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Recent Advances in Predictive Modelling and Material Innovation in Concrete Creep Analysis—A Review

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ABSTRACT

Concrete creep, which is characterised by the gradual, time-dependent deformation under sustained loading, remains a critical factor for structural durability, safety and long-term performance. This review synthesises key advancements in creep research, tracing its evolution from early foundational experimental studies and empirical models such as Bažant's B3 to contemporary materials innovations and emerging computational frameworks. Novel contributions and notable developments include the integration of Finite Element Analysis (FEA), Bayesian optimisation, and fractional calculus, which have significantly improved predictive accuracy under diverse and varying environmental conditions. The study characterised the pivotal role material innovation plays in this evolution and progression, with recent focus on the development of high-performance and sustainable concretes. These advanced materials include Ultra-High-Performance Concrete (UHPC),

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Recycled Aggregate Concrete (RAC), Ground Granulated Blast-Furnace Slag (GGBFS) modified concrete, Rice Husk Ash (RHA) composites, and nano-modified concretes, all aimed at enhancing creep resistance and sustainability. The study also examines the influence of temperature, humidity, and sustained stress on creep behaviour, highlighting the need for robust multiscale models. Emerging trends, such as artificial intelligence, mesoscopic modelling, and eco-efficient materials, are identified as transformative tools for future research and applications. By bridging historical insights with modern innovations, this work provides a strategic framework for the design of resilient, durable, and sustainable infrastructure systems in the face of evolving performance demands and environmental challenges.

Keywords: Stress-Strain Relation; Creep Deformation; Material-Specific Creep; Advanced Materials; Predictive Creep Models; AI-Based Deformation Model

1. Introduction

Concrete is the backbone of modern engineering infrastructure, yet its long-term performance is disadvantaged by the creep phenomenon, which is the time-dependent and gradual deformation under sustained loads. When subjected to sustained loads, concrete exhibits gradual strain accumulation that can compromise long-term structural integrity. As concrete structures age, strain accumulation can lead to serviceability issues or even catastrophic failure. Some researchers have addressed the long-term effects of creep, shrinkage, ageing, and corrosion in civil engineering structures, emphasising their impact on structural mechanical resistance and safety [1]. They introduced various models for predicting creep and shrinkage in concrete structures.

While early studies established foundational stress-strain relationships [2–4], they primarily addressed short-term elastic responses and linear behaviour. These models, though valuable, cannot predict long-term performance under complex loading and environmental conditions. Therefore, a deeper understanding of the nonlinear interactions governing creep has become essential. This requires leveraging advanced mathematical frameworks and sophisticated computational techniques to account for these nonlinearities, plasticity, and environmental influences.

Unlike brittle fracture, which results in sudden material failure once a critical stress level is exceeded, creep deformation represents a gradual, time-dependent strain response under sustained loading. This progressive deformation does not initiate immediately but develops over prolonged service durations, influenced by factors such as stress magnitude, temperature, and material properties. In engineering applications, particularly in load-bearing structures and high-temperature environments, creep can lead to significant dimensional changes, reduced load-carrying capacity, and long-term serviceability issues if not properly accounted for in design and maintenance strategies.

The understanding of creep behaviour is essential for designing long-lasting infrastructure, especially in cases involving prestressed concrete beams, high-rise buildings, and long-span bridges [5,6]. Over the years, extensive studies have aimed to understand the mechanisms, contributing factors, and predictive models of creep deformation of engineering materials, ensuring reliable infrastructure development [7]. The review highlights the historical journey of creep research while exploring cutting-edge trends in computational advancements, predictive technologies, novel experimental methodologies and sustainable practices for the future [8–11].

Traditional predictive models, such as Bažant's Model B3 [7] and international design codes (ACI 209, BS 8110, CEB-FIP, etc. [12]), have provided empirical and theoretical frameworks for estimating creep strain. However, these models often rely on simplified assumptions and are limited in their ability to account for nonlinearities, multiaxial stress states, and evolving material properties. Creep prediction studies have highlighted the influence of shrinkage and stress relaxation on concrete creep, yet their predictive scope remains constrained by analytical rigidity and lack of adaptability to modern materials [13].

Recent advancements have introduced computational techniques such as Finite Element Methods (FEM), machine learning (ML), Bayesian optimisation, and fractional calculus [14,15] to enhance predictive accuracy. These approaches show promise in capturing complex interactions, including environmental influences like temperature and humidity [16–18]. Bayesian optimisation is a probabilistic, data-driven method for calibrating creep model parameters using prior knowledge and observed data. It enhances predictive reliability through efficient parameter estimation, uncertainty quantification, and adaptive refinement. In concrete creep modelling, it supports real-time calibration and integration of advanced materials such as UHPC, RAC, and nano-modified concretes. On the other hand, fractional calculus is a branch of mathematical analysis that generalises classical calculus by allowing derivatives and integrals of non-integer (fractional) order. It uses non-integer derivatives to model creep in UHPC and nano-modified concretes, capturing complex rheology and long-term deformation with greater accuracy than traditional methods. However, their integration into mainstream design practice is still limited, and validation across diverse material types remains insufficient.

With the emergence of innovative materials such as Ultra-High-Performance Concrete (UHPC)[10], nano-modified concretes[19], and Recycled Aggregate Concrete (RAC)[20], emphasis on material-specific creep behaviour has introduced new variables into concrete creep analysis. These advanced materials demonstrate significant potential for enhancing structural durability while aligning with sustainability goals. Numerical simulations, particularly Finite Element Methods (FEM), also bridge the gap between experimental findings and practical applications, ensuring precise predictions of long-term deformation[21,22]. While these materials offer sustainability and performance benefits, their long-term deformation characteristics under realistic service conditions are not yet fully understood.

Practical applications discussed include optimising prestressed concrete beams[23], and material-specific creep deformation for different types of concrete, improving the performance of composite materials, and ensuring durability under extreme environmental conditions. Sustainability emerges as a core theme, with eco-friendly materials like GGBFS-modified concrete and recycled aggregates offering dual benefits for performance and environmental responsibility[24].

Emerging trends highlight the transformative potential of artificial intelligence (AI) in enhancing predictive capabilities, fostering interdisciplinary collaboration among engineers, material scientists, and data analysts. Fractional calculus methods further expand the boundaries of creep modelling by providing dynamic, time-sensitive insights[25,26].

Despite decades of research and the emergence of advanced computational techniques, there remains a critical gap in accurately predicting creep deformation in advanced concrete materials under complex, multiaxial stress states and variable environmental conditions.

While traditional and existing models offer foundational insights into concrete creep, they fall short in capturing nonlinear and multivariable interactions such as time-dependent interactions between material composition, loading history, and environmental fluctuations. The limited integration of AI-driven predictive tools into mainstream design practices underscores the need for hybrid modelling frameworks that combine empirical robustness with computational adaptability.

Therefore, this review addresses the critical research gap by consolidating traditional and modern approaches to creep modelling, with a focus on capturing nonlinear creep behaviour under multiaxial stress and variable environments, evaluating the performance of advanced materials in long-term deformation, integrating AI-driven models with empirical laws for robust prediction, and bridging experimental findings with computational simulations for practical design applications.

2. Theoretical Framework and Creep Mechanism

The foundational principles and the mechanics of creep behaviour in concrete, at the microscopic level, are driven by viscoelastic and viscoplastic mechanisms, including intergranular slippage, hydration reactions, and pore deformation[27]. These behaviours are influenced by aggregate characteristics, cement matrix properties, and external conditions[28].

Figure 1 presents a schematic overview of the microstructural mechanisms that drive creep in concrete, highlighting the cyclic relationship between intergranular slip, pore evolution, and hydration during long-term loading. Intergranular slip occurs at the aggregate-paste interface, initiating stress redistribution. Pore evolution follows, with deformation and coalescence altering moisture transport and internal stress fields. Continued hydration densifies the matrix through C-S-H (calcium silicate hydrate) formation and consumption of unhydrated cement grains. These processes reinforce one another, forming a feedback loop that governs creep behaviour, especially in advanced and high-performance concretes such as UHPC and nano-modified systems, where dense microstructures and extended hydration profiles amplify the interdependence of mechanical and chemical evolution. The calcium silicate hydrate is the primary product of cement hydration and the main binding phase in concrete. It forms when water reacts with the silicate compounds in Portland cement, producing a gel-like substance that fills pores and binds aggregate particles together.

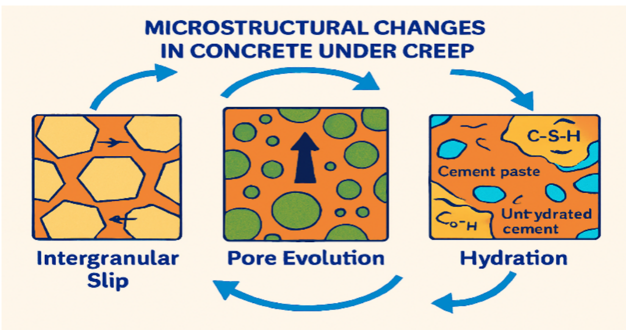

Figure 1. A schematic diagram of microstructural changes in concrete under creep.

Source: Diagram created by the authors as part of the current study.

2.1. Stages and Mechanics of Creep Deformation

Creep deformation in concrete is typically characterised via three distinct stages [13]. Initially, the rate of creep is high, but it slows down as time progresses. When the sustained load is removed from concrete, it undergoes an immediate reduction in strain, followed by a gradual recovery. This process is called creep recovery.

In other words, in elastic deformation, the recovery occurs upon the release of the load. In anelastic deformation, recovery occurs gradually over time as the internal structure adjusts, whereas in plastic deformation, the change is permanent, and rupture occurs. This distinction is crucial in understanding material behaviour under varying stress conditions, particularly in the study of creep deformation. Further understanding of the phenomenon of stages and mechanics of creep deformation can be found in the works published by some authors [29–33].

Figure 2 illustrates how a material deforms progressively under sustained load. The figure underscores the need for time-dependent constitutive models that go beyond linear elasticity, and it validates the use of strain decomposition as discussed in the subsequent section. The figure underscores the need for time-dependent constitutive models that go beyond linear elasticity, and it validates the use of strain decomposition. It also highlights the importance of long-term monitoring and environmental sensitivity in structural design.

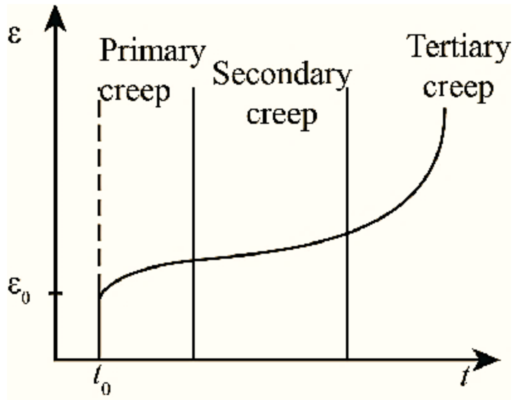

Figure 2. Creep Curve indicating three different stages [13].

The three distinct stages of creep deformation are:

1. **Primary Creep:** Characterised by a rapid initial deformation with a decreasing strain rate as stress redistributes.
2. **Secondary Creep:** Exhibits a long-lasting, nearly constant strain rate, where the material seems to stabilise or reach a temporarily steady state
3. **Tertiary Creep:** Marked by an accelerating deformation as internal damage accumulates, leading to impending failure, which requires accurate predictive modelling to mitigate risks.

This phenomenon has been studied extensively and presented in the previous researches [34–38].

The creep deformation of a material increases up to the fracture point with time under constant stress and temperature, as shown in the simplified form of **Figure 2**, where the deformation starts from initial elastic strain, and progresses to primary creep, secondary creep and up to tertiary creep at constant loading, and at continuous loading, it results the fracture point (total failure).

Additionally, environmental factors, notably temperature and humidity, can significantly accelerate these stages [39]. Detailed microstructural analyses and cavity-area models provide insight into how such external conditions interact with the material's internal structure to influence creep rates [40,41]. Empirical and analytical studies have emphasised the role of environmental factors such as temperature, humidity, and chemical exposure in shaping these stages of creep [11,16,17].

Concrete, like any other engineering material, is subject to changes in physical and mechanical properties, including expansion, contraction, cracking, and elastic deformation under stress and temperature change. The numerical value of this elastic deformation, including creep and shrinkage, is dependent on several factors, which include the following:

1. The effect of the Environment
2. The age of the concrete
3. The mix proportion of the concrete
4. The material constituents of the concrete

Another form of concrete deformation under stress is Shrinkage, which is a result of the settlement of solids and the loss of free water from the concrete. This is influenced by the action of temperature, humidity and the surrounding environment [42–45].

2.2. Stress-Strain Relationships in Concrete

The behaviour of concrete under load is governed by the stress-strain relationships, which are fundamental to understanding and predicting creep behaviour. Stress and Strain are two of the most important variables in the study of Materials Science and its application in engineering, particularly in the study of Engineering Materials. The relationship between stress, stress-to-strength ratio, and creep deformation in concrete exhibits both linear and non-linear behaviours, particularly at higher stress levels. When concrete is subjected to sustained loading, it first undergoes instantaneous elastic deformation due to stress. Over time, the concrete continues to deform, but at a gradually decreasing rate. This time-dependent increase in strain is known as creep.

Hooke's Law is a fundamental principle in solid mechanics that describes the linear relationship between stress and strain in elastic materials. In the context of concrete, Hooke's Law is primarily used to model the instantaneous elastic response of the material under load. Though concrete is a quasi-brittle and heterogeneous material, it exhibits linear elastic behaviour at low stress levels, making Hooke's Law a useful approximation in early-stage loading and structural analysis.

Understanding the stress-strain relationship as described by Hooke's Law and the impact of creep deformation on concrete is crucial for designing durable and safe structures. Therefore, Hooke's Law, as a mathematical model, plays a vital role in predicting and mitigating the effects of creep deformation. Within the elastic limit, Hooke's Law establishes linear behaviour, where the modulus of elasticity (E) is defined as shown in Equation (1). The equation of Young's Modulus (E) is a property and measure of a material's stiffness and describes its ability to resist deformation under stress rupture. It is foundational in solid mechanics and materials science, especially in the current work domain of concrete creep and structural modelling [3,46,47].

$$E = \frac{Stress}{Strain} = \frac{\sigma}{\varepsilon} \tag{1}$$

Where E is the Young's modulus, σ and ε the stress and strain, respectively. This relationship specifically quantifies the ratio of stress to strain in the elastic region of a material's behaviour. In the context of creep deformation, Young's modulus helps define the initial elastic response when a material is subjected to sustained loading, and it is primarily related to the crushing strength of the concrete [46]. Young's modulus (E) plays a critical role in quality control, material testing, and material selection during design. In structural analysis, it enables the prediction of deformation under load, which is essential for calculating deflections in beams, columns, and slabs. It also ensures consistency in manufactured materials by serving as a benchmark for mechanical performance. Furthermore, E is fundamental in creep and long-term deformation studies; in concrete, the initial modulus governs early-age behaviour, but progressively evolves as a time-dependent parameter due to creep, a central focus of the present research.

As illustrated in **Figure 3**, the applicability of the elastic modulus (E) is constrained by several foundational assumptions. First, the linear elastic assumption holds only within the initial elastic region of the stress-strain curve; beyond the yield point, where plastic deformation dominates, the relationship becomes invalid. Second, the model presumes isotropic material behaviour, which fails to capture the directional dependencies inherent in anisotropic systems such as fibre-reinforced composites or layered concrete. Third, E is sensitive to environmental conditions, particularly temperature and moisture, posing challenges in real-world scenarios where concrete is exposed to fluctuating climates. Fourth, for viscoelastic materials like concrete, E evolves over time due to creep and stress relaxation, necessitating more sophisticated, time-dependent constitutive models. Finally, microstructural features such as porosity, microcracking, and aggregate distribution significantly influence the effective modulus, requiring empirical calibration or multiscale modelling to accurately reflect material behaviour.

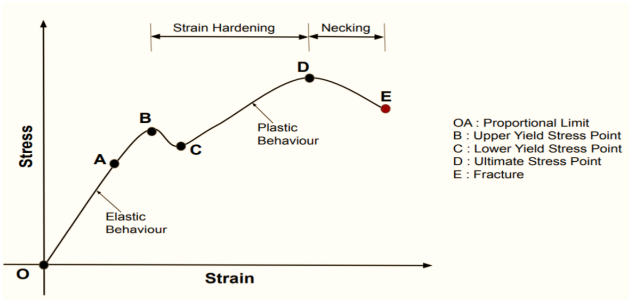

Figure 3. Typical stress-strain curve[47].

In three dimensions, the general form of Hooke's Law is given by a more advanced tensorial formulation in Equation (2). This allows for a detailed description of multiaxial stress states as they occur in real-life concrete materials[3]. Unlike the scalar form of Equation (1), this tensor form of Equation (2) accounts for directional dependence. It is a generalised form of Hooke's Law used in continuum mechanics. It's essential when dealing with anisotropic, heterogeneous, or complex materials, including fibre-reinforced composites, crystalline solids, and concrete with layered aggregates.

$$\sigma_{ij} = E_{ijkl}\epsilon_{kl} \tag{2}$$

Where σ_{ij} represents the components of the stress tensor, E_{ijkl} represents the components of the stiffness (or elasticity) tensor, and ϵ_{kl} represents the components of the strain tensor.

The generalised and tensorial form of Hooke's Law in Equation (2) is powerful but complex. Determining the full stiffness tensor requires extensive testing, especially for anisotropic materials, and assumes linear elasticity, which makes it unsuitable for large strains or plastic deformation. It is computationally demanding in simulations and may break down under environmental effects such as temperature, humidity and ageing, which are critical in materials like concrete.

However, creep introduces additional deformation beyond this elastic behaviour over time and under sustained loads. While the initial elastic response of concrete is characterised by its Young's modulus, prolonged loading induces time-dependent deformation, manifesting as creep strain accumulation. This behaviour is influenced by microstructural factors such as hydration products, aggregate distribution, and environmental conditions, and must be accounted for in long-term structural performance models[3,46,47].

Stress exceeds the elastic limit, and nonlinear creep behaviour often dominates due to microstructural changes in the material. At this stage, the nonlinear models of Equation (3) become imperative. The relation that captures the onset of plastic and time-dependent deformations is given by the power law relationship often used to describe nonlinear stress-strain behaviour, particularly in materials undergoing plastic deformation.

$$\sigma = K \cdot \varepsilon^n \tag{3}$$

Where K is the strength coefficient, and n is the strain hardening exponent[48–51].

Equation (3) models how materials harden with increasing strain beyond the elastic limit. It is commonly applied in metal plasticity, but is also adapted for nonlinear concrete behaviour. The strain hardening exponent (n) indicates how rapidly the material strengthens; If $n = 1$, stress increases linearly with strain. If $n < 1$, the material shows diminishing hardening. If $n > 1$, it hardens more aggressively. While concrete is not typically modelled with this exact form in creep studies, the power law can be adapted to describe nonlinear viscoelastic or viscoplastic behaviour, especially in high-stress regimes or early-age deformation. In the framework of the current creep studies, it could be used to approximate instantaneous nonlinear response before time-dependent effects dominate. It also serves as a constitutive base for more complex models incorporating creep and microstructural evolution.

Recent studies also incorporate temperature and humidity variations to refine these models further. Recent progress in creep modelling highlights the critical role of temperature and humidity in concrete deformation. Once considered secondary, these factors now shape predictive accuracy, as demonstrated in studies which quantify their influence on long-term creep behaviour[52]. On the other hand, elevated temperatures accelerate hydration and microstructural changes, increasing creep, while humidity levels influence moisture gradients; dry conditions intensify shrinkage, whereas high humidity moderates internal moisture gradients, but may cause other long-term effects. Modelling approaches have evolved to incorporate this sensitivity. Bažant's B3 refinements added climate-responsive curves; Daou and Raphael's Bayesian calibration leveraged local climate data. Other authors employed machine learning with sensor input to forecast creep under dynamic environmental conditions [20]. These advancements enhance structural resilience, especially in tropical regions like Calabar, South-Eastern Nigeria, and support sustainable design by promoting efficient, adaptive use of materials.

More advanced models further incorporate the concepts of true stress and strain to account for instantaneous geometrical changes. The True Stress and True Strain, which account for such changes in cross-sectional area and length during deformation, are given by Equations (4) and (5). True stress and true strain are foundational in continuum mechanics and material characterisation, especially when dealing with large deformations.

$$\sigma_{true} = \frac{F}{A_{instant}} \tag{4}$$

and

$$\epsilon_{true} = \ln\left(\frac{l_{instant}}{l_o}\right) \tag{5}$$

Where F is applied force, $A_{instant}$ is instantaneous cross-sectional area, $l_{instant}$ is instantaneous length, and l_0 is original length of the specimen.

True stress accounts for the instantaneous cross-sectional area of a specimen during deformation, offering a more accurate representation than engineering stress, which relies on the original area of a specimen. This distinction becomes critical in post-yield analysis, particularly during necking in tensile tests, where the material's geometry evolves significantly. However, its practical implementation faces challenges in measuring the instantaneous area, which is difficult during complex deformation. On the other hand, true strain, also referred to as logarithmic strain, quantifies cumulative deformation by considering the continuous change in length throughout the loading of a specimen. It offers superior accuracy over engineering strain in large deformation scenarios, making it indispensable in forming simulations and plasticity-based constitutive models. Despite its advantages, true strain assumes homogeneous deformation, which may not reflect localised phenomena such as cracking in concrete.

Both true stress and true strain are essential components in the modelling of nonlinear material behaviour. In the context of concrete, their integration is most relevant in confined compression tests. These measures can also be embedded within hybrid constitutive models that combine elastic, creep, and viscoplastic components, enhancing the reliability of long-term deformation predictions. Furthermore, in high-resolution simulations such as finite element analyses involving strain localisation or evolving geometries, true stress and strain formulations provide the necessary accuracy to capture complex mechanical responses. Their inclusion supports the development of robust, predictive frameworks for materials subjected to multi-axial and time-dependent loading conditions.

These formulations underpin much of the modern understanding of creep and help improve the accuracy of creep predictions by linking micro-level material changes to macroscopic behaviour and overall structural performance [3].

For concrete, the relationship between stress and strain follows linear elastic behaviour, meaning strain increases proportionally with applied stress. However, when considering creep-strain, the material undergoes long-term deformation under constant stress. In concrete, creep-strain is almost directly proportional to the stress-strength ratio, but only up to about one-third of the material's strength. In terms of stress-strength ratio, an upper limit from 0.3 to 0.6 has been suggested. In compression tests, microcracking begins from 0.4 to 0.6, altering creep behaviour [53]. Beyond this limit, non-linear effects start to appear, and deformation accelerates, potentially leading to structural failure over time.

This behaviour is particularly crucial for long-span bridges, high-rise buildings, and dams, where creep must be accounted for in design to ensure durability and prevent excessive deformation.

2.3. Total Strain Decomposition in Concrete Creep Analysis

A fundamental approach in the modelling and analysis of creep involves the decomposition of the total strain, $\sum \varepsilon(t)$ into distinct components. It is a total strain decomposition model commonly used in concrete mechanics and time-dependent deformation analysis.

The total strain $\sum \varepsilon(t)$in concrete under sustained load consists of elastic, creep, shrinkage, and thermal strains, represented mathematically by Equation (6). This equation expresses the total strain in a concrete element as the sum of distinct strain components that evolve over time. Each term represents a different physical mechanism contributing to deformation[50].

$$\sum \varepsilon(t) = \varepsilon_{ins}(t) + \varepsilon_{cr}(t) + \varepsilon_{sh}(t) + \varepsilon_T(t) \quad (6)$$

where

$\varepsilon_{ins}(t)$ is the instantaneous elastic strain, occurring immediately upon load application.

$\varepsilon_{cr}(t)$ is Time-dependent creep strain, gradually increasing under prolonged loading.

$\varepsilon_{sh}(t)$ is Shrinkage strain, resulting from moisture loss and drying effects.

$\varepsilon_T(t)$ is the thermal strain, influenced by temperature variations affecting material expansion and contraction.

This decomposition enables precise modelling of deformation behaviour, accounting for each component's contribution to the overall strain[50,54]. This decomposition framework is essential for accurately predicting long-term structural performance, particularly in high-stress environments such as bridges, tunnels, and skyscrapers. It is suitable for both analytical and numerical models in the calibration of complex, real-world systems. However, the total strain decomposition model is limited by its oversimplification of concrete behaviour, as it assumes linear and independent strain components while neglecting coupled effects, evolving material properties, and damage mechanisms.

2.4. Standardised Creep Testing Protocols and Methodological Comparisons

Table 1 presents a structured comparison of three categories of creep testing protocols, namely ASTM C512/C512M-24, ISO 1920-9:2009, and Custom Lab Protocols across five key factors. The accurate assessment of concrete creep requires standardised testing protocols that ensure consistency across material types, environmental conditions, and types of loading. Two internationally recognised standards govern laboratory creep testing:

1. ASTM C512/C512M-24: Standard Test Method for Creep of Concrete in Compression
   This method involves subjecting moulded concrete cylinders to sustained longitudinal compressive load under controlled environmental conditions. It is limited to concrete with a maximum aggregate size of 50 mm and is widely used for comparing creep potentials across mix designs. The test assumes proportionality between stress and creep up to 40% of compressive strength and highlights the influence of paste content on creep strain.
2. ISO 1920-9:2009: Testing of Concrete—Part 9: Determination of Creep of Concrete Cylinders in Compression
   This standard outlines the procedure for measuring creep in standard concrete cylinders under sustained compressive load. It allows for variation in curing and storage conditions to simulate early prestress or service environments. ISO 1920-9 is particularly useful for international benchmarking and harmonisation of creep data.

Table 1. Comparative Overview of Creep Testing Methods.

Method	**Standard**	**Load Type**	**Specimen Type**	**Environmental Control**	**Key Features**
ASTM C512/C512M-24	ASTM International	Sustained compression	Moulded cylinders (≤50 mm)	Controlled temperature and RH	Widely used in North America; paste-sensitive calibration
ISO 1920-9:2009	ISO	Sustained compression	Standard cylinders	Customisable curing/storage	International standard; adaptable to prestress simulation
Custom Lab Protocols	Research-specific	Variable (uniaxial, cyclic)	Cylinders, prisms, beams	Often climate-controlled chambers	Enables tailored testing for UHPC, RAC, nano-concretes

Source: Compiled by the authors based on ASTM International, 2024 and International Organisation for Standardisation, 2009.

Custom Lab Protocols refer to research-specific creep testing procedures that go beyond standardised methods like ASTM C512 or ISO 1920-9. These protocols are designed to accommodate non-conventional materials, complex loading conditions, or unique environmental simulations that standard tests can't fully capture.

While both ASTM and ISO standards provide robust frameworks for creep testing, their applicability varies by region, material type, and research objective. ASTM C512 is more prescriptive and suited for comparative studies across conventional mixes, whereas ISO 1920-9 offers flexibility for simulating real-world service conditions. Advanced research often supplements these standards with custom protocols using strain gauges, LVDTs, and climate chambers to capture creep in innovative materials like UHPC and RAC under multiaxial or cyclic loading. These methodological distinctions are critical when calibrating predictive models, validating simulation outputs, or benchmarking material performance. For example, the Alvik Bridge case study (Section 5.3) illustrates key limitations of these standard models, which failed to capture asymmetric drying creep, reinforcing the need for moisture-sensitive testing and calibration protocols.

3. Development and Evolution of Creep Studies

3.1. Chronology of Creep Research

The study and analysis of concrete creep has evolved significantly over the last four decades, moving from empirical models to data-driven, computationally optimised frameworks. Initial approaches to creep studies relied on empirical observations and evolved into the development of simplistic constitutive laws, such as the predictive framework, Bažant's Model B3, and further groundwork was provided in design codes like ACI 209 and CEB-FIP. Although these early models provided a foundational understanding, they often relied on oversimplified assumptions and failed to capture multiaxial stress effects and the influence of long-term environmental factors [54]. These early models relied heavily on empirical coefficients, underscoring the need for more adaptable, precise and advanced solutions.

Subsequent and more recent developments have enriched these frameworks by incorporating probabilistic methods [55] and by embracing real-time monitoring data, thereby reducing reliance on simplified assumptions of elastic-plastic representations toward dynamic models that capture the continuum of deformation stages.

The following graphical illustration in **Figure 4** highlights key milestones chronologically and illustrates the research progression; evolution, shifts, and emerging innovations in the field of creep analysis and prediction, from Classical Models to Contemporary Innovations (1985–2025) [55–59].

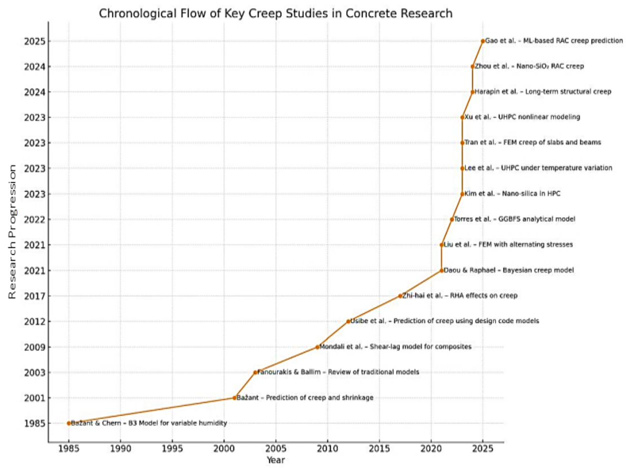

Figure 4. Chronological flow of key creep studies.

The timeline of creep research reflects a gradual deepening of theoretical rigour, broadening of material innovation, and a sharp rise in computational sophistication in the last decade. Each stage has built upon the limitations of the former, pushing toward a more reliable, predictive, and sustainable approach to managing long-term concrete deformation. As the studies of creep rupture continue to evolve, the insights gained from these integrated approaches of experimental and innovative computational techniques presented here will be critical for developing resilient, adaptive, and environmentally responsible infrastructure, ensuring durability and sustainability in the face of growing global demands.

3.2. Limitations of Existing Models

Previous design code models for predicting creep deformation in concrete have several limitations. Despite the evolution of creep models and advancements in creep rupture studies, many traditional creep models, such as those incorporated in earlier versions of CEB-FIP (1990) and ACI 209 (1992), suffer from oversimplifications, including assumptions of linearity and a limited calibration range [60]. These models often fail to accommodate the complexities of modern high-performance materials or the variable nature of environmental conditions, and this neglect of innovative materials results in less accurate predictions when applied to modern structures. Consequently, this gap has encouraged research into integrating real-time environmental monitoring and long-term experimental data, which has become essential for refining predictive accuracy [13,41].

1. **Simplifications and Assumptions:** Many models rely on simplifications and assumptions that may not accurately capture the complex behaviour of concrete under sustained loads. For example, they often assume linear relationships and ignore factors like microstructural changes over time.
2. **Material Variability:** Concrete is a heterogeneous material, and its properties can vary significantly. Existing Models may not account for this variability, leading to inaccurate predictions.
3. **Environmental Conditions:** Factors such as humidity, temperature, and exposure to aggressive environments can significantly affect creep behaviour. Many models do not fully incorporate these environmental influences.
4. **Long-Term Predictions:** Predicting creep deformation over long periods is challenging, and current models may not be reliable for long-term predictions.
5. **Multiaxial Stress Conditions:** Most models are calibrated for uniaxial stress conditions and may not accurately predict creep behaviour under multiaxial stress states.
6. **Lack of Calibration for New Materials:** As new concrete materials and technologies emerge, existing models may not be calibrated to account for their unique properties, leading to potential inaccuracies.

A wide range of creep prediction models have been developed to address the time-dependent deformation of concrete under sustained load. These models vary significantly in their theoretical foundations, empirical calibration, and applicability to modern concrete technologies. To facilitate comparative analysis and model selection, **Table 2** summarises key characteristics of several widely adopted frameworks, including their accuracy, limitations, and applicable conditions. This overview supports critical evaluation of model suitability for both conventional and advanced concrete systems.

Table 2. Comparative Overview of Concrete Creep Models.

Model	Accuracy	Limitations	Applicable Conditions
B3 (Bažant and Baweja)	High accuracy for normal and high-strength concrete; accounts for ageing and humidity effects	Requires calibration; complex formulation; limited for early-age prediction	Long-term prediction; diverse mix designs; validated across global datasets
ACI 209	Moderate accuracy; empirical basis with simplified parameters	Limited ageing effects; less reliable for modern concretes	Standard U.S. practice; normal-strength concrete; design-level estimates
CEB-FIP MC90	Good accuracy for conventional concretes; includes shrinkage and ageing	Less adaptable to UHPC or recycled aggregates; empirical coefficients	European codes; prestressed structures; moderate environmental variability
AS 3600	Regionally calibrated; reasonable accuracy for Australian conditions	Limited global applicability; simplified ageing and humidity effects	Australian practice; normal-strength concrete; moderate climates
BS 8110	Basic empirical model; low complexity	Outdated; limited predictive capability; neglects ageing and drying creep	UK legacy structures; preliminary design; conservative estimates
SABS 0100	Region-specific calibration; moderate accuracy	Limited validation outside South Africa; simplified creep curves	South African practice; standard concrete grades; dry and warm climates

Source: Compiled by the authors based on Bažant and Baweja (1995), ACI 209R (2008), CEB-FIP Model Code 1990, AS 3600 (2018), BS 8110 (1997), and SABS 0100 (2000).

To address the limitations of current design code models for predicting creep deformation in concrete, several solutions and future trends are emerging: Advances in Material-Specific Investigations, Computational and Modelling Approaches to Creep Prediction, Sustainable Practice and Green Innovations, and Smart Infrastructure and Real-Time Monitoring.

3.3. Advances in Material-Specific Investigations

Innovative and advanced materials have significantly expanded the scope of creep research, and in response to limitations in traditional concrete formulations, significant breakthroughs have been achieved through materials in this area. Bažan et al in 2015 developed a creep prediction model to determine creep in conventional plain concrete [61]. The results showed that creep behaviour changes when the constituents of concrete production are altered; therefore, a realistic assessment needs to be conducted. One advancement in reinforced concrete to prevent creep deformation is the use of Rice Husk Ash (RHA) Concrete. In the modification of concrete constituents, an experimental study was carried out on a comprehensive creep analysis of concrete containing Rice Husk Ash (RHA) with varying content in concrete from 0% to 20% [62]. The authors' detailed analysis revealed that a variation of 15% was best suited for the reduction of creep deformation in composite concrete. This approach in optimising binder ratios in RHA concrete has proven effective in mitigating creep effects.

High-Strength Lightweight Concrete (HSLW) **c**ombines reduced density with high structural capacity, offering a promising balance between performance and material economy [63]. This property balances high load-bearing capacity with reduced creep deformations as presented by Lu in 2023 [64]. In his study, a comprehensive investigation was conducted into concrete creep using the creep mechanism and parameters of High-Strength Lightweight Concrete (HSLC), the creep characteristics of High-Strength Concrete (HSC), and finally, using Light-Weight Concrete (LWC). The analyses and reviews discovered that HSC can improve the creep resistance of concrete by making the cement matrix denser by adding admixtures such as Silica fume or changing the curing conditions of the concrete.

As highlighted earlier in studies by some authors, Ultra-High-Performance Concrete (UHPC) exhibits low creep deformation due to its dense microstructure matrix and high durability [10]. However, it remains sensitive to slight environmental variations [65]. Their studies demonstrated the unique creep behaviour of UHPC, particularly its resilience under high-stress applications.

In reinforced materials, various theoretical studies have been conducted. Notable amongst them is the study of the theoretical approach to predict the second-stage creep behaviours of the short fibre composite by using the shear-lag model and imaginary fibre method [56], and the creep behaviour of the creeping matrix was predicted using a creep exponential law. The works of more authors highlight how supplementary cementitious materials like GGBFS and Nano-Modified Concretes enhance creep resistance while promoting sustainability [19,24]. Further analytical studies have explored eco-friendly alternatives by incorporating Recycled Aggregate Concrete (RAC) enhanced with nano-silica additives and optimised formulations using machine learning techniques [20,24]. These innovations not only reduce carbon emissions but also maintain comparable long-term creep performance and improve early-age creep resistance, supporting broader sustainability objectives. They explored the long-term creep behaviour of recycled aggregate concrete (RAC). Their research revealed that RAC exhibits higher creep strains compared to natural aggregate concrete (NAC), highlighting the importance of considering creep in sustainable construction practices. Adam et al in 2019 [58] investigated the effect of nano-silica on the creep resistance of high-performance concrete. Results showed that incorporating nano-silica significantly reduced creep strain, enhancing the overall performance of the concrete. The work of Mohammadi et al. (2023) [66] investigated the impact of nanosilica incorporation on the bioactivity and in vivo behaviour of calcium aluminate cement (CAC). Their results showed that nanosilica enhances the cement's hydration rate, mechanical strength, and biological performance. Specifically, the modified CAC exhibited improved apatite formation, reduced inflammatory response, and better tissue integration in vivo. These findings support the role of nanosilica in optimising CAC for biomedical applications, particularly in bone repair and dental materials.

Another advanced and eco-friendly alternative is Geopolymer Concrete, which offers enhanced creep resistance compared to Portland cement-based mixes. Materials like geopolymer binders offer sustainable advantages alongside improved creep resistance/performance. Authors [65] investigated the creep behaviour of geopolymer concrete under different loading conditions. The study demonstrated that geopolymer concrete exhibits superior creep resistance compared to traditional Portland cement concrete, offering potential benefits for long-term structural applications. Recent studies highlight the effectiveness of eco-friendly inhibitors like Arabic gum and guar gum in mitigating steel corrosion in reinforced concrete exposed to harsh environments. These natural compounds form protective films that reduce chloride ingress and enhance electrochemical stability. Compared to traditional inhibitors, they offer lower toxicity and better sustainability [67]. Also, recent advancements in nanotechnology have enabled the functionalization of Portland cement with photocatalytic nanoparticles such as TiO_2 and ZnO to enhance its self-cleaning and antibacterial properties. Varying the ratios of TiO_2/ZnO with polyethylene glycol promotes dye degradation and inhibits E. coli and S. mutans, while enhancing hydration and tensile strength [68].

3.4. Computational and Modelling Approaches to Creep Prediction

Recent advancements in computing power and data science have drastically improved the accuracy and versatility of creep prediction by simulating the creep behaviour of materials. The complexity of creep deformation has driven the adoption of these advanced computational techniques, such as the Finite Element Method (FEM). The Finite Element Analysis (FEA) is an approximation technique useful in solving boundary-value problems in the mechanics of solids [69,70]. The Finite Element Method (FEM) has been extensively used to analyse creep deformation in concrete structures. It allows for detailed modelling of the complex behaviour of concrete under sustained loads, accounting for factors such as geometry, boundary conditions, and material properties.

Custom subroutines and GUIs such as ABAQUS and ANSYS's "usercreep" have been developed to incorporate dynamic material behaviour into FEA models. This method simulates the creep deformation of engineering materials under complex geometries and variable environmental conditions [71–73]. Previous researchers developed a finite element program for analysing creep behaviour, incorporating the effect of ageing and temperature on the rate of creep deformation [74,75].

An overview of classical and novel solution methods for FEM analysis of creep in structures has been provided [76]. In this study, the authors emphasised the importance of questioning the accuracy of routine FEM analysis and ensuring meaningful results. It is recommended that numerical simulations should integrate empirical data to model stress-strain relationships over time, enabling precise deformation predictions in real-world structures [77].

Recent advancements have utilised meso-mechanical modelling to simulate the progression of stress and strain in concrete over time. Finite Element Method (FEM) analyses have also been applied to assess creep behaviour in beams and flat slabs, employing viscoelastic models integrated with Prony series interpolation via ANSYS software. These simulation approaches have proven instrumental in capturing the deterioration mechanisms of concrete under sustained loading, particularly across varied environmental conditions.

Advances in simulation techniques have enabled detailed modelling of stress evolution and strain accumulation in concrete over time using meso-mechanical approaches. Finite element analyses have also been employed to investigate creep behaviour in structural elements such as beams and slabs, often incorporating viscoelastic models with Prony series interpolation. These computational frameworks have proven highly effective in capturing the degradation of concrete under sustained loading, especially when accounting for varying environmental conditions.

The Modified Hyperbolic Sine Law is another computational technique adopted as a mathematical formulation that effectively captures the nonlinear response of creep strain under varied stress conditions [41].

Fractional calculus-based models have emerged as a powerful predictive algorithm tool that captures non-linear, time-dependent behaviours of materials under varying external factors such as temperature variations, humidity levels, and cyclic loading [78–81]. These models, often expressed through non-integer differential operators, can be embedded into classical FEA platforms such as ABAQUS and ANSYS via custom viscoelastic subroutines. This integration allows for time-dependent stiffness evolution and memory effects, enhancing the simulation efficiency of long-term creep deformation. Similarly, AI-based models, particularly those trained via supervised learning or Bayesian frameworks, can be coupled with FEA workflows to dynamically calibrate constitutive parameters, refine boundary conditions, or predict creep strain fields based on historical data. Such hybrid approaches combine empirical robustness with computational adaptability, enabling more accurate life-cycle predictions and supporting design optimisation for complex concrete systems under sustained loads.

Additionally, the Mesoscopic Composite Models bridge the gap between microstructural damage mechanisms and macroscopic deformation, providing insights into the micro-level changes that manifest as progressive creep at the structural level [82].

Table 3 below highlights the comparison in the strengths, limitations, integration potential and other parameters for both experimental and computational approaches to creep studies, underscoring their complementary roles in advancing creep modelling and prediction.

Table 3. Comparative Summary of Experimental vs. Numerical Models for Concrete Creep.

Parameter	Experimental Models	Numerical Models
Examples	Long-term creep tests on UHPC, RAC, nano-modified concretes	B3 model, Bayesian optimisation, fractional calculus, FEA with creep laws, machine learning models
Methodