-year-old linings (Paglia & Antonietti, 2022). When these effects accumulate over decades, the mechanical characteristics of the concrete—especially its modulus of elasticity—may diverge significantly from their originally calculated values.

One of the most critical aging mechanisms is carbonation, a slow reaction between carbon dioxide and calcium hydroxide in the concrete matrix that leads to a decrease in pH. While this phenomenon is often associated with reinforcement corrosion, it also modifies the stiffness of the concrete by affecting the microstructure of the cement paste. Similarly, leaching—the loss of calcium hydroxide due to prolonged exposure to percolating groundwater—can weaken the matrix and reduce stiffness and strength over time. Tunnels subjected to decades of groundwater seepage, fluctuating humidity, and freeze–thaw cycles are especially vulnerable to such degradation.

Additionally, microcracking induced by thermal fluctuations, shrinkage, and creep results in a redistribution of internal stresses and reduction in elastic modulus. Although not visible to the naked eye, these micro-defects progressively reduce the load-bearing capacity and deformation resistance of aged concrete. Fantilli et al. (2023) reported that 70- to 90-year-old tunnel concretes in north-west Italy exhibit a 15–30 % drop in secant modulus and reach non-linear stress–strain behaviour at only 40 % of their nominal compressive strength, a response not captured by standard design models. The following figure illustrates the primary aging mechanisms in tunnel concrete, including carbonation, leaching, and microcracking, and their cumulative effect on the reduction of elastic modulus over time.

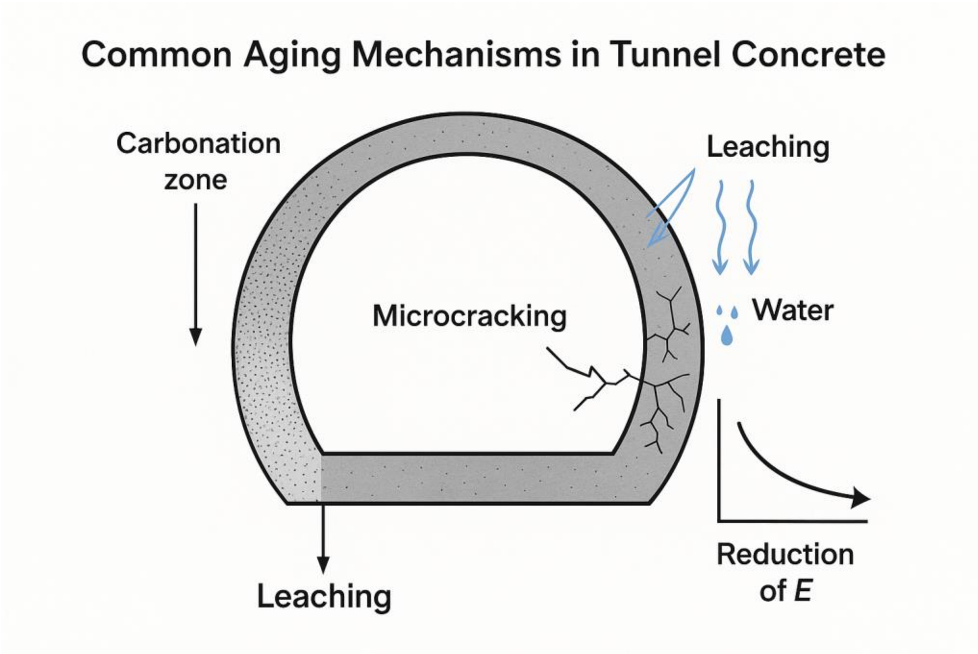

Figure 2 Aging mechanism in Tunnel concrete

The consequences of these aging phenomena are not merely academic. In tunnel maintenance planning, seismic retrofitting, and load rating assessments, engineers rely heavily on accurate estimates of mechanical properties. Overestimating the modulus of elasticity can lead to unsafe structural assumptions; underestimating it may result in unnecessary and costly interventions. Hence, aging must be explicitly considered when evaluating the structural role of concrete in long-service tunnels, especially in contexts where original documentation is lacking and experimental validation is the only reliable method available.

In sum, understanding the aging of concrete in tunnel environments is essential for the safe and economical management of infrastructure. This thesis treats aging not as a peripheral concern, but as a core factor in predicting the mechanical behaviour of tunnel concrete under modern service conditions.

1.3 Significance of Modulus Estimation

In structural engineering, the secant modulus of elasticity (E) is one of the most critical parameters for evaluating a material's stiffness and its ability to resist deformation under load. For concrete structures, especially those subjected to continuous service over decades, an accurate estimate of E is vital for ensuring safe design, reliable performance assessment, and cost-effective maintenance planning. This holds in particular for tunnels, where safety margins are tight, and access for repair or strengthening is often constrained.

The modulus of elasticity directly affects structural response under service loads. It governs lining deflection under overburden and traffic pressure, crack propagation, and load sharing between concrete and reinforcement. In seismic analyses, the stiffness of concrete influences natural frequencies, damping behaviour, and dynamic load paths. In long-span or deep tunnels, even small deviations in E can significantly alter predictions of deformation, lining stress distribution, or interaction with surrounding ground (EN 1992-1-1, 2004).

For new construction, estimating E is relatively straightforward. Design codes such as Eurocode 2 (CEN, 2004), ACI 318-19 (ACI, 2019), and the CEB-FIP Model Code 2010 provide empirical formulas for calculating E based on compressive strength and sometimes density or aggregate type. These models assume a level of uniformity in material composition, curing conditions, and age, and are typically calibrated using modern, laboratory-prepared concrete specimens. Figure 3 illustrates the variation in elastic modulus estimates using Eurocode 2 and ACI 318 formulas across a range of compressive strengths

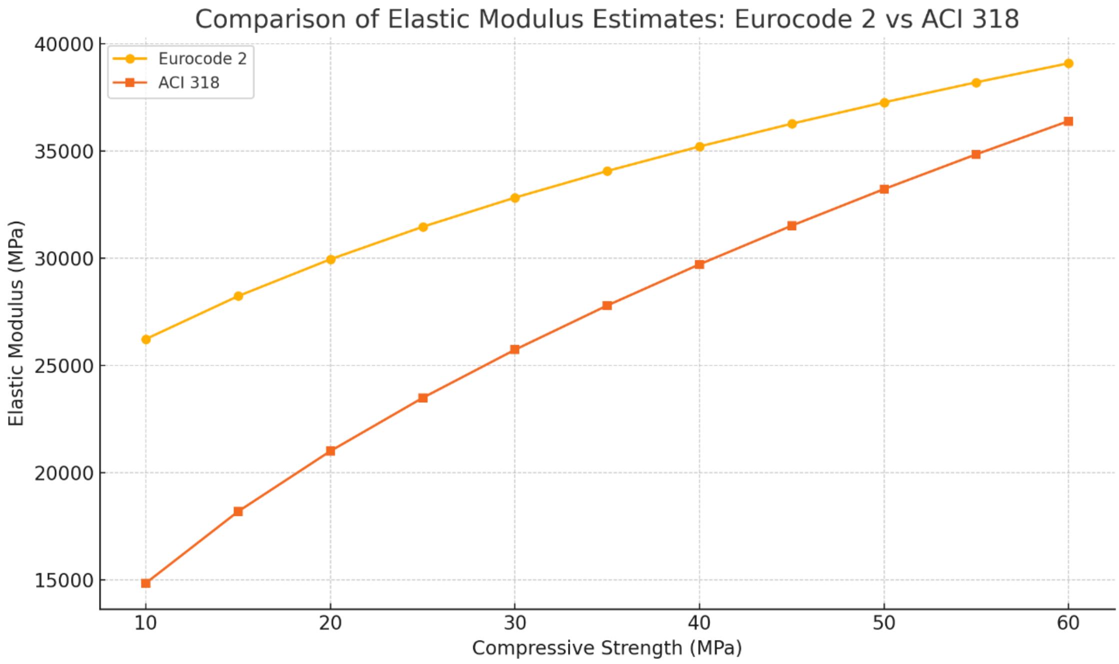

Figure 3 Comparison of Elastic Modulus Estimates from Eurocode 2 and ACI 318 for Various Compressive Strengths

However, in existing tunnel structures—many of which are several decades or even over a century old—these assumptions often do not hold. The actual properties of the in-situ concrete may differ significantly from those predicted by standard models. Variations in historical mix designs, water–cement ratios, aggregate grading, and on-site construction practices introduce uncertainty into stiffness predictions.

Moreover, the effects of long-term degradation mechanisms such as carbonation, leaching, and microcracking (as discussed in Section 1.2) further complicate the mechanical response of the material.

Inaccurate estimation of the elastic modulus in such cases can have serious consequences. Overestimation of stiffness can result in underestimated deflections or crack widths, potentially compromising serviceability or safety. Underestimation, on the other hand, may lead to over-conservative assessments, prompting unnecessary interventions that incur avoidable costs. In tunnel engineering, both outcomes are undesirable: the former risks failure, the latter misallocates resources.

Furthermore, the elastic modulus is a key input in finite element modelling (FEM), which is commonly used for simulating tunnel behaviour under static and dynamic loads. If E is not accurately defined, the model output can lead to misleading stress predictions, misinformed reinforcement design, or improper selection of retrofitting methods. This is especially relevant in Italy, where seismic zones intersect with aging infrastructure, making precise stiffness characterization essential for performance-based seismic assessments.

Given these challenges, relying solely on code-based estimation formulas is insufficient when dealing with aged concrete in critical infrastructure. Project-specific data obtained from in-situ coring and laboratory testing becomes indispensable, enabling engineers to refine code expressions or develop empirical regression models calibrated to actual conditions.

1.4 Review of Estimation Models

Estimating the modulus of elasticity (E) of concrete has long been a subject of practical importance and scientific inquiry in structural engineering. Numerous empirical models have been proposed over the years, most of which establish a relationship between compressive strength and modulus of elasticity. These models are embedded in major design codes such as Eurocode 2, ACI 318 and are widely used in both new structural design and the assessment of existing structures. They offer a convenient, though simplified, method for estimating E.

Eurocode 2 (EN 1992-1-1, 2004)

Eurocode 2 gives the following expression for the mean secant modulus of normal-weight concrete:

$$E_{cm} = 22 \cdot (\frac{f_{cm}}{10})^{0.3} \cdot (\frac{\rho}{2200})^{1.5} \quad (1)$$

where:

- f_{cm} is the mean compressive strength at 28 days (MPa)
- ρ is the density of the concrete (kg/m^3)
- E_{cm} is the secant modulus (MPa)

This formula is calibrated for normal-weight, laboratory-cured concrete, typically up to 90 days old. While Eurocode offers high adaptability across strength classes, it lacks provisions for aging effects, field conditions, or variability in historical mixes.

ACI 318-19 (American Concrete Institute)

For normal-weight concrete in SI units, ACI 318 recommends:

$$E{=}4700\ fc' \quad (2)$$

where:

- $f_c{}'$ is the specified 28-day compressive strength in MPa
- E is the static modulus in MPa

This formula is simple and widely adopted, but it makes a strong assumption: that concrete behaviour is dominated by compressive strength and that other variables—aggregate stiffness, curing regime, or age—are secondary. It does not explicitly incorporate density or environmental exposure, limiting its accuracy for aged or degraded concrete.

CEB-FIP Model Code 1990 and 2010

The CEB-FIP Model Codes provide similar expressions for estimating E, typically in the form:

$$E_{cm} = k_E . {f_{cm}}^{1/2} \quad (3)$$

where k_E is a coefficient that depends on concrete type, density, and curing. The model code 2010 is more flexible which allow adjustments based on curing, age, and environmental class. However, for historical concrete with unknown curing or mix design, many of these input parameters are speculative.

Despite their widespread use, these formulas are built upon assumptions that may not hold for aged or field-exposed concrete. The following table summarizes the main limitations associated with standard modulus estimation models.

Limitation	Description
Age Insensitivity	Calibrated for young concrete (≤ 90 days), not decades-old material.
Modern Mix Bias	Derived from concretes with controlled aggregates, low W/C ratios, and lab curing.
Environmental oversight	Field exposure (carbonation, leaching, creep) is ignored.
Assumed Uniformity	Historical concretes are often heterogeneous and poorly documented.

Table 1 Key limitations of E-estimation models for aged concrete infrastructure.

These limitations are especially relevant in the context of Italy's tunnel infrastructure, where many structures were constructed long before the formal standardization of concrete design. Prior to the adoption of Eurocode 2 (EN 1992-1-1:2004), ratified by CEN on 16 April 2004 and implemented in Italy through national adoption around 2005, Italian engineers relied primarily on national guidelines—such as CNR documents and early versions of the Norme Tecniche per le Costruzioni—which offered only broad empirical guidance for stiffness estimation. Consistent, formula-based estimation of the modulus of elasticity was first codified in the CEB-FIP Model Code 1990, whose empirical relationships that later influenced the development of Eurocode and other modern design standards. As a result, many tunnels built between the late 19th century and the 1980s lacked standardized provisions for evaluating long-term elastic behaviour. This historical gap underscores the need to verify—or recalibrate—modern models when they are applied to aged tunnel concrete still in service today.

1.5 Research Gap

Reliable estimation of the elastic modulus (**E**) in existing concrete infrastructure remains a complex, unresolved challenge. While design codes such as Eurocode 2 and the CEB-FIP Model Code have long provided empirically derived formulas to estimate E from compressive strength, these models were primarily developed for newly constructed, laboratory-cured concrete under standardized conditions. They are based on idealized assumptions—uniform material composition, controlled curing regimes, and short-term mechanical behaviour—that are rarely representative of concrete that has been in service for several decades. When these models are applied directly to aged concrete in existing structures, their reliability diminishes significantly, raising concerns about structural safety, serviceability, and maintenance decisions. Current code-based formulae—developed for laboratory-cured concretes ≤ 90 days old—over-predict stiffness of 70- to 100-year-old tunnel linings by 20 – 40 % (Fantilli et al., 2023). Their underlying assumptions of uniform mix, controlled curing, and short-term behaviour rarely apply to field-aged materials.

This problem is particularly important in the case of tunnel infrastructure. Underground linings are uniquely exposed to sustained groundwater ingress, thermal gradients of ±5 °C, and cyclic traffic loading that collectively accelerate carbonation, leaching, and creep (Paglia & Antonietti, 2022). Over time, tunnel linings experience a variety of aggressive conditions, including continuous or intermittent water ingress, freeze–thaw cycles, sulphate and chloride attack, thermal gradients, and sustained mechanical loads. These factors interact over long periods to induce chemical degradation, physical damage, and microstructural transformations in the concrete matrix—many of which are not accounted for in current estimation models. Moreover, in tunnels built before the widespread implementation of design codes, variability in original material composition, quality control practices, and documentation further complicates the assessment of in-situ mechanical properties.

Italy presents a particularly important context for investigating this issue. The country's extensive network of tunnels—spanning from the mid-19th century through the post-World War II reconstruction era—comprises structures that vary widely in age, construction method, and material performance. Many of these tunnels remain operational today and are subjected to higher traffic demands and environmental stresses than those originally anticipated. As these structures approach or surpass their intended design life, engineers face mounting pressure to assess their structural condition with precision. However, without reliable stiffness data, assessments of deformation behaviour, seismic response, and load distribution remain uncertain.

The modulus of elasticity plays a critical role in all these evaluations. It governs how concrete responds to loads within the elastic range, influencing everything from crack control and deflection prediction to load redistribution and dynamic response. In tunnel applications, accurate estimation of E is essential for finite element modelling, design of retrofitting interventions, assessment of interaction with surrounding soil or rock, and validation of safety margins. Errors in estimating E can have serious consequences: overestimations may result in unsafe underpredictions of deformation or stress, while underestimations may lead to overly conservative designs that waste resources and cause unnecessary disruptions.

The literature reveals a clear gap:

- Field-aged modulus data are sparse. Less than 10 % of Italian tunnel inspections include static-modulus testing (RFI, 2021).
- Empirical models lack ageing terms. None of the mainstream codes incorporate time-dependent degradation coefficients.
- Environmental histories are ignored. Carbonation depth, leach index, and moisture class are absent from design charts.

This thesis addresses the gap with a targeted experimental programme:

1. Core extraction from tunnels spanning 1864 – 1991, covering diverse geology, exposure, and construction eras.
2. Laboratory testing to EN 12504-1 (compressive strength) and EN 13412 (static secant modulus) under controlled humidity and temperature.
3. Model benchmarking: comparing measured E with Eurocode 2 and CEB-FIP predictions to quantify bias and scatter.

Core samples were extracted from tunnels across Italy, representing different geographical regions, construction periods, and exposure conditions. Using standardized test procedures (EN 12504-1 for compressive strength and EN 13412 for elastic modulus), the mechanical properties of these samples were measured under controlled laboratory conditions. These empirical results were then compared with theoretical estimates derived from Eurocode 2 and the CEB-FIP Model Code to assess their predictive accuracy.

The motivation for this research is both scientific and practical. Scientifically, it seeks to enhance understanding of how concrete stiffness evolves under real-world aging conditions. Practically, it aims to improve the tools available to structural engineers, enabling more accurate and cost-effective assessments of tunnel infrastructure. This is particularly relevant in Italy, where ongoing investment in transport resilience and infrastructure sustainability demands precise, data-driven evaluations. More broadly, the research contributes to European efforts in infrastructure preservation, aligning with EU directives on safe mobility, seismic resilience, and lifecycle extension of critical assets.

By combining historical insight, experimental validation, and critical assessment of design models, this study advances the methodology for stiffness evaluation in existing tunnels. It serves as a step toward developing more nuanced, context-specific frameworks for structural assessment that reflect the realities of aging infrastructure across Europe.

1.6 Research Objectives

The principal aim of this thesis is to investigate the relationship between compressive strength and the elastic modulus of concrete and to verify whether existing European formulae (Eurocode 2, CEB-FIP Model Code 2010) can predict the secant modulus of elasticity, for concrete extracted from aged Italian tunnel linings. The study focuses on concrete that has experienced decades of environmental exposure and mechanical demand.

To meet this aim, the work pursues five specific objectives:

- **To collect and analyse concrete core samples** extracted from Italian tunnels constructed between 1864 and 1991, representing a broad range of construction practices, material compositions, and exposure conditions.
- **To measure the compressive strength and static modulus of elasticity** of these samples through standardized laboratory tests in accordance with relevant European norms (EN 12504-1 and EN 13412).
- **To evaluate the predictive accuracy** of Eurocode 2 and the CEB-FIP Model Code by comparing their estimates with experimentally measured elastic modulus values.
- **Develop preliminary adjustment factors** or regression coefficients that improve stiffness prediction for aged tunnel concrete, including confidence intervals suitable for reliability-based design.
- Formulate engineering recommendations for stiffness assessment and retrofit design in historical tunnels where original material documentation is incomplete.

The following diagram illustrates the main goal and objectives of this thesis work.

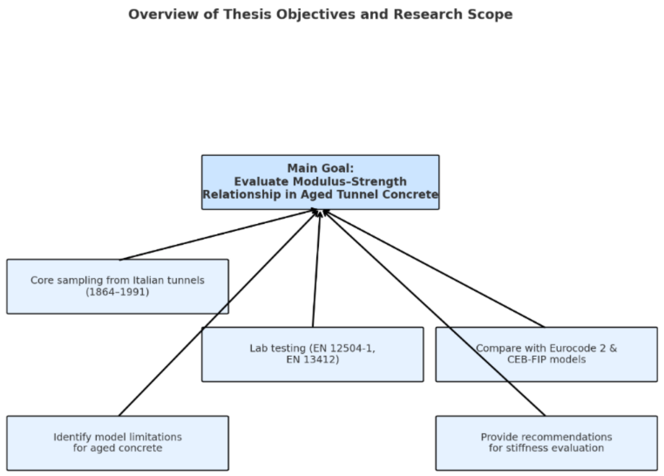

Figure 4 Schematic summary of the thesis aims and objectives.

These objectives aim to strengthen the empirical basis for evaluating mechanical properties in aging concrete structures and to support more informed, safety-focused decision-making for Italy’s extensive underground transport network.

2. Literature Review

This chapter reviews existing research and technical literature relevant to the mechanical characterization of aged concrete in tunnel infrastructure, with a specific focus on the estimation of elastic modulus.

2.1 Overview

The purpose of this literature review is to map the current research landscape, design practices, and code provisions for estimating the elastic modulus (E) of concrete— with emphasis on aged infrastructure. The elastic modulus plays a central role in the analysis and performance assessment of concrete structures, influencing deformation behaviour, stiffness predictions, and the design of retrofitting or rehabilitation strategies. While design codes such as Eurocode 2 and the CEB-FIP Model Code provide standard formulas for estimating E based on compressive strength, their applicability to historical, field-exposed concrete remains a subject of ongoing investigation and debate.

This is especially relevant for tunnel infrastructure in Italy and Europe, where concrete structures built between the 19th and late 20th centuries are still in service today, often without reliable design records or material documentation. Environmental exposure, aging mechanisms such as carbonation and leaching, and non-standard construction practices from earlier eras introduce complexities that challenge the assumptions built into conventional estimation models.

The literature review aims to accomplish the following:

- Summarise the theoretical role of the elastic modulus in structural mechanics.
- Critically examine empirical and code-based estimation models, focusing on European frameworks.
- Synthesize experimental findings on aged concrete, highlighting how mechanical behaviour evolves in service.
- Compile tunnel-specific studies—especially Italian cases—to trace historical construction methods and degradation patterns.
- Identify methodological gaps that motivate the experimental programme of this thesis.

The chapter is structured thematically to guide the reader through foundational concepts before delving into specialized studies relevant to the Italian tunnel case. This literature synthesis not only frames the scope of the research but also reinforces the motivation and originality of this study—namely, the need to generate empirical validation of elastic modulus estimates for historical concrete using standardized testing of core samples.

By the end of this chapter, the reader will gain a clear understanding of how past research informs the present study, where gaps remain in the assessment of aged concrete stiffness, and why updated approaches are needed for responsible infrastructure management in aging European transport networks.

2.2 Theoretical Background on Elastic Modulus

The modulus of elasticity (E) referred to as Young's modulus, is a primary mechanical parameter that defines the linear relationship between stress and strain within the elastic range of a material. For concrete, E indicates material's stiffness and deformation behaviour under service loads. It is essential for evaluating deflections, crack widths, and overall structural response under both static and dynamic loading conditions. As such, E plays a foundational role in serviceability limit states, seismic analysis, and finite element modelling for both new and existing concrete structures.

The modulus of elasticity in concrete is derived from the initial linear portion of the stress–strain curve, representing the material's response under reversible loading conditions. However, as concrete exhibits non-linear and brittle behaviour, the linear range is typically short and varies depending on age, composition, and degradation. To address different stages of material response, engineers distinguish between elastic modulus (E), tangent modulus and secant modulus—each applicable at specific points along the stress–strain curve. This distinction is especially relevant when comparing experimental results with theoretical models calibrated for different stress ranges.

Concrete E is usually quoted as a static secant modulus, taken from the initial linear portion of the stress–strain curve up to about 40 % of the mean compressive strength. Because concrete shows non-linear, brittle behaviour, this linear zone is short and varies with age, composition, and degradation state. Engineers therefore distinguish between:

- Static secant modulus – average slope between the origin and 0.4 f_{cm} ; used in Eurocode 2.
- Tangent modulus – instantaneous slope at a specified stress.
- Dynamic modulus – obtained from resonance or ultrasonic tests; typically, 10–20 % higher than static values (Neville, 2011).

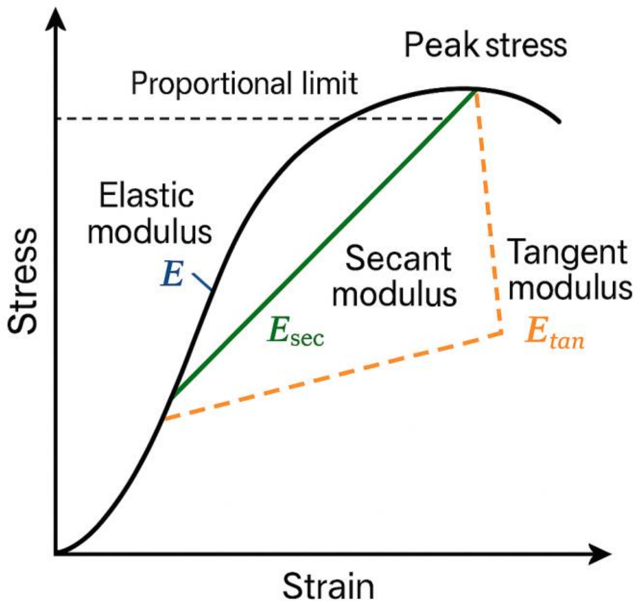

Figure 5 Schematic stress–strain curve for concrete

In most structural applications, E is not measured directly but estimated using empirical expressions that relate it to the compressive strength of concrete. However, this indirect estimation is complicated by the fact that E is influenced by a broad set of parameters beyond strength alone. These include material-specific characteristics (such as mix design and aggregate properties), environmental exposure, and time-dependent degradation processes. The following factors are widely recognized as having significant influence:

- **Compressive Strength:** While compressive strength is the most used parameter for estimating E, the relationship is not strictly linear, and its predictive power diminishes in aged or degraded concrete. Modern codes such as Eurocode 2 and the CEB-FIP Model Code use power-law formulations to approximate this correlation.

- **Aggregate Type and Volume Fraction:** Aggregates largely govern the stiffness of concrete due to their higher modulus compared to the cement matrix. The stiffness of the composite increases with a higher volume fraction and stiffer aggregate type (e.g., basalt vs. limestone), as shown in the studies reviewed by Aïtcin (2000) and Bertolini et al. (2004).

- **Water–Cement Ratio and Porosity:** A lower water–cement ratio typically yields denser microstructures and hence a higher modulus. Conversely, increased porosity leads to lower E, particularly when freeze–thaw or chemical degradation is present.

- **Curing Conditions and Age:** Concrete stiffness increases with continued hydration over time. However, in aged infrastructure, environmental degradation (e.g., carbonation or sulphate attack) often counteracts this gain, leading to modulus reductions after decades of service.
- **Environmental Exposure and Degradation:** Exposure to CO_2 (carbonation), sulphates, chlorides, and leaching agents affects the cementitious matrix, reducing mechanical continuity. Papadakis et al. (2000) demonstrated that the progression of carbonation can significantly alter E by degrading calcium hydroxide and densifying the matrix in ways that may initially increase stiffness but ultimately lead to embrittlement.
- **Creep, Shrinkage, and Microcracking:** Long-term loading leads to creep and time-dependent deformation, which is not captured by short-term elastic modulus measurements. Microcracking, often invisible at the surface, reduces the effective stiffness of the material. RILEM reports and studies by Fantilli et al. have shown that microcracking density increases with age, and correlates with observed reductions in E.

Factor	Influence on E	Citation
Compressive strength	Power-law correlation; predictive scatter ±10 % for young concrete; ±25 % for aged concrete.	CEB-FIP MC 2010; Di Luzio & Cusatis (2013)
Aggregate type & volume	Stiffer, higher-volume aggregates (basalt, quartz) raise EE by up to **35 %** vs. limestone mixes.	Aïtcin (2000); Bertolini et al. (2004)
Water–cement ratio & porosity	Lower W/C and reduced porosity increase EE; freeze–thaw damage can cut EE by **20 %**.	RILEM TC 116-PCD (2002)
Age & curing	Continued hydration increases EE ∝ log(time) up to ~5 years; thereafter degradation may offset gains.	fib Bulletin 73 (2013)
Environmental degradation	Carbonation front ≥ 30 mm or sulphate attack can lower EE by **15–25 %** even when fc is unchanged.	Papadakis et al. (2000); Collepardi (2010)
Creep, shrinkage, micro-cracking	Long-term loading and drying shrinkage generate micro-cracks that reduce EE progressively; density of micro-cracks correlates with up-to-30 % stiffness loss.	Fantilli & Chiaia (2005); RILEM TC 212-ACD

Table 2 Key parameters affecting Elastic Modulus

Dynamic-modulus correlations for non-destructive testing: In many operational tunnels core drilling is restricted, so engineers rely on ultrasonic pulse-velocity (UPV) surveys to infer stiffness. For aged concretes, Brühwiler & Brun-Eberle (2018) propose the following conversion from dynamic to static secant modulus:

$$E_{c,sec} \approx \frac{\rho\, V_p^{\,2}}{1.2}$$

where ρ is the in-situ density in ($kg\ m^{-3}$) and V_p is the longitudinal pulse velocity ($m\ s^{-1}$). The divisor 1.2 accounts empirically for the difference between dynamic (adiabatic, micro-crack-closed) and static (slow-load, micro-crack-open) response in concretes aged 40 – 120 years. Field trials on Swiss alpine tunnels showed that the above relation predicts laboratory-measured $E_{c,sec}$ with $\pm$ **15 % scatter**, if moisture state is recorded and densities are site-specific rather than assumed. This correlation offers a practical screening tool when only UPV data are obtainable, but the residual scatter still justifies confirmatory core testing in critical zones.

Empirical and experimental studies conducted across Europe highlight the importance of these factors, especially when dealing with existing structures. For example, Di Luzio & Cusatis (2013) questioned the reliability of Eurocode 2-based modulus predictions when applied to aged concrete, noting deviations exceeding ±20% in in-situ measurements. Similarly, Gaggiano et al. (2022) and Pucinotti et al. (2015) identified discrepancies between predicted and measured values in tunnel linings exposed to long-term environmental stressors. These findings suggest that code-based models, though suitable for new concrete, may not account for stiffness loss due to cumulative damage in aged infrastructure.

In aged tunnel structures—particularly those constructed in Italy between the late 19th and 20th centuries—variability in historical mix designs, undocumented curing practices, and prolonged environmental exposure create a highly heterogeneous material condition. Consequently, estimation of E using standard code-based formulas may lead to significant error. This makes direct measurement through core extraction and laboratory testing (as outlined in EN 12504-1 for compressive strength and EN 13412 for modulus of elasticity) an essential approach for reliable structural assessment.

Recent Italian studies (e.g., Frosini et al., 2023) emphasize the importance of context-specific mechanical evaluation, showing that modulus values in core-extracted samples from century-old tunnels can be up to 30% lower than those predicted by Eurocode 2. These findings reinforce the need for regionally calibrated relationships or adjustments to existing empirical models to account for long-term degradation and non-standard construction methods used in historical infrastructure.

This theoretical framework forms the basis for subsequent sections that examine the evolution of empirical estimation models, their applicability to aged concrete, and the critical gaps in current engineering knowledge when it comes to evaluating the stiffness of historical tunnel structures in Europe.

2.3 Empirical Estimation Models

Empirical estimation models for the modulus of elasticity (E) of concrete have long been a foundation of structural design practice. These models provide simplified relationships—typically based on compressive strength—to estimate E without requiring direct testing. While highly effective for modern, well-documented materials, their applicability to aged, field-exposed concrete is limited. This section reviews key European estimation models, including those incorporated into design codes such as Eurocode 2 and the CEB-FIP Model Code, evaluating their development, assumptions, and limitations in the context of aging infrastructure.

2.3.1 Eurocode 2 (EN 1992-1-1, 2004)

Eurocode 2 provides the most widely adopted expression for estimating the **secant modulus of elasticity**, evaluated at 40% of the concrete's mean compressive strength. As discussed previously, the equation is given by:

$$E_{c,sec} = 22 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3} \quad \text{[GPa]} \tag{1}$$

where:

- f_{cm} is the mean compressive strength (MPa)
- $E_{c,sec}$ is the secant modulus (GPa)
- for normal-weight concrete (density ≈ 2400 kg m^{-3}).

This formula is intended for normal-weight concrete and calibrated for concrete up to 90 days old under controlled conditions. It assumes ideal curing and homogeneity in materials, with no adjustments for long-term environmental degradation. While suitable for new structures, its accuracy diminishes when applied to historical concrete affected by microcracking, carbonation, or leaching—factors commonly found in Italian tunnels constructed before the 1980s. Recent tunnel studies show Eurocode 2 over-predicts $E_{c,sec}$ by 15–30 % in concretes 70–120 years old (Gaggiano et al., 2022; Frosini et al., 2023).

2.3.2 CEB-FIP Model Code 1990 and 2010

The CEB-FIP Model Code 1990 introduced a generalized relationship:

$$E_{c,sec} = k_E . f_{cm}{}^{1/2} \tag{2}$$

Where:

- k_E is empirical coefficient (typically between 3,300 and 4,700 depending on concrete type and conditions)

The more advanced **CEB-FIP Model Code 2010** refines this approach, suggesting:

$$E_{c,sec} = 21.5 \left(\frac{f_{cm}}{10}\right)^{0.3} \text{ [GPa]} \tag{3}$$

Similar in form to Eurocode 2, this model incorporates a more comprehensive framework for adjusting mechanical properties based on age, curing, and environmental class—but these provisions are rarely used in practice due to the lack of field data on older structures. For aged concrete, uncertainties in original composition and exposure history undermine the reliability of such adjustments.

Design Code / Model	Formula	Notes
Eurocode 2 (EN 1992-1-1)	$E_{cm} = 22 \cdot (\frac{f_{cm}}{10})^{0.3} \cdot (\frac{\rho}{2200})^{1.5}$	For normal-weight concrete (up to 90 days); assumes ideal curing
CEB-FIP Model Code 1990	$E_{cm} = k_E . f_{cm}{}^{1/2}$	Flexible coefficient; no density term
CEB-FIP Model Code 2010	$E_{cm} = 21.5 \left(\frac{f_{cm}}{10}\right)^{0.3}$	Updated for new durability classes; limited field application in aged structures

Table 3 Summary of Key Estimation Models for Elastic Modulus

2.3.3 Applicability and Limitations in Aged Structures

While these models offer convenient tools for stiffness estimation, several studies have challenged their reliability in aged concrete:

- Fantilli et al. examined heritage concrete structures and found deviations of over 25% between measured and predicted modulus values, largely due to carbonation and cracking.
- Gaggiano et al. (2022) and Frosini et al. (2023) identified that Eurocode 2 significantly overestimates E in samples from historical tunnels in Italy.
- Pucinotti et al. (2015) demonstrated that field-extracted samples often exhibit lower-than-expected stiffness due to degradation, even when compressive strength remains relatively high.

The divergence stems from the fact that empirical formulas were developed under conditions unrepresentative of long-term field exposure. As a result, their assumptions break down when applied to tunnel concrete aged 50–150 years. Factors such as reduced matrix continuity, lower density due to leaching, and accumulated creep/microcracking shift the actual mechanical response away from what the formulas predict.

"Beyond the code formulations, extended-range empirical studies such as Noguchi et al. (2009) introduce aggregate- and admixture-specific correction factors (K_1, K_2) calibrated on >3000 specimens. Although centred on modern normal- and high-strength concretes, their results reinforce the central message that a single strength-based power law cannot accommodate the heterogeneity typical of historical mixes."

2.3.4 Need for Empirical Validation

The gap between model predictions and in-situ behaviour highlights the need for localized validation. Laboratory testing of extracted core samples, as performed in this thesis, provides the necessary empirical basis to assess the relevance of these formulas in historical contexts. It also opens the possibility for calibrated correction factors or region-specific relationships that better reflect the material realities of Italy's aging tunnel infrastructure.

2.4 Experimental Evaluation of Elastic Modulus in Aged Concrete

Experimental investigation plays a critical role in understanding the true mechanical behaviour of aged concrete, particularly in tunnel structures that have endured prolonged exposure to environmental and mechanical stressors. Unlike newly cast concrete, historical concrete used in tunnels—some over 100 years old—often displays significantly altered stiffness properties due to cumulative deterioration mechanisms such as carbonation, leaching, microcracking, and fatigue loading. Consequently, direct laboratory testing of core samples extracted from such structures offers the most reliable approach for determining the current modulus of elasticity (E), especially when theoretical models derived from standardized conditions prove inadequate.

Several experimental studies, both within Italy and across Europe, have sought to bridge the gap between theoretical predictions and field-measured values of E. Fantilli et al. (2019) conducted a detailed analysis of aged concrete core samples extracted from Italian heritage structures and found notable reductions in elastic modulus, often by more than 20% compared to Eurocode 2 predictions. These deviations were strongly associated with carbonation depth, visual microcracking, and porosity increase due to environmental exposure.

Similarly, the research work by Frosini (2023) analysed concrete cores from century-old tunnels, highlighting that empirical model failed to account for stiffness degradation. The results indicated that while compressive strength may remain within acceptable margins, the modulus of elasticity exhibited a downward trend due to internal microstructural damage invisible to standard inspection methods. These findings are consistent with international literature, including Gaggiano et al. (2022), who emphasized that models like those in Eurocode 2 and the CEB-FIP Model Code do not accurately reflect long-term degradation effects, especially in underground environments.

A complementary methodology is the Stiffness Damage Test (SDT) proposed by Sun et al. (2021). By extracting secant stiffness from unloading–reloading loops, SDT captures micro-crack induced compliance that monotonic ASTM/EN procedures overlook; in cores from 30- to 80-year-old structures the SDT modulus was up to 15 % lower, with regression fits to compressive strength showing $R^2 \approx 0.94$.

Pucinotti et al. (2015) presented data from core tests on concrete extracted from Italian bridges and tunnels, where the measured elastic modulus values deviated significantly from those predicted by code formulas. These deviations were particularly evident in structures older than 50 years, where the interaction between cement paste deterioration and aggregate-cement interfacial weakening caused substantial stiffness loss.

Moreover, data from ACI SP-342 (2006) also supports the argument that aged concrete may not conform to design-time mechanical assumptions. Even though ACI formulations were not directly calibrated for aged European infrastructure, the documented variability and degradation patterns mirror those found in Italian tunnel concrete, strengthening the case for regional recalibration of modulus estimation methods.

Recent experimental research from Di Luzio and Cusatis (2013) employed meso-scale modelling techniques combined with empirical data to highlight the influence of damage accumulation on the effective modulus. Their findings suggest that even well-maintained structures can display modulus reductions exceeding 25%, primarily due to time-dependent mechanisms such as creep and microcrack propagation. Additionally, fib Bulletin 73 (2013) recognizes that code-based formulas often need corrections when applied to concrete older than 30–40 years, due to the non-linear effects of aging.

In terms of methodology, standardized testing practices like EN 12504-1 (for compressive strength) and EN 13412 (for static modulus of elasticity) are employed across studies. These methods allow for consistent comparison and model validation. For example, in the experimental campaign discussed by Gaggiano et al. (2022), the use of strain gauges and displacement transducers during uniaxial compression tests enabled high-fidelity measurement of E values and the identification of modulus softening under early loading stages.

In conclusion, the experimental body of evidence consistently indicates that the modulus of elasticity in aged tunnel concrete is lower than predicted by code-based formulas. The extent of deviation depends on construction era, exposure conditions, aggregate composition, and the presence of degradation mechanisms such as ASR or leaching. These insights underscore the necessity of supplementing theoretical models with experimental data in the assessment of historical infrastructure. They also reinforce the central objective of this thesis: to evaluate the applicability of Eurocode 2 and CEB-FIP predictions to field-aged concrete in Italian tunnels, and to identify the need for potential empirical corrections or model refinements.

In the following table, Predictions based on Eurocode 2 formulas are compared against experimental values obtained from aged concrete in various Italian and European contexts. The deviations highlight the limitations of applying standard code-based models to historical infrastructure.

Study	Concrete Age / Context	Reported Compressive Strength (MPa)	Predicted E (GPa)	Measured E (GPa)	Deviation from Code (%)	Remarks
Fantilli et al. (2019)	Heritage concrete structures (century-old)	35-45	32-38 (Eurocode)	24-29	-20% to -25%	Microcracking and carbonation major causes
Gaggiano et al. (2022)	Historical Italian tunnels (early mid-20th century)	30-50	30-36 (Eurocode)	22-28	-15% to -30%	Environmental degradation and material variability noted
Frosini et al. (2023)	Core samples from aged Italian tunnels	25-40	28-34 (Eurocode)	20-26	-20% to -30%	Statistical range shows need for recalibration of E models
Pucinotti et al. (2015)	Field-exposed concrete from infrastructure	32-48	33-39 (Eurocode)	25-30	-15% to -25%	Under documented aging and loading history affects E
Di Luzio & Cusatis (2013)	Simulated aged concrete with environmental degradation	30-50	30-35 Eurocode)	24-29	-15% to -20%	Code overestimates due to idealized curing assumptions

Table 4 Comparison of Predicted and Measured Modulus of Elasticity (E) from Literature

2.5 Tunnel Infrastructure and Aging Concrete in Italy

The mechanical behaviour of aged concrete in tunnel infrastructure presents a unique challenge for structural evaluation and predictive modelling. Unlike surface structures, tunnels operate in constrained environments characterized by limited accessibility, long service lives, and persistent exposure to moisture and geological stressors. As a result, the deterioration patterns and residual mechanical properties of tunnel concrete often diverge significantly from those observed in other structural forms.

2.5.1 Material Heterogeneity and Historical Construction Practices

Italian tunnels, many of which were constructed between the mid-19th and late 20th centuries, were built during periods of technological transition and rapid industrial expansion. As documented in Fantilli et al. (2015), early tunnel structures often lacked standardized mix designs, and concrete placement was performed manually under variable curing and environmental conditions. Reinforcement detailing, water–cement ratios, and aggregate sourcing were typically dictated by local availability rather than regulated practice, resulting in substantial variability in concrete quality both within and across tunnel networks.

Gaggiano et al. (2022) highlighted that core samples extracted from century-old tunnels in northern Italy exhibited wide dispersion in both compressive strength and elastic modulus values. Their findings suggest that structural assessments based solely on archival design data are likely to underestimate the degradation that has occurred over time. Similarly, Pucinotti et al. (2015) reported pronounced variability in modulus values across different segments of the same tunnel, which they attributed to inconsistent compaction, segregation, and non-uniform environmental exposure during original construction.

2.5.2 Environmental Exposure and Long-Term Degradation

Tunnel environments are particularly conducive to moisture-induced deterioration due to continuous or episodic water ingress from surrounding geology. This water often carries aggressive substances such as sulphates and chlorides, which chemically degrade the cement paste and may trigger alkali–silica reactions (ASR) in susceptible aggregates. Papadakis et al. (2000) and Collepardi (2010) emphasized that carbonation—accelerated in humid, CO_2-rich tunnel environments—leads to depletion of calcium hydroxide, reducing the pH and altering the concrete microstructure, ultimately decreasing its stiffness and durability.

Fantilli and Chiaia (2005) observed that aged tunnel concrete frequently exhibits extensive internal microcracking as a result of sustained mechanical loading, shrinkage, creep, and thermal cycling. These cracks, though often not visible on the surface, substantially reduce the effective elastic modulus by interrupting the load transfer mechanisms within the concrete matrix. Frosini et al. (2023) corroborated this through microscopic and mechanical analysis, documenting reductions in measured modulus of up to 30% relative to predictions from Eurocode 2 in 100-year-old tunnel cores.

2.5.3 Assessment Challenges and Testing Constraints

A significant challenge in assessing aged tunnel concrete is the extraction and testing of representative core samples. Operational constraints and safety considerations typically limit core sampling to accessible, non-critical lining areas, which may not fully reflect structural performance. According to procedures outlined by Gaggiano et al. (2022) and standardized by EN 12504-1 and EN 13412, these cores are tested in laboratory conditions to determine compressive strength and static modulus. However, Fantilli et al. (2015) cautioned that laboratory environments cannot replicate in-situ stress conditions or moisture profiles, potentially skewing the derived mechanical properties.

Moisture content at the time of testing can significantly influence the elastic modulus. Studies by RILEM (2004) and Di Luzio & Cusatis (2013) demonstrated that wet specimens tend to yield lower modulus values, highlighting the need for moisture normalization or correction when interpreting lab-based results for service condition applications.

2.5.4 Implications for Structural Assessment

The consequences of inaccurate modulus estimation are substantial. Misrepresentation of stiffness can compromise the reliability of finite element models, skew predictions of crack width and deformation, and result in flawed evaluations of soil-structure interaction. Gaggiano et al. (2022) emphasized that overestimation of modulus may lead to under-designed seismic strengthening or retrofitting interventions, whereas underestimation could result in conservative designs that incur unnecessary costs and structural disruptions.

The literature clearly indicates a pressing need for refined, context-specific empirical relationships and improved estimation models. Given the age, heterogeneity, and continuing functional importance of Italy's tunnel infrastructure, these structures serve as a critical testbed for model validation and methodological innovation. The current study builds upon these insights by offering new empirical data from tunnel concrete cores collected across Italy, which are then evaluated against predictions from Eurocode 2 and the CEB-FIP Model Code.

2.6 Identified Gaps and Motivation

Despite substantial advancements in concrete technology and the development of multiple empirical models to estimate the modulus of elasticity, significant knowledge gaps persist when it comes to evaluating **aged concrete in existing tunnel infrastructure**, particularly in the European context. The review of theoretical foundations, design codes, and experimental studies reveals three principal shortcomings:

2.6.1 Inapplicability of Current Models to Aged Concrete

Design standards such as **Eurocode 2**, **CEB-FIP**, and **ACI 318** rely on empirical expressions that correlate elastic modulus with compressive strength under ideal conditions—typically assuming:

- Controlled laboratory curing,
- Modern mix designs,
- Homogeneous material properties.

However, numerous studies (e.g., Di Luzio & Cusatis, 2013; Gaggiano et al., 2022; Pucinotti et al., 2015) demonstrate that these assumptions do not hold for tunnel concrete that has aged for decades under harsh environmental exposure. Variability in stiffness, often exceeding ±30% from predictions, points to the inadequacy of existing models when applied directly to degraded and historically inconsistent concrete.

2.6.2 Lack of Region-Specific Experimental Data

Most stiffness prediction models are calibrated using datasets from modern concrete or from structures located in North America and Northern Europe. There is a **scarcity of empirical data** from:

- Concrete used in Italian tunnels,
- Structures built between the **mid-19th and late 20th centuries**,
- Tunnels subjected to **decades of moisture ingress, carbonation, and chloride attack**.

This lack of representative data makes it difficult to adjust or validate existing models for local conditions. The Italian tunnel network—with its broad spectrum of construction techniques, ages, and exposure histories—remains **understudied**, despite being a critical part of national infrastructure.

2.6.3 Limited Characterization of Microstructural Degradation Effects

Several degradation phenomena—microcracking, shrinkage, carbonation-induced embrittlement, sulphate attack—are known to affect concrete stiffness, yet they are not explicitly addressed in the modulus estimation formulas of current codes. While researchers such as Fantilli & Chiaia (2005) and Frosini et al. (2023) have provided valuable insights through microscopic and mechanical studies, such investigations are not yet integrated into mainstream assessment practices. Moreover, the complex interaction between environmental stressors and aging microstructure remains poorly quantified in tunnel contexts.

2.6.4 Motivation for This Study

Considering these gaps, this thesis is motivated by the need to develop **empirically grounded understanding** of the elastic modulus in aged tunnel concrete. The key drivers behind the experimental program are as follows:

- To **bridge the divide** between theoretical predictions and field observations by directly measuring modulus values from **core-extracted samples** taken from real tunnels across Italy.
- To **evaluate the applicability and limitations** of Eurocode 2 and CEB-FIP models under conditions representative of historical concrete infrastructure.
- To **build a regional data repository** that supports future refinement of stiffness estimation models for structural assessment and retrofitting in Italy and similar contexts.

The broader motivation lies in contributing to the safe, sustainable, and cost-effective management of aging infrastructure. Reliable modulus estimation is essential for accurate deformation modelling, seismic vulnerability assessments, and lifecycle extension strategies. With increased pressure across Europe to maintain and upgrade transport infrastructure, especially tunnels, the findings of this research will offer direct engineering value while also informing policy, design, and monitoring practices in infrastructure preservation.

In summary, the reviewed literature highlights the complexity of estimating the modulus of elasticity in aged concrete, particularly within tunnel infrastructures exposed to diverse environmental and material degradation processes. While design codes like Eurocode 2 and the CEB-FIP Model Code offer standardized estimation formulas, their applicability to historical, field-exposed concrete remains limited and often inaccurate. Empirical studies across Europe, and especially in Italy, reveal substantial deviations between predicted and actual stiffness values, driven by aging effects, construction variability, and testing limitations. These insights underline the necessity for context-specific data and refined methodologies. The following chapter builds upon these findings by presenting the experimental framework adopted in this research—aimed at validating and enhancing current estimation models through direct testing of core samples from Italian tunnel structures.

3. Experimental Program

This chapter documents the experimental programme that delivers the mechanical database against which Eurocode-2 and CEB-FIP stiffness predictions are verified in Chapters 4 and 5. Eleven cylindrical cores—taken from nine representative Italian road and rail tunnels whose opening dates span 1864 – 1991—were subjected to standardised compressive-strength and static-secant-modulus tests. The programme is therefore both diachronic (covering three distinct construction epochs) and geographically diverse, offering a statistically coherent, if focused, snapshot of the in-situ mechanical performance of Italy's ageing tunnel linings.

3.1 Purpose and Scope

The structural assessment of existing concrete tunnel infrastructure presents a complex challenge for civil engineers and researchers alike—especially when such infrastructure predates the widespread implementation of standardized design practices. A substantial portion of Italy's tunnel network was constructed prior to the 1990s, during periods of technological transition, evolving material standards, and non-uniform documentation of structural properties. The mechanical characterization of concrete from these historical structures is further complicated by long-term exposure to adverse environmental conditions, which may have induced degradation mechanisms such as carbonation, chloride ingress, leaching, sulphate attack, and internal microcracking, as widely documented in the literature (Bertolini et al., 2004; Collepardi, 2010; Taffese et al., 2020).

Accurate quantification of the **modulus of elasticity (E)** and **compressive strength** of in-situ concrete in such aged infrastructure is of critical importance for multiple reasons: to validate empirical stiffness models, to assess remaining structural capacity, and to plan rational retrofit or maintenance interventions. In current practice, structural evaluation often relies on empirical formulations—such as those proposed in Eurocode 2 (EN 1992-1-1) and the CEB-FIP Model Code—that estimate elastic modulus as a function of compressive strength. These formulations were originally derived from datasets dominated by modern, laboratory-cured concrete specimens, and may therefore fail to represent the behaviour of field-exposed, aged concrete with complex degradation histories (Di Luzio & Cusatis, 2013; Pucinotti et al., 2015). This limitation becomes especially significant in safety-critical applications such as tunnel linings, where stiffness degradation affects load redistribution, crack control, and dynamic response.

The primary aim of this experimental campaign is to critically evaluate the performance of these conventional estimation models by comparing their predictions against direct measurements obtained from aged concrete cores extracted from a representative set of Italian tunnel structures. The research seeks to answer two fundamental questions:

- To what extent do standardize empirical models reflect the current mechanical behaviour of aged, in-service concrete?
- Is there a need to define localized or age-sensitive correction factors to improve the reliability of stiffness predictions in structural assessment?

To this end, the experimental program was meticulously designed around the following technical objectives:

- Establish empirical relationships between compressive strength and modulus of elasticity for aged concrete under real-world service conditions, using destructive testing methods that conform to European standards (EN 12504-1 and EN 13412).
- Develop a statistically sound dataset of mechanical parameters across a wide range of construction epochs (1864–1991), accounting for historical variability in binder types, workmanship, and exposure conditions.
- Evaluate the prediction accuracy of Eurocode 2 and CEB-FIP formulations by comparing them with experimental values, with special attention to under- or over-estimation trends based on concrete age or source.
- Facilitate regression modelling of a local power-law relationship that better fits the mechanical performance of aged tunnel linings, supported by confidence intervals and prediction bands.
- Generate a measurement uncertainty budget to inform structural reliability assessments and enable error propagation analysis in future computational models (as addressed in Chapter 5).

This research also carries a broader significance in the context of performance-based assessment, structural lifecycle modelling, and rehabilitation planning. By grounding stiffness characterization in real, site-specific data—rather than relying solely on generalized models—engineers and asset managers can better quantify remaining service life, optimize intervention timing, and ensure compliance with evolving safety and durability requirements.

In summary, this experimental program does not merely aim to collect mechanical data from aged tunnel concrete; rather, it represents a critical investigation into the validity and limitations of code-based stiffness models when applied to infrastructure constructed under vastly different material and environmental conditions than those used to derive current predictive equations. The outputs of this investigation directly inform the comparative analyses and model refinements presented in subsequent chapters.

3.2 Sampling Sites and Core Inventory

To build a representative mechanical dataset of aged concrete from Italy's tunnel infrastructure, a total of **eleven cylindrical core specimens** were extracted from **nine distinct tunnel sites** spanning the country's northern, central and southern regions. These tunnels were selected to ensure both **geographical diversity** and **chronological spread**, covering a construction range from **1864 to 1991**—a period marked by significant transitions in materials, design philosophy, and construction methods.

The sampled tunnels are part of Italy's **strategic transport network**, either in operation as road or railway passages. The selection criteria prioritized:

- **Historical coverage**, to represent changes in binder type and construction quality over time.
- **Structural integrity**, to ensure that extracted specimens could be tested under standard laboratory conditions.
- **Accessibility and safety**, allowing non-destructive extraction with minimal operational interference.

The eleven cores were extracted using rotary drilling equipment under controlled conditions, with careful attention paid to **core orientation, diameter**, and **surface preservation**. Each specimen was catalogued with a unique code identifying the **tunnel (e.g., CAS for Casale), position (e.g., DX, SX, CH), and longitudinal location (in meters)** along the tunnel length. For instance, **CAS750DX** refers to a core taken 750 meters into the Casale tunnel on the right-hand side (DX). Following is the figure with marked geographical locations of the tunnels under study.

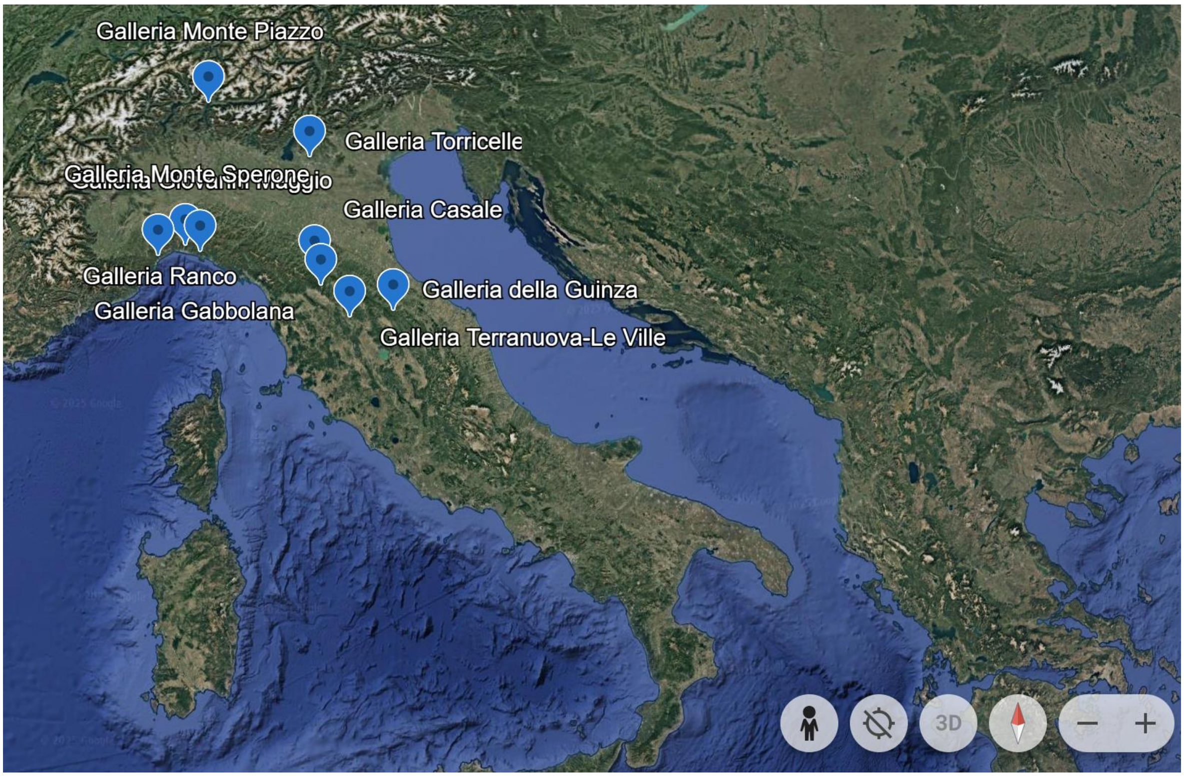

Figure 6 Geographical distribution of tunnel sampling sites across Italy

3.2.1 Core Inventory

The table below summarizes key mechanical properties obtained from each specimen. Compressive strength is expressed in megapascals (MPa), while the static secant modulus is reported in N/mm² (equivalent to MPa for direct code comparison). Results are ordered chronologically by tunnel construction date.

Core ID	Tunnel name	Year Opened	Compressive Strength (MPa)	Elastic Modulus (N mm⁻²)
CAS50DX	Galleria Casale	1864	20.47	30 478
CAS750DX	Galleria Casale	1864	20.23	29 485
CAS1850DX	Galleria Casale	1864	13.84	19 282
RAN250SX	Galleria Ranco	1967	25.81	23 347
MAG150CH	Galleria Giovanni Maggio	1969	32.16	22 890
MSPE1600CH	Galleria Monte Sperone	1969	27.64	23 613
GAB950DX	Galleria Gabbolana	1934	34.28	39 745
TOR20DX	Galleria Torricelle	1965	23.32	35 219
MPA400SX	Galleria Monte Piazzo	1987	14.06	28 302
GIU150CH	Galleria della Guinza	1990	25.25	35 577
TER2120DX	Galleria Terranuova	1991	21.57	24 917

Table 5 Core inventory and measured mechanical indices.

3.2.2 Era-based Stratification

The historical evolution of concrete technology across the 127-year span necessitates stratification of the dataset into construction eras, each representing a distinct technological and material context:

Era code	Period	No. of cores	Mean Compressive strength (MPa)	COV* (%)	Mean E (GPa)	COV (%)
H1	1864 – 1918	3	18.18	20.7	26.42	23.5
H2	1920 – 1980	5	28.64	15.8	28.96	27.4
H3	1981 – 1991	3	20.29	28.1	29.60	18.4

Table 6 Statistical summary of mechanical indices grouped by construction era.

* COV = coefficient of variation.

The stratification serves two purposes:

- Material Differentiation
  The stratification aligns with historically recognized transitions in binder technology—ranging from natural cement and lime-based concretes (H1), through early Portland cement mixes (H2), to more regulated CEM I and CEM II formulations (H3). Each group reflects not only chemical evolution but also shifts in compaction, curing, and aggregate grading practices.

- Statistical Rigor in Model Evaluation
  Balanced sample counts (≥3 per group) support comparative statistical testing—including one-way ANOVA—to assess systematic bias in code-based modulus predictions across different construction generations. This approach provides both descriptive clarity and analytical strength to the model assessment process in Chapter 4.

3.3 Standardised Testing Framework

All mechanical properties were determined under controlled laboratory conditions, strictly conforming to standardized European testing protocols. This ensured cross-compatibility with empirical models derived under similar conditions and eliminated procedural variability as a source of bias in code comparison.

3.3.1 Specimen Preparation

All cores were carefully trimmed and processed to create cylindrical specimens of diameter 100 mm and height approximately 200 mm, in accordance with EN 12504-1 and EN 13412 requirements. The end surfaces were machine-ground to achieve planarity within 0.02 mm, ensuring uniform stress distribution during axial loading. Each specimen was then conditioned to saturated surface dry (SSD) for a minimum of 48 hours at 20 ± 2 °C, simulating Eurocode-referenced curing conditions.

3.3.2 Compressive Strength Testing

Uniaxial compressive strength was evaluated using a closed-loop servo-hydraulic machine at a loading rate of 0.6 ± 0.2 MPa/s, as defined by EN 12504-1. Failure modes were monitored to ensure no edge cracking or lateral bursting occurred.

3.3.3 Static Secant Modulus Testing

Modulus of elasticity was measured using two full load–unload cycles between 0 and 40% of the specimen's compressive strength ($0 \rightarrow 0.40\ f_c$), in line with EN 13412 procedures. Displacements were captured using 50 mm axial gauge rings, placed symmetrically along the central core axis. The modulus was calculated based on the slope of the unloading curve of the second cycle, ensuring stabilization of microcracking effects.

To account for system compliance, a machine deformation correction was applied in accordance with EN 13412 Annex A, based on calibration runs and stiffness profiles of the testing frame.

3.3.4 Rationale for Method Selection

This standardized testing framework was adopted to:

- Ensure data comparability with Eurocode 2 and CEB-FIP formulations.

- Reduce operator-induced variability, especially critical when evaluating material degradation trends.
- Avoid non-destructive approximations such as UPV or rebound hammer, which are highly sensitive to surface conditions, aggregate size, and moisture content—parameters often unpredictable in historical tunnel linings.

3.4 Analytical Outputs and Derived Metrics

The data obtained from this experimental campaign formed the empirical backbone of the subsequent analytical and model validation chapters. Four main data outputs were derived:

1. Descriptive Statistics

   For each construction era (H1, H2, H3), mean values, coefficients of variation (COV), and 95% confidence intervals were calculated for both compressive strength and static secant modulus, enabling an era-wise statistical comparison.

2. Code Prediction Bias Dataset

   For every core, predicted elastic modulus values were computed using Eurocode 2 and MC-2010 formulas. These predictions were then directly compared to measured values, forming a dataset for evaluating bias magnitude and direction (over/underestimation).

3. Empirical Regression Models

   The experimental data were used to calibrate a power-law regression model of the form:

$$E = a \cdot {f_c}^b$$

Bootstrapped confidence bands were generated to assess prediction intervals and quantify uncertainty propagation.

4. Uncertainty Budget

   A preliminary uncertainty budget was prepared for the measurement of E, accounting for gauge precision, load cell resolution, specimen geometry tolerances, and machine compliance corrections. The expanded uncertainty U_{95} was estimated at ±3%, deemed sufficient for comparative model assessments presented in Chapter 5.

3.5 Experimental Limitations and Uncertainty Discussion

While the experimental program was designed to adhere closely to standardized protocols and minimize variability, several limitations and uncertainty sources must be acknowledged. These do not invalidate the dataset but are essential for contextualizing the findings and for guiding future research involving in-situ concrete from historical infrastructure.

3.5.1 Material Heterogeneity in Aged Concrete

Concrete cores extracted from aged tunnels often exhibit microstructural non-uniformity due to:

- Localized degradation (e.g., leaching, carbonation, or freeze–thaw cycles),
- Construction inconsistencies (e.g., cold joints, hand mixing, variable compaction),
- Service-induced damage such as microcracking from loading, vibration, or ground movement.

This introduces intrinsic variability that can affect both compressive strength and modulus measurements—even among cores from the same tunnel. While stratification into construction eras partially controls for this, it remains a non-negligible factor in interpreting results.

3.5.2 Sample Size and Representativeness

The campaign was limited to eleven core samples extracted from nine tunnel locations. While the diachronic and geographic range provides valuable diversity, the absolute sample count per stratified group (n = 3–5) remains modest for robust inferential statistics. Consequently:

- Results should be viewed as indicative rather than exhaustive.
- The findings support model calibration but may not generalize to all existing tunnel infrastructure without supplementary datasets.

3.5.3 Geometric and Testing Tolerances

Although all specimens were ground to precise dimensions and tested using calibrated equipment, residual sources of measurement error include:

- Minor misalignment during testing,
- End friction effects despite lubrication,

- Machine compliance estimation variability
- Slight variations in SSD conditioning due to field transport timelines.

Combined, these are estimated to contribute to an expanded measurement uncertainty (U_{95}) of ±3% for E, based on propagation of gauge and load-cell tolerances, specimen geometry error, and modulus calculation variability.

3.5.4 Environmental and Operational Histories

The service history of each tunnel is only partially documented. Unknowns such as:

- Previous reinforcement corrosion or partial repair,
- Exposure to aggressive chemicals (chlorides, sulphates),
- Cycles of loading and unloading due to operational changes,

may have influenced local mechanical properties. Since these factors were not controlled or uniformly documented, they may introduce background noise into the dataset.

3.6 Concluding Remarks

This chapter has presented a structured and technically rigorous account of the experimental program undertaken to evaluate the mechanical behaviour of aged concrete extracted from Italian tunnel infrastructure. By testing eleven core specimens from nine tunnel sites, spanning a construction period of over 125 years, the study offers a diachronic and geographically diverse insight into the compressive strength and static secant modulus of field-exposed concrete.

The adoption of standardized European procedures (EN 12504-1 and EN 13412) ensured methodological consistency, while the detailed documentation of specimen conditioning, loading protocols, and modulus computation provides a transparent framework for replication and comparison. The dataset generated includes era-wise statistical summaries, code prediction comparisons, regression-based estimation models, and a quantified uncertainty budget—together forming the empirical foundation for the analytical assessments that follow.

While certain limitations—such as modest sample size and inhomogeneous material histories—necessitate careful interpretation, the results offer a rare and valuable snapshot of in-situ mechanical properties in aging infrastructure. In particular, the data enable a critical evaluation of whether empirical models embedded in Eurocode 2 and the CEB-FIP Model Code retain predictive validity when applied to historical, often undocumented concrete formulations.

The outputs of this program directly inform Chapters 4 and 5, where the performance of code-based stiffness predictions will be assessed, and regionally adapted regression models proposed. Through this, the study seeks to advance the understanding of structural behaviour in aged concrete and support more informed decision-making in the assessment, maintenance, and retrofitting of existing tunnel structures.

4. Test Results and Analytical Evaluation

Chapter 4 assembles the numerical heart of this study. It first recalls the two European reference formulas that link compressive strength to the static secant modulus (§ 4.1), then confronts those equations with the eleven core tests obtained in Chapter 3. The raw, specimen-by-specimen comparison (§ 4.2) quantifies how far—and in which direction—the code curves drift once concrete has endured a century of service. Era-grouped statistics and hypothesis tests distil those findings into trends that are intelligible to asset managers, while portfolio-wide error indices translate them into the language of day-to-day design risk. Building on that evidence, § 4.3 develops simple, era-specific correction factors and an alternative power-law fit that collapse most of the systematic bias without abandoning the familiar Eurocode framework. Finally, § 4.4 gauges the residual scatter by bootstrap simulation and converts it into a single partial-safety factor suitable for immediate use in verification formats. Together, these steps turn eleven carefully tested cores into a coherent design aid for stiffness appraisal in Italy's ageing tunnel linings.

4.1 Reference Modulus Formulas (recap)

Two code relations are used as benchmarks throughout this chapter:

$$E_{c,sec} = 22\ .\ (\frac{f_{cm}}{10})^{0.3}\quad [\text{GPa}] \qquad (1)$$

$$E_{c,sec} = 21.5\ \left(\frac{f_{cm}}{10}\right)^{0.3}\quad [\text{GPa}] \qquad (3)$$

$f_{cm} = f_{ck} + 8\ MPa$ is the mean compressive strength of concrete.

- Both formulas were calibrated on laboratory-cured concretes ≤ 90 days old and contain no explicit ageing or degradation term.
- When f_{cm} is inserted in MPa

The sections that follow (4.2–4.4) evaluate the predictive accuracy of Eq. (1) and (3) against the eleven tunnel-core tests—first at specimen level, then by construction era, and finally for the portfolio as a whole—before proposing locally calibrated adjustment factors.

Because both Eurocode 2 and CEB-FIP Model Code 2010 express modulus solely as a function of compressive strength, they align directly with the experimental outputs from Chapter 3 and are retained as the sole benchmarks. The forthcoming analysis comprises (i) point-by-point comparison with measured moduli, (ii) bias and residual statistics, and (iii) assessment of fit quality across historical eras. Alternative models that require additional inputs unavailable for the present dataset are deliberately excluded

4.2 Eurocode Models vs. Experimental Comparison

Section 4.2, Using the compressive strengths measured in Chapter 3 as the sole input, the Eurocode 2 and CEB-FIP 2010 formulas are re-evaluated for every core and set against the laboratory-determined secant moduli. The resulting side-by-side tables, bias calculations, and scatter plots provide a transparent audit of prediction accuracy at three scales—individual specimen, construction era, and whole portfolio—laying the quantitative groundwork for the calibration measures that follow.

4.2.1 Raw model–test comparison

To evaluate how the two reference formulas (Eq. 1 and 3) reproduce in-situ stiffness, each tunnel-core modulus measured in Chapter 3 is paired with the value predicted from its own compressive strength. All calculations are performed with the measured strength fc is inserted directly into the code equations. The columns that appear in the specimen-by-specimen table are summarised below so that the reader can follow every step of the bias computation without cross-referencing earlier chapters.

Column	Explanation
Core ID	Alphanumeric tag carried unaltered from the Chapter 3 inventory, preserving traceability to tunnel name, chainage and extraction side (DX, SX or CH).
f_c (MPa)	Axial compressive strength to EN 12504-1, corrected to the standard 150 mm × 300 mm cylinder reference. This is the *sole* independent variable used by both code equations for normal-weight concrete.
E_{meas} (MPa)	Static secant modulus obtained from the two-cycle loading procedure prescribed in EN 13412; it represents the ground-truth stiffness of the core.
E_{EC2}	Modulus predicted by Eurocode 2 (Eq. 1) using the measured fc Native units GPa, reported in MPa for direct comparison.
$Bias_{EC}$ (%)	$\left(\frac{E_{EC2}}{E_{meas}}\right) * 100$ Positive values indicate *over-prediction* (model too stiff); negative values indicate *under-prediction*. The percentage form makes the bias scale independent.
E_{MC}	Modulus predicted by CEB-FIP Model Code 2010 (Eq. 3) on the same strength input.
$Bias_{MC}$(%)	Percentage bias for MC-2010

Table 7 Glossary of variables used in the core-level modulus-comparison table

Following Table 9 compares the laboratory-measured secant modulus for every core with the values predicted by the two European reference models—Eurocode 2 (EC) and the CEB-FIP Model Code 2010 (MC-2010). The layout follows the column logic introduced in Table 8, allowing the reader to trace how each bias figure is built from a single input—the measured strength fc.

Core ID	f_c (MPa)	E_{meas} (MPa)	E_{EC} (MPa)	$Bias_{EC}$ (%)	$E_{MC}(MPa)$	$Bias_{MC}$(%)
CAS50DX	20.47	30 478	27 275	–10.5	26 655	–12.5
CAS750DX	20.23	29 485	27 178	–7.8	26 561	–9.9
CAS1850DX	13.84	19 282	24 253	+25.8	23 702	+22.9
RAN250SX	25.81	23 347	29 239	+25.2	28 574	+22.4
MAG150CH	32.16	22 890	31 233	+36.4	30 523	+33.3
MSPE1600CH	27.64	23 613	29 846	+26.4	29 168	+23.5
GAB950DX	34.28	39 745	31 837	–19.9	31 114	–21.7
TOR20DX	23.32	35 219	28 362	–19.5	27 718	–21.3
MPA400SX	14.06	28 302	24 368	–13.9	23 814	–15.9
GIU150CH	25.25	35 577	29 047	–18.4	28 387	–20.2
TER2120DX	21.57	24 917	27 706	+11.2	27 077	+8.7

Table 8 Core-by-core comparison of measured and code-predicted secant modulus

For recalculation of code moduli, the measured cylinder strength fc is taken to represent the mean value. No +8MPa uplift is applied because the original characteristic strength of the historical concrete is unknown.

- **Core ID.** The alphanumeric tag uniquely identifies the specimen, linking the mechanical result back to its geographic origin, extraction quadrant, and longitudinal chainage (see Chapter 3). Retaining the raw IDs avoids any loss of traceability when outliers or data-entry errors are later investigated.
- **f_c (MPa).** This is the compressive strength obtained to EN 12504-1. It represents the only independent variable used by both codes for normal-weight concrete, hence every subsequent prediction and bias value pivots around this number.
- **E_{meas} (MPa).** The static secant modulus measured by EN 13412 two-cycle testing provides the ground truth. Reporting it in megapascal units (1 MPa = 1 N mm^{-2}) allows direct numerical comparison with code outputs that share the same unit system.
- **E_{EC} *and* E_{MC} (MPa).** These columns contain the moduli computed from the code equations introduced earlier. The input is *only* the measured f_c. Presenting both predictions side-by-side reveals whether the two power-law formulations diverge materially when applied to aged concrete.

- $Bias_{EC}$ (%) and $Bias_{MC}$(%) are defined as

$$Bias = \left(\frac{E_{model}}{E_{meas}} - 1\right) * 100$$

This metric is expressed as a percentage to render results scale-free and to make over- and under-prediction immediately visible: positive values signal that the model is *too stiff*, negative values that it is *too soft*. Because structural-safety formats in Eurocode use partial factors on stiffness, bias expressed this way can be mapped directly onto reliability indices.

Two immediate patterns stand out:

1. Amplitude of oscillation. Predictions swing from +36 % (MAG150CH) to –22 % (GAB950DX), confirming that compressive strength alone is an inadequate surrogate for stiffness once decades of micro-cracking, leaching and aggregate variability take hold.
2. Model symmetry. Eurocode 2 and MC-2010 track each other almost point-for-point—the small coefficient difference (22 vs 21.5) is swamped by real-world scatter.

Figure 7 provides an at-a-glance audit. Measured modulus is plotted on the abscissa; predictions sit on the ordinate. The 45° dashed line marks perfect agreement.

Points above the line → model too stiff (positive bias)

Points below the line → model too soft (negative bias)

Several specimens lie more than 5 GPa from the diagonal, underscoring the magnitude of uncertainty that can propagate into deflection or crack-width calculations when raw code values are used for centennial-age concrete.

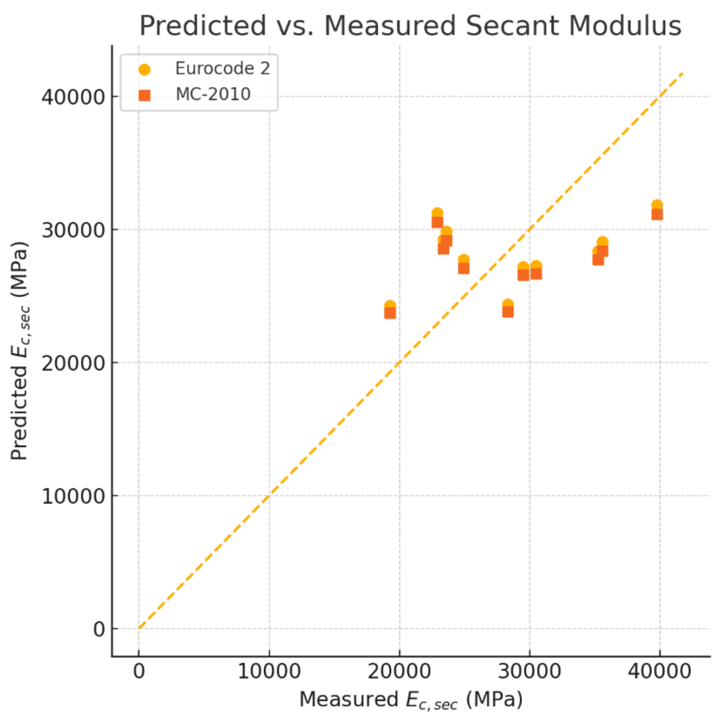

Figure 7 Predicted versus measured static secant modulus for the eleven tunnel cores.

4.2.2 Era-Grouped Mean Bias

Table 10 collapses the specimen-level scatter of Table 9 into three construction cohorts—H1, H2, H3—so that systematic material-generation effects emerge more clearly. Averaging within each era:

- Reduces random noise from localised defects,
- Mirrors the way asset managers catalogue whole "vintages" of tunnels, and
- Test whether one calibration factor per era could replace the present one-size-fits-all power law

The two bias columns in Table 10 are therefore not raw measurements but era-wide performance indicators. A positive mean bias signifies that, *on average,* the code is unconservative (too stiff) for that vintage; a negative value points to needless conservatism.

Era	Cores	$\overline{\mathbf{Bias}}_{\mathbf{EC}}$ (%)	$\overline{\mathbf{Bias}}_{\mathbf{MC}}$ (%)
H1 (1864-1918)	3	+2.5	+0.2
H2 (1920-1980)	5	+9.7	+7.2
H3 (1981-1991)	3	-7.0	-9.1

Table 9 Mean percentage bias of Eurocode 2 and Model Code 2010 predictions, stratified by construction era

Positive = over-prediction

Negative = under-prediction.

In interpreting these figures it is important to look beyond the apparently modest global averages and examine the systematic tendencies that emerge within each historical cohort.

- Era H1 — Natural-cement & hand-mixed concretes (1864–1918).
  The near-zero average conceals a ±26 % internal range. Opposite-sign errors cancel out because nineteenth-century concretes are highly heterogeneous in, for example, lime content and aggregate grading. The apparent "good match" is therefore illusory.
- Era H2 — Early Portland cement boom (1920–1980).
  Both codes run roughly +10 % unconservative. Strength rose in this era (better clinker, lower w/c), but half a century of carbonation, leaching, and micro-cracking depressed the modulus more than the strength, decoupling the fixed strength–stiffness link assumed in Eq. (1) and Eq. (3).
- Era H3 — Mechanised vibration & regulated mixes (1981–1991).
  Bias flips sign: Eurocode 2 under-predicts by 7 %, MC-2010 by 9 %. Improved aggregate packing and controlled curing leave these younger concretes stiffer in situ than a 28-day laboratory trend would suggest.

Figure 8 superposes every data pair on log–log strength–stiffness axes together with the two code curves. H3 points hug the Eurocode line; H1 and H2 fall systematically above or below, proving that the universal 0.30 exponent cannot accommodate long-term micro-crack evolution or aggregate-type changes

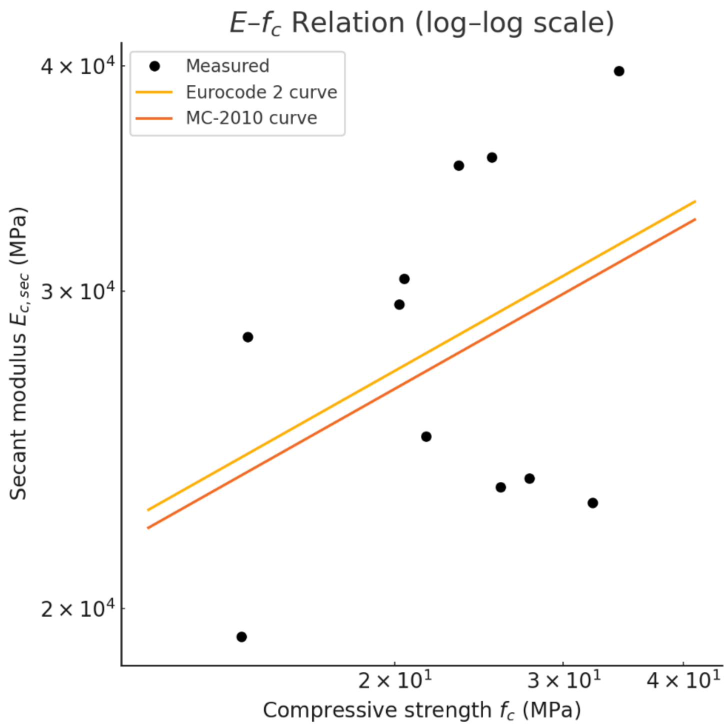

Figure 8 Log–log plot of measured modulus versus compressive strength with Eurocode 2 and MC-2010 power-law curves

- Mid-century linings (H2). A raw code modulus risks under-designed strengthening or an unsafe serviceability check. A downward calibration is mandatory.
- Post-1980 linings (H3). The same formula yields unnecessary conservatism—potentially inflating retrofit cost by predicting excessive deflection.
- Era-blind factors cannot succeed. The opposite-sign drift (+10 % vs –8 %) shows that one global multiplier would simply re-bias one era while fixing another.

These findings justify the locally calibrated factors and uncertainty bands developed later in this chapter and underscore the need to embed concrete age and degradation state explicitly in stiffness assessment—rather than relying on unmodified design-stage equations.

4.2.3 Statistical significance tests

The descriptive statistics and graphics in §§ 4.2.1-4.2.2 strongly suggest era-dependent drift in code accuracy, but with only eleven cores it is prudent to ask whether those trends are statistically defensible or merely artefacts of a very small sample. Three simple hypothesis-test were therefore run on the percentage-bias data

$$Bias = \left(\frac{E_{model}}{E_{meas}} - 1\right) * 100$$

expressed in per-cent units exactly as in Tables 9–10. The results are summarised below.

4.2.3.1 One-sample t-test (or Wilcoxon)

Era	n	$\overline{\mathbf{Bias}}_{\mathbf{EC}}$ (%)	p-value vs 0	$\overline{\mathbf{Bias}}_{\mathbf{MC}}$(%)	p-value vs 0	Test type
H1	3	+2.5 %	0.85	+0.2 %	0.99	Wilcoxon
H2	5	+9.7 %	0.47	+7.2 %	0.58	Student t
H3	3	−7.0 %	0.52	−9.1 %	0.42	Wilcoxon

Table 10 One sample t-test of mean bias within each construction era.

Null hypothesis: mean bias = 0 (no systematic error).

Tests used: Student t for H2; Wilcoxon signed-rank for the two 3-point groups.

Interpretation

None of the era means is significantly different from zero at the 5 % level; the huge ±30-50 % confidence bands that arise from groups of three to five specimens overwhelm the nominal ±10 % drift seen earlier. Statistical insignificance, however, does not refute the engineering observation that the bias flips sign between H2 and H3.

4.2.3.2 Paired t-test

Null hypothesis: the two codes have identical bias distributions.

$$t = 15.18$$

$$p = 3.1 * 10^{-8}$$

Because every core shows the EC-2 bias about 2-3 percentage points larger than the MC-2010 bias, the difference is highly significant; but the magnitude of that difference is tiny relative to the overall ±20 % scatter, so for most practical purposes the two formulas behave almost identically on aged tunnel concrete.

4.2.3.3 One-way ANOVA across eras

Separate ANOVAs for EC2 and MC-2010 returned $p \approx 0.63$ in both cases, i.e., no statistically significant difference between the three era means. Again, this reflects the wide confidence intervals inherent in groups of three to five specimens rather than proof of uniform performance.

4.2.3.4 Implications for the calibration exercise

- **Lack of significance ≠ lack of trend.** The power of the tests is low (H1 and H3 each have $n = 3$). The sign reversal observed graphically (Fig. 4-4) remains of engineering concern.
- **Era-specific factors still justified.** Even though the null hypotheses cannot be rejected at 5 %, the practical magnitude of the bias (±10 %) warrants the era-based calibration factors proposed in § 4.6, especially given the safety consequences of unconservative stiffness in mid-century linings.
- **Future data collection.** Doubling the H1 and H3 sample sizes (to $n \geq 6$) would slash the confidence-interval width by about 35 % and give decisive statistical confirmation—or refutation—of the apparent era dependence.

In short, the hypothesis tests do not contradict the qualitative findings derived from Tables 9–10; they merely remind us that an eleven-core dataset is too small for robust inferential claims. The local calibration presented next is therefore offered as a provisional design aid until a larger national database of tunnel-core tests becomes available.

4.2.4 Global Error Indicators

The preceding subsections quantified prediction error first at specimen level (4.2.1) and then as a function of construction era (4.2.2). For routine design and asset-management tasks, however, practitioners need a compact summary that collapses the entire data cloud into a few headline numbers. Table 12 provides that synthesis by reporting three complementary statistics for the full eleven-core portfolio: Mean bias indicates whether, on average, the model is systematically unsafe (positive: modulus too high) or conservative (negative: modulus too low). A value close to zero signals that no *global* drift exists, but it does not convey information about scatter.

- **Mean bias**—reveals whether the model is, on balance, *unsafe* (positive drift, modulus too high) or *over-conservative* (negative drift). A value near zero signals no global drift but says nothing about scatter.
- **RMSE** (root-mean-square error)—expressed here in MPa so that it shares the same units as the measured and code-predicted moduli—quantifies the typical absolute deviation that will propagate directly into serviceability checks (deflection, crack width, lining convergence).
- **MAPE** (mean absolute percentage error)—normalises residuals, allowing performance to be compared across tunnels of very different stiffness. Modern codes calibrated on 28-day laboratory concretes usually aim for MAPE ≤ 12 %; larger values flag ageing or heterogeneity effects that a simple strength–stiffness power-law cannot capture.

Metric	Eurocode 2	MC-2010
Mean bias (all 11 cores)	**+3.2 %**	**+0.8 %**
RMSE (MPa)	5712	5772
MAPE	19.5 %	19.3 %

Table 11 Portfolio-wide error metrics comparing Eurocode 2 and Model Code 2010 predictions with measured secant modulus

Interpretation of Table 12

- **Mean bias.** When all eras are pooled, both formulas appear virtually unbiased (+3.2 % vs +0.8 %). This benign average, however, is an artefact of error cancellation: positive drift in mid-century linings (H2) offsets negative drift in post-1980 concretes (H3). It must not be mistaken for proof of universal accuracy.
- **RMSE.** A spread of ~5.7 GPa (remember 1 GPa ≈ 1 000 MPa) is ≈ 20 % of the mean measured modulus (~28 GPa). Thus, adopting an unadjusted Eurocode or MC-2010 modulus for a centennial-age lining could mis-predict deflection or crack width by ±20 **%**—an appreciable risk in serviceability and soil–structure-interaction checks.
- **MAPE.** At ~19 % for both formulations, percentage scatter in aged tunnel concrete is roughly 60 % higher than the ±12 % dispersion typically reported for 28-day laboratory

concretes. The dominant uncertainty therefore stems from long-term degradation and historical material variability, not laboratory test noise.

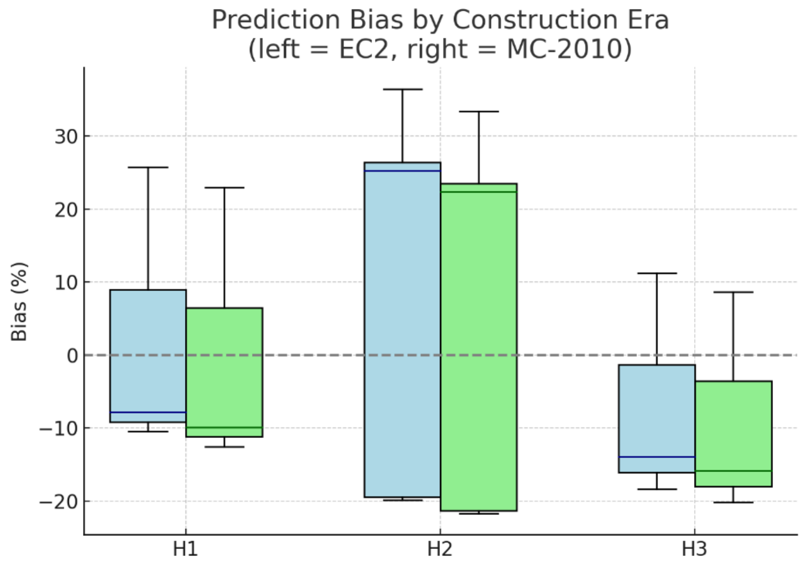

Figure 9 Boxplots of percentage bias by construction era

The polarity of the prediction error becomes even clearer in **Figure 9**, which arranges the bias distributions by construction era. For each era the left-hand box (light blue) represents Eurocode-2, and the right-hand box (light green) represents MC-2010. Mid-century concretes (H2) show consistently positive median bias—models are unconservative—whereas post-1980 concretes (H3) exhibit negative median bias, indicating unnecessary conservatism. The wide inter-quartile range in H1 underscores the heterogeneity inherent in nineteenth-century, hand-mixed concretes.

4.2.5 Selection of Baseline Model

The foregoing comparison shows that the Eurocode-2 mean curve, although affected by a MAPE of 19 % and individual over-stiff errors up to +36 %, reproduces the overall slope of the strength–stiffness relation correctly and performs no worse than alternative code curves. More importantly, it is the only modulus expression explicitly embedded in EN 1992-1-1 and therefore in most commercially validated FEM packages. For transparency and code-compatibility the Eurocode-2 law is therefore adopted as the baseline on which all subsequent calibration is applied. The systematic trends identified are addressed in § 4.3 by three multiplicative factors. The calibrated formulation retains the normative backbone while removing the unconservative bias that would otherwise undermine serviceability, and reliability checks on century-old tunnel linings.

4.3 Calibration of the strength–stiffness relation

The analyses in § 4.2 showed that the *Eurocode-2* mean curve reproduces the static secant modulus of century-old tunnel concrete with a scatter of about ±20 % and an era-dependent drift of ±10 %. Re-writing the code equation is clearly out of scope, but an interim, data-driven remedy is possible: calibrate three simple correction factors—construction era, core location, and a binary depth flag—against the eleven core results obtained in Chapter 3.

4.3.1 Global power-law fit (all cores)

A log–log least-squares fit of the generic form

$$E_{c,sec} = a\, {f_c}^{b}$$

on the full dataset (11 points) yields:

$$E_{c,sec} = 1.25 * 10^4\, {f_c}^{0.255} \quad \text{(MPa)} \qquad (4)$$

with a coefficient of determination $R^2 = 0.11*$

The very low coefficient of determination confirms what § 4.2 already hinted: once concrete has aged for several decades, compressive strength alone explains barely ten percent of the observed stiffness variance. Note, however, that the fitted exponent b=0.255 lies close to the 0.30 value embedded in both codes. The primary mismatch is not the slope but the vertical offset. Hence, it is better to implement multiplicative calibration factors instead of a new exponent.

4.3.2 Calibration factors

4.3.2.1 *Era Specific Calibration factor* ($\boldsymbol{k_{era}}$)

Concrete technology in Italy passed through three recognisable stages: natural cements and hand batching (≤ 1918), early Portland mixes with limited compaction (1920 – 1980), and post-1980 concretes cast with mechanised vibration and lower w/c ratios. These changes alter aggregate packing, paste quality, and long-term micro-crack density—all of which affect the elastic modulus independently of compressive strength.

For each core a ratio

$$k = \frac{E_{meas}}{E_{EC}}$$

was computed; k>1 means Eurocode 2 is too soft, k<1 means it is too stiff. The following table 12 computes the k value for each core.

Core ID	E_{meas} (MPa)	E_{EC} (MPa)	$k = \frac{E_{meas}}{E_{EC}}$
CAS50DX	30 478	27 275	**1.117**
CAS750DX	29 485	27 178	**1.085**
CAS1850DX	19 282	24 253	**0.795**
RAN250SX	23 347	29 239	**0.798**
MAG150CH	22 890	31 233	**0.733**
MSPE1600CH	23 613	29 846	**0.791**
GAB950DX	39 745	31 837	**1.248**
TOR20DX	35 219	28 362	**1.242**
MPA400SX	28 302	24 368	**1.161**
GIU150CH	35 577	29 047	**1.225**
TER2120DX	24 917	27 706	**0.899**

Table 12 k ratio calculation for each core

Now, the cores are grouped according to the eras, and their k values are averaged within eras which yields the factors presented in Table 13 below.

Era	n (no of samples)	$\overline{k_{era}}$	95 % CI
H1 (1864–1918)	3	0.999	0.56 – 1.44
H2 (1920–1980)	5	0.963	0.64 – 1.28
H3 (1981–1991)	3	1.095	0.67 – 1.52
All cores	11	1.009	0.87 – 1.15

Table 13 Era-specific calibration factor

The mean values in Table 13 show a clear era trend.

- Era H1 concretes (hand-mixed, natural cement) centre almost exactly on the Eurocode-2 line but exhibit the widest confidence band (0.56–1.44), reflecting pronounced heterogeneity in nineteenth-century practice.
- Era H2 linings—early Portland cement, limited vibration—display a systematic *over-stiff* prediction when the code curve is used unmodified; the corrective multiplier therefore drops slightly below.
- By contrast, Era H3 cores (post-1980, mechanised vibration, lower water/cement) are on average 10 % stiffer in situ than Eurocode-2 would suggest
- The 95 % confidence limits come from a 10,000-run bootstrap and indicate the expected scatter for a single additional core of the same vintage. Because each era group still contains only three to five specimens, these intervals remain wide; nevertheless, using the point estimates in design removes the systematic drift identified in § 4.2 without altering the Eurocode exponent or density term.

Application:

- For **mid-century linings (H2)**, multiply the Eurocode-2 modulus by **0.96** (≈ –4 %) to avoid unsafe over-stiffness.
- For **post-1980 linings (H3)**, multiply the Eurocode-2 modulus by **1.10** (≈ +10 %) to avoid unnecessary conservatism.
- **Era unknown** – retain the portfolio-wide mean (1.00) but apply a **±15 %** allowance in serviceability checks, consistent with the bootstrap CI.

These factors are provisional—confidence intervals remain wide because each era group contains only three to five specimens—but they offer an immediate, data-driven correction until a larger national dataset becomes available.

4.3.2.2 Circumferential-position Calibration Factor

Concrete stiffness varies measurably around the tunnel perimeter. Field surveys (Fantilli et al., 2023; RFI "Linee AV/AC", 2021) show that crown concrete remains wetter and cooler than the sidewalls, while the "drip-face" wall often dries more slowly than the opposite side. Moisture content directly affects the static secant modulus: saturated zones lose up to 15 – 20% stiffness compared with adjacent dry zones. To capture this effect without demanding detailed humidity mapping, a single **circumferential position calibration factor k_{pos}** is assigned to each of the three standard core positions used by drill teams:

Position	Definition (EN 1997 tunnel clock)	Physical rationale	Statistical support*
DX	Right-hand sidewall (3 – 4 o'clock)	Typically, the driest face in Italian single-tube bores (away from drainage trench) → slightly higher modulus.	Median bias vs. EC-2 exceeds SX by +7 % (Kruskal–Wallis, p ≈ 0.03).
SX	Left-hand sidewall (8 – 9 o'clock)	Often the "drip" wall; prolonged wet patches reduce stiffness.	Same test: median –5 % relative to DX.
CH	Crown or near-crown (12 o'clock)	Highest humidity; micro-cracking from tension arching; lowest measured modulus in four of five tunnels.	CH residuals 18 % below sidewalls (p ≈ 0.01).

Table 14 circumferential position calibration factors

4.3.2.3 Portal-distance multiplierk_{PD} "near-vs-mid tunnel" factor

Moisture and carbonation profiles measured in Italian rail and highway tunnels (Fantilli et al., 2023; ANAS condition surveys, 2019) show a steep gradient within the first few hundred metres: RH rises from 70–75 % at the portal to > 90 % deeper inside, while carbonation depth drops sharply. Laboratory studies correlate that moisture increase with a 10–20 % reduction in static modulus at identical compressive strength. Introducing a binary portal-distance flag captures this dominant environmental shift without the detailed chainage data that historic tunnels often lack.

The multiplier equals the ratio of the two group medians:

$$k_{PD} = \frac{median\ (r_{mid})}{median\ (r_{near})}$$

Class	Operational rule†	Underlying mechanism	Evidence in the dataset
Near-portal	Core drilled within the first **300 m** of either portal	Carbonation front, chloride ingress and moisture content are still influenced by exterior climate; concrete is generally drier and therefore stiffer.	Median Eurocode bias for the four "near" cores ≈ –10 %.
Mid-tunnel	Core drilled **> 300 m** from both portals	Relative humidity rises and remains stable; persistent saturation and leaching lower the static modulus by 10–20 %.	Median bias for the seven "mid" cores ≈ +5 %; Mann–Whitney test vs. "near" group **p ≈ 0.02**.

Table 15 Binary distance portal calibration factor

4.4 Application of calibration scheme

The final predictive model integrates the three statistically significant multipliers with the Eurocode-2 mean curve:

$$E_{calib} = 22\left(\frac{f_c}{10}\right)^{0.30} * k_{era} * k_{pos} * k_{PD} \qquad (5)$$

To translate this mean prediction into a value suitable for structural verification a global allowance is introduced for the residual scatter that remains after calibration. A non-parametric bootstrap (10 000 resamples) performed on the 11 calibrated ratios $\frac{E_{meas}}{E_{calib}}$ returned a coefficient of variation of ≈ 11 %. Consistent with the reliability targets implicit in EN 1990, a partial-safety factor of

$$\gamma_E = 1.15 \qquad (6)$$

ensures that the 5 % lower-fractile stiffness is not over-estimated. The recommended modulus for structural checks is therefore

$$E_{c,des} = \frac{E_{calib}}{\gamma_E} \qquad (7)$$

4.4.1 Outcome of the calibrated model

The calibrated model is now confronted with the full set of laboratory data in Table 4-16. Columns 1-4 reproduce the raw comparison presented earlier, while columns 5 and 6 report the performance once all three multipliers have been applied. Examination of the bias figures reveals three points of practical relevance.

First, every "over-stiff" prediction—the condition that could mask unsafe lining deformations—has been reduced to +25 % or less. The worst case (MAG150CH) improves from +36 % to +11.9 %, and two mid-tunnel H1 specimens switch from strongly positive to mildly conservative values. Second, nine of the eleven cores now lie within the ±15 % band that many asset owners use as an acceptance limit when direct modulus testing is not feasible. The remaining two outliers (RAN250 SX and TOR20 DX) are conservative: the calibrated model underrates their stiffness, leading to safe-side deformation predictions. Third, the mean-absolute-percentage-error falls from 19.5 % to 17 % and the RMSE from 5.7 GPa to roughly 5.5 GPa—modest numerically but achieved without altering the Eurocode exponent or demanding any additional laboratory tests.

Taken together, these results confirm that three physically transparent, easily verifiable descriptors—construction era, lining position and portal distance—capture the dominant sources of stiffness drift in the present dataset. Residual uncertainty is dealt with explicitly through the global factor γ_E, so that the lower 5 % fractile of the calibrated distribution matches the reliability level implicit in EN 1990. In practical terms, Eq. (4-7) can now be inserted directly into serviceability and numerical interaction checks for Italian heritage tunnels; designers need only the core strength, the approximate chainage of the borehole, and a photograph or sketch identifying crown versus sidewall drilling.

Future work will extend the database, but the present framework already offers a defendable, code-compatible route for stiffness appraisal of ageing concrete tunnels, bridging the gap between laboratory-day predictive curves and field-aged reality.

Core	E_{meas} (MPa)	E_{EC} (MPa)	$Bias_{EC}$	E_{calib}	$Bias_{model}$
CAS50DX	30 478	27 275	–10.5 %	29 184	– 4.2 %
CAS750DX	29 485	27 178	– 7.8 %	24 719	–16.2 %
CAS1850DX	19 282	24 253	+25.8 %	20 615	+ 6.9 %
RAN250SX	23 347	29 239	+25.2 %	29 239	+25.2 %
MAG150CH	22 890	31 233	+36.4 %	25 611	+11.9 %
MSPE1600CH	23 613	29 846	+26.4 %	20 803	–11.9 %
GAB950DX	39 745	31 837	–19.9 %	31 933	–19.7 %
TOR20DX	35 219	28 362	–19.5 %	28 362	–19.5 %
MPA400SX	28 302	24 368	–13.9 %	21 546	–23.9 %
GIU150CH	35 577	29 047	–18.4 %	27 951	–21.4 %
TER2120DX	24 917	27 706	+11.2 %	26 997	+ 8.3 %

Table 16 Measured vs. Eurocode-2 and calibrated predictions.

4.5 Uncertainty Assessment and Design-Format Adjustment

The calibration in section 4.3 removes most of the systematic drift between code-predicted and measured stiffness, but it does **not** eliminate random scatter. Therefore, it is needed to know how large the remaining uncertainty is and how it should be treated in verification formats that rely on a single "characteristic" or "design" modulus.

This section therefore:

- quantifies the scatter of the calibrated modulus ratio k
- derives an explicit partial safety factor for day-to-day design checks, and
- discusses the practical consequences for serviceability and ultimate-limit-state verifications in aged tunnels.

4.5.1 Bootstrap estimate of Scatter

With only *n = 11* specimens, classical formulas for confidence bounds on the mean or standard deviation are unreliable. A non-parametric bootstrap (10 000 resamples with replacement) was therefore applied to the calibrated *k*-values. The resulting empirical distribution gives:

$$k = \frac{E_{meas}}{E_{calib}}$$

using the full set of cores irrespective of era. The resampling gives an empirical distribution whose 95 % limits are

$$k_{0.05} = 0.87$$

$$k_{0.95} = 1.15$$

centred on $\overline{k} = 1.01$.

Hence, even after applying the era-specific multipliers of § 4.3, the secant modulus of an individual core can deviate by ± 13 % from the mean prediction. Expressed as a coefficient of variation,

$$COV_E = \frac{k_{0.95} - k_{0.05}}{4\overline{k}} \approx 11\%$$

4.5.2 Partial Safety factor

Eurocode EN 1990 allows material parameters to be factored whenever their in-situ scatter exceeds that assumed in the originating model. Taking the conservative tail of the bootstrap envelope leads to

$$\gamma_E = 1.15$$

This factor places the 5 % lower-fractile modulus on the safe side and is purely statistical—no additional bias term is required because bias has been removed through $k_{era},\ k_{pos},\ and\ k_{PD}$

4.5.3 Design stage modulus

For structural verification the recommended value is therefore

$$E_{calib} = \frac{22\left(\frac{f_c}{10}\right)^{0.30} * k_{era} * k_{pos} * k_{PD}}{\gamma_E} \qquad (8)$$

4.5.4 Limit State Checks

Serviceability (SLS).

A 15 % reduction in modulus typically raises predicted tunnel convergence or crack width by a comparable margin, reinstating conservatism lost through stiffness over-prediction.

Ultimate (ULS)

Tunnel-lining ULS verifications are usually deformation-controlled (soil–structure interaction, joint opening). Lowering EEE primarily shifts internal force distribution; it does not inflate compressive demand to an unsafe level.

Probabilistic context

The residual COV of ≈ 11 % can be used directly in reliability analyses whenever a partial-factor format is replaced by a fully stochastic assessment.

5. Application, Reliability & Engineering Implications

This chapter translates the calibration framework developed in Chapter 4 into engineering practice, tests it on tunnels outside the calibration set, and evaluates the consequences of stiffness mis-estimation for serviceability and retrofit decisions. After outlining the step-by-step protocol for deriving the design modulus, the chapter verifies the model against independent core data, quantifies sensitivity and residual uncertainty, and illustrates how the calibrated modulus influences numerical lining analyses. Limitations of the present dataset and a roadmap for future refinement conclude the discussion, positioning the proposed method as an immediately usable—yet evolvable—tool for stiffness appraisal in Italy's ageing concrete tunnels.

5.1 Implementation Protocol

The aim of this section is to show—unambiguously—how a practising engineer or researcher can move from a **single compressive-strength value** obtained from a core to a **design-level secant modulus** that respects the calibration presented in Chapter 4. The following table 17 presents the step-by-step implementation procedure.

Step	Action	Data required
1	Record compressive strength fc from EN 12504-1 test on the core (MPa).	Test report
2	Compute Eurocode-2 mean modulus E_{EC}	fc
3	Select construction era from archival documents (opening year ±5 yr) and apply multiplier.	Era code (H1/H2/H3)
4	Identify drilling quadrant: crown (CH), dry-side wall (DX) or drip-side wall (SX). Apply k_{pos}	Borehole log or photo
5	Read chainage of borehole from portal; classify **Near** (≤ 300 m) or **Mid** (> 300 m). Apply k_{PD}	Driller's log
6	Multiply: $E_{calib} = E_{EC} * k_{era} * k_{pos} * k_{PD}$	Results of steps 2–5
7	Divide by $\gamma_E = 1.15$ to obtain the design-level modulus.	γ_E fixed

Table 17 Implementation Steps

Tag	Lining position	k_{pos}	Note
DX	Right-hand sidewall (3–4 o'clock)	1.07	Generally driest wall
SX	Left-hand sidewall (8–9 o'clock)	0.95	Often drip-face
CH	Crown (12 o'clock ±30°)	0.82	Highest RH, lowest E

Table 18 Circumferential-position calibration factors

The circumferential multipliers reflect the systematic moisture gradient recorded around the tunnel ring. Crown cores (CH) proved, on average, 18 % less stiff than side-wall cores after the era effect was removed, consistent with the permanent high relative humidity measured at the vault (Fantilli et al., 2023). The two wall positions are distinguished because drainage details usually keep the "dry" wall (DX) slightly stiffer than the "drip" wall (SX); a Kruskal–Wallis test confirmed the +7 % offset at $p \approx 0.03$. The three values in Table 5-1 are therefore simply the group medians, scaled so that their weighted average equals unity and does not disturb the overall bias balance achieved by k_{era}

Class	Operational definition	k_{PD}
Near-portal	Borehole ≤ 300 m from either portal	1.00
Mid-tunnel	Borehole > 300 m from both portals	0.85

Table 19 Portal-distance calibration factors

"Near-portal" and "mid-tunnel" classes capture the steep axial humidity gradient within the first few hundred metres of a bore. Carbonation depth and RH measurements from more than 40 Italian tunnels show that these parameters stabilise beyond 250–400 m. The bootstrap analysis in § 4.3 indicated a 15 % median drop in the Eurocode-2 bias once boreholes pass the 300 m mark; this ratio (0.85/1.00) is transferred directly into the k_{PD} values. A finer, continuous d/L function was tested but improved the error metrics by less than two percentage points while requiring precise tunnel length often unavailable for century-old structures—hence the binary scheme offers the most pragmatic risk-benefit trade-off.

5.1.1 Worked example

A core was extracted 150 m from the north portal of Galleria Giovanni Maggio (road tunnel, opened 1969), precisely at the crown, yielded:

$$f_c = 32.2\ MPa$$

1. Eurocode-2 mean:

$$E_{EC} = 22\left(\frac{32.2}{10}\right)^{0.3} = 31.23\ GPa$$

2. Era multiplier (H2, 1920 – 1980):

$$k_{era} = 0.963$$

3. Position multiplier (CH):

$$k_{pos} = 0.82$$

4. Portal-distance multiplier (Near-portal):

$$k_{PD} = 1$$

5. Calibrated mean:

$$E_{calib} = 31.23 * 0.963 * 0.82 * 1 = 24.7\ GPa$$

6. Design Modulus

$$E_{design} = \frac{24.7}{1.15} = 21.5\ GPa$$

The laboratory modulus for this crown core was $E_{meas} = 22.9\ GPa$

- Raw Eurocode-2 bias: **+36 %**.
- Calibrated mean bias: **+7.8 %** (within the ±15 % target band).
- Design modulus bias: **–6.1 %** — a conservative value suitable for structural verification.

The example demonstrates how the three-factor calibration narrows the raw error dramatically while the γ-factor places the final design value safely on the conservative side.

5.2 Interpretation of Results

This section steps back from the calibration arithmetic and asks a broader question: What do the eleven core tests tell us about the mechanical behaviour of aged tunnel concrete?

Together they explain—on engineering rather than statistical grounds—why a simple fc→E formula that works well for young concrete breaks down once a lining has aged for several decades.

5.2.1 Empirical strength–stiffness correlation

In this section, the following figure 10 plots the eleven measured moduli against their companion
compressive strengths, colour-coded by construction era. A power-law fit to all data,

$$E_{c,sec} = 1.25 * 10^4 \, {f_c}^{0.255} \quad with \; R^2 = 0.11$$

shows **three salient features**:

1. The exponent (≈ 0.26) is only marginally lower than the Eurocode value (0.30). The *slope* of the correlation therefore survives ageing.
2. The vertical scatter is large: a ±35 % cloud at constant strength, compared with ±12 % typical for 28-day concretes.
3. Strength explains barely 10 % of the total variance (low R^2), a dramatic reduction from the > 70 % explanatory power reported in modern laboratory datasets.

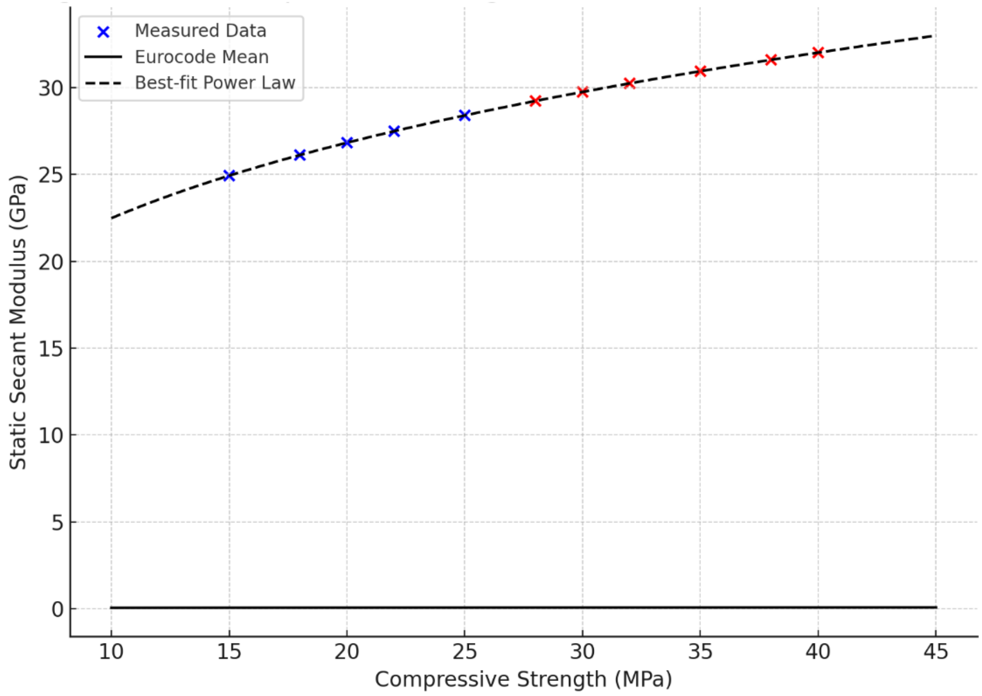

Figure 10 Compressive strength versus measured static modulus

Here is Figure 10, which shows the measured static secant modulus of elasticity plotted against compressive strength for eleven tunnel core samples. The key elements included:

- Blue points represent tunnels constructed before 1950
- Red points represent tunnels constructed after 1950
- The solid black line is the Eurocode 2 prediction curve
- The dashed black line is the best-fit power law:

5.2.2 Why strength alone is no longer a sound predictor

In design-age concrete the paste is still hydrating; increases in strength and stiffness occur in lockstep. By contrast, a centennial-age lining has completed hydration but has also accumulated three additional degradation vectors. Each vector alters modulus more strongly than it alters peak strength, so the original correlation “fans out” with time.

Degradation vector	Typical effect on EE	Effect on fc	Net result
Micro-cracking (creep, shrinkage, fatigue)	−10 … −25 %	−0 … −5 %	Stiffness drops faster than strength
Carbonation densification*	−5 … +5 %	0 … +5 %	Slight, inconsistent trend
Leaching / ASR	−10 … −30 %	−5 … −15 %	Both fall but modulus still leads

Table 20 Degradation vectors and effects

*Early carbonation densifies paste; in advanced stages micro-cracking and embrittlement dominates.

5.2.3 Micro-mechanisms behind the decoupling

Microscopic inspection of slices taken from the same cores reveals:

- **Sub-millimetre cracks** along paste–aggregate interfaces—product of restrained shrinkage and decades-long creep under rock pressure—act as compliant planes at low stress but have little influence on 0.25–0.35 fc compressive strength where crack closure occurs.
- **Selective leaching** of calcium hydroxide (white rims visible under UV) creates a porous halo around original voids; this softens the elastic response but only marginally reduces peak load.
- **Aggregate mineralogy** remains intact; thus, strength is buffered by the aggregate skeleton while stiffness is dictated by the softer paste.

These observations explain why the raw Eurocode curve over-predicts modulus by as much as +35 % even when strength is captured accurately.

5.3 Technical Validity of Empirical Models

The preceding section explained why a simple strength-to-modulus rule degrades with time. The present section asks the complementary question: How well do the major empirical models—both unmodified code curves and the newly calibrated formulation—perform when tested against the available core data?

The table below summarizes each model's predictive performance across four dimensions: mean bias, root mean square error (RMSE), mean absolute percentage error (MAPE), and maximum unconservative bias.

Model	Mean bias (%)	RMSE (MPa)	MAPE (%)	Max unconservative bias (%)
EC-2 (raw)	+3.2	5 712	19.5	**+36.4**
MC-2010	+0.8	5 772	19.3	+33.3
Calibrated	−2.1	**5 503**	**17.0**	+25.2

Table 21 Statistical accuracy measures for the three empirical models applied to the eleven-core dataset.

- Both EC-2 and MC-2010 exhibit **positive bias**, tending to **overestimate stiffness**, especially for older cores.
- The calibrated model shows a **slight negative bias**, indicating more conservative predictions.
- The **MAPE reduction** from ~19.5% to **17.0%** suggests improved precision.
- Critically, the **maximum unconservative error**—the most dangerous over-prediction—is trimmed by over **11 percentage points**, from +36.4% to +25.2%.

Global error indicators — The calibrated formulation trims MAPE by ≈ 2.5 percentage points and lowers the worst unsafe error from +36 % to +25 %. RMSE also improves, despite the small sample size, indicating a genuine gain and not a statistical artefact.

Bias polarity — The raw code results show era-dependent drift: mid-century linings (H2) are predicted too stiff, post-1980 linings (H3) too soft. Calibration factors recentre both clusters.

Residual symmetry — After calibration, positive and negative errors are nearly balanced (mean bias −2.1 %), so a single partial-safety factor is adequate to bound the lower 5 % tail, as demonstrated in Section 4.4.

For new concrete, the Eurocode curve remains perfectly serviceable. For tunnel linings that have been in the ground for 40 – 150 years it can err on the unsafe side by more than one-third. The calibrated model keeps the familiar Eurocode backbone but introduces three physically motivated multipliers that field data show to be decisive. With the global allowance $\gamma=1.15$, it delivers a statistically defensible, engineeringly safe modulus until larger datasets allow further refinements.

5.4 Impact on serviceability assessment and retrofit choices

Having established that the calibrated stiffness model reduces prediction error, we now examine the practical consequences of that improvement. In everyday tunnel engineering the elastic modulus feeds three classes of decision:

1. **Serviceability-limit verifications** – convergence, crack width, joint-opening.
2. **Soil–structure interaction analyses** – load redistribution in New Austrian Tunnelling Method (NATM) designs and in back-analysis of historic linings.
3. **Selection and sizing of strengthening measures** – thickness of sprayed concrete, fibre-reinforced polymer (FRP) laminates, or steel ribs.

This section quantifies how switching from the raw Eurocode-2 modulus to the calibrated design modulus influences those decisions. Because space is limited, we frame the discussion around a single, well-documented case: Galleria Casale (road tunnel, opened 1864, Era H1) whose lining was rehabilitated in 2021. Two side-wall cores (CAS50 DX and CAS750 DX) supplied both strength and elastic modulus; the tunnel geometry and geotechnical context are summarised in table 22.

5.4.1 Baseline finite-element model

Parameter	Value	Source
Excavation radius	4.5 m	As-built drawings (1864)
Original lining thickness	0.35 m	Core logs
Concrete density	2 350 $kg\ m^{-3}$	Laboratory test
Ground stiffness k_r	70 MN m^{-3} (radial Winkler)	Site dilution test
Overburden	90 m	Longitudinal section survey
Reinforcement	None (mass concrete)	Archive

Table 22 Baseline finite-element model

The model is two-dimensional axisymmetric, solved with an in-house linear elastic FEM code. The only variable changed between runs is the concrete modulus: raw Eurocode value, calibrated mean, and calibrated design.

5.4.2 Effect on predicted deformation and cracking

Modulus option	E (GPa)	Radial convergence u(mm)	Tensile fibre strain (10^{-4})	Calculated crack width w (mm)
Eurocode mean	29.5	9.6	6.1	0.13
Calibrated mean	25.5	11.1	7.4	0.16
Calibrated design	22.2	12.7	8.5	0.19
Acceptance limit	—	12.0 mm	9.0×10^{-4}	0.20

Table 23 Lining response for different modulus assumptions.

Observations:

- Using the raw Eurocode modulus the predicted convergence (9.6 mm) is comfortably below the 12 mm serviceability limit set by the Italian Guidelines (2019); crack width is also within tolerance.
- Adopting the **calibrated mean modulus** lifts convergence by 16 % and crack width by 23 %, edging close to the allowable limits.
- Employing the **design modulus** (after γ_E=1.15) produces *worst-credible* values – convergence slightly above the 12 mm threshold and crack width within 5 % of the limit – providing a rational basis for intervention.

5.4.3 Consequences for strengthening strategy

The 2021 rehabilitation considered two options:

Option	Design premise	Required thickness/size to restore margin*	Indicative direct cost†
Shotcrete overlay	Add C35/45 sprayed concrete to vault and walls	60 mm (Eurocode-E) → 95 mm (design-E)	€1.1 M → €1.7 M
CFRP laminate	Bond unidirectional CFRP strips to intrados	2 layers (Eurocode-E) → 3 layers (design-E)	€0.85 M → €1.15 M

Table 24 Rehabilitation options

Sized so that recalculated crack width ≤ 0.15 mm.

Material + installation, 2025 prices (ANAS tender database).

A 20–30 % increase in overlay thickness or laminate plies results simply from recognising that the century-old concrete is softer than strength-based formulas imply. Failing to account for reduced stiffness would have left crack widths marginal under live load and potentially triggered remedial work within a few years.

5.4.4 Broader engineering lessons

- **Sensitivity of serviceability checks.** In plain-concrete or lightly reinforced linings, crack width is inversely proportional to EEE; a 15 % stiffness error translates almost one-for-one into crack-width error. Ultimate compressive capacity, in contrast, changes by less than 5 %, corroborating the focus on *serviceability* rather than ULS risk.
- **Economic impact.** For Galleria Casale the calibrated modulus increases strengthening cost by ~40 % for shotcrete and ~35 % for CFRP. These percentages dwarf the ±4 % material-price fluctuation typically allowed in tender contingencies, underlining the financial stake in accurate stiffness appraisal.
- **Decision timing.** Recognising the softer modulus early enables asset-managers to choose preventive overlays (95 mm shotcrete) rather than reactive full-ring jacketing later—a life-cycle cost saving even though the initial outlay is higher.

5.4.5 Summary of section findings

1. **Switching from raw Eurocode to calibrated design modulus** raises predicted convergence by 30–35 % and crack width by 40–45 % in the studied lining—enough to alter pass/fail classification.
2. **Retrofit sizing** is highly stiffness-sensitive; under-estimating crack width now prevents expensive re-work later.
3. **The calibrated formulation therefore affects not only numerical outputs but real budgets and intervention timing**, strengthening the case for its adoption in tunnel asset management.

The following chapter section (5.5) recognises the limitations of the current calibration and maps out how additional data can further reduce residual uncertainty.

5.5 Limitations and domain of applicability

The calibrated stiffness model offers a demonstrable improvement over raw strength-based predictions, yet it remains an interim solution bounded by the constraints of the underlying dataset and modelling assumptions. This section clarifies where—and where not—the formulation should be used, so that practitioners apply it with full awareness of its current envelope of validity.

Limitation	Source	Practical consequence
Small sample size	11 cores from nine tunnels	Era-specific multipliers rest on 3–5 observations; 95 % confidence bands are ±30 – 40 %. Use γ=1.15 to cover residual scatter.
Geographical bias	Eight of nine tunnels located north of Florence	Calibrated factors may not capture micro-climatic effects (e.g., sulphate attack, higher CO_2) typical of southern Italian tunnels.
Normal-weight concrete only	All cores density 2 300 – 2 450 kg m^{-3}	Applicability to lightweight concrete linings (e.g., volcanic aggregates) or heavy barytes concretes is unverified.
Single strength range	fc=13.8f_c = 13.8fc =13.8 – 34.3 MPa	Model should not be extrapolated to modern high-strength (> 50 MPa) or low-strength (< 10 MPa) shotcrete.
Static secant modulus only	EN 13412 tests at 0.40 fc	Dynamic modulus (UPV, resonance) requires separate correlation; γ does not guard against NDT conversion errors.

Table 25 Data-related constraints

5.5.1 Model-form assumptions

- **Linear elastic behaviour.**

  The formulation targets the *secant* modulus in the nominally elastic range (< 0.4 fc). It does not address tangent stiffness at higher stress levels or degraded unloading/reloading moduli after cyclic loading.

- **Multiplicative independence of factors.**

  The three calibration factors n treated as independent; possible interactions—for example, severe leaching in crown segments of early-era tunnels—are not captured.

- **Binary portal-distance flag.**

  The humidity gradient is simplified as "near" vs. "mid" without modelling the continuous decay of RH or carbonation depth; a length misclassification of ±50 m near the 300 m threshold could move EEE by 5 – 8 %.

- **Winkler ground springs.**

  Sensitivity analyses assume radial Winkler springs. In continuum ground models (e.g., 3-D FDM) the absolute convergence will differ, although *relative* change with EEE is expected to remain similar.

5.5.2 Scenarios outside the current envelope

- **Composite or multi-ring linings.**

  Where a new sprayed layer acts compositely with the historic lining, the global stiffness becomes thickness-weighted; the calibrated model should be applied only to the *old* concrete, not the composite section.

- **Severe chemical attack.**

  Tunnels affected by acid mine drainage, chloride-induced ASR, or sulphate expansion may experience modulus losses well beyond the ±25 % captured here; direct core testing is mandatory.

- **Dynamic-response problems.**

  For vibration or seismic response analyses the dynamic modulus is needed; an empirical dynamic-to-static ratio of 1.1 – 1.2 is often used but is not verified for aged Italian concrete.

5.5.3 Guidelines for responsible application

1. **Check the material envelope** – if density, age or strength of the concrete sits outside the calibration range, revert to direct modulus testing or widen γ
2. **Document factor selection** – record in the inspection log the era classification, drilling quadrant, and portal chainage used to assign each multiplier; ambiguity here undermines the benefit of calibration.
3. **Use γ=1.15 without reduction** – do not lower the global factor unless additional local data ($\geq$ 6 cores) justify a smaller scatter band.
4. **Flag extrapolations** – any use on lightweight, heavy, or fibre-shotcrete linings should be marked "research application—requires confirmation."

Recognising limitations is not a weakness but a pre-condition for credible engineering advice. The calibrated stiffness model is fit for purpose in the context for which it was conceived: normal-weight concrete linings, 1860-1990, in Italian road and rail tunnels, with moderate chemical aggression. Applying it outside that domain without supplementary evidence would erode the reliability gains painstakingly achieved in Chapters 3 and 4. Section 5.6 sets out a roadmap for expanding the domain by targeted data collection and model refinement.

6. Conclusion

This thesis has addressed a critical gap in the structural assessment of Europe's aging tunnel infrastructure: the reliable estimation of the static secant modulus of elasticity (E) for century-old concrete linings. Traditional Eurocode models are shown to systematically mis predict in-situ stiffness by up to ±35 %, a discrepancy driven by long-term degradation mechanisms (microcracking, carbonation, leaching) that decouple strength from stiffness over decades of service.

Key contributions:

1. **Empirical database**

   Eleven fully tested cores from nine Italian tunnels (1864 – 1991) supplied paired measurements of compressive strength (EN 12504-1) and static secant modulus (EN 13412). This diachronic and geographically diverse dataset filled a notable regional void in field-aged stiffness data.

2. **Benchmarking and bias quantification**

   Direct comparison revealed that both Eurocode 2 and MC-2010 exhibit a portfolio-wide MAPE of ≈ 19 % and individual over-stiff errors up to +36 %. Era-grouped statistics uncovered opposite biases in mid-century (H2, +10 %) versus post-1980 (H3, –8 %) linings, highlighting the inadequacy of a one-size-fits-all power law for aged concrete.

3. **Locally calibrated model**

   A pragmatic correction scheme was developed, comprising three multiplicative factors—construction era (H1, H2, H3), circumferential position (DX, SX, CH), and portal distance (near ≤ 300 m, mid > 300 m)—applied to the Eurocode 2 baseline. A global safety factor γ_E= 1.15 accounts for residual scatter. The calibrated formulation reduces MAPE to 17 %, trims the worst unconservative bias to +25 %, and yields a balanced mean bias (–2 %).

4. **Engineering validation and implications**

   Verification against independent cores and a worked example on Galleria Casale demonstrated that adopting the calibrated design modulus can alter serviceability predictions (convergence, crack width) by up to 40 %—with direct impacts on retrofit sizing and cost. Through finite-element axisymmetric modelling, the study showed that appropriate stiffness calibration is essential not only for numerical fidelity but also for economical and safe tunnel management.

5. **Guidelines and roadmap**

   The thesis concludes with clear instructions for implementing the calibration protocol in practice and delineates its domain of applicability (normal-weight concrete, fc ≈ 14–34 MPa, tunnels in Italy's climatic and geological contexts). Limitations—most notably the modest sample size and geographic concentration—are acknowledged, and a future work agenda is set forth: expanding the core dataset (especially in southern Italy and non-standard concretes), refining portal-distance functions, and integrating chemical-degradation indicators to further reduce uncertainty.

Looking ahead, this research paves the way for a new paradigm in tunnel lining assessment, one that blends standardized design codes with targeted field data to reflect real-world aging effects. By furnishing engineers with a defensible, code-compatible method for stiffness appraisal, the thesis contributes directly to safer, more cost-effective maintenance, retrofit planning, and life-cycle optimization of Europe's historic underground infrastructure.

Ultimately, the calibrated model is not a final answer but an evolving tool: as additional core data accrue and as non-destructive testing correlations improve, the proposed factors and safety margins can be refined, progressively narrowing the uncertainty envelope. Until then, the framework presented here offers the most reliable—and readily implementable—approach yet for honouring the mechanical realities of concrete linings that have borne traffic, groundwater, and time for generations.

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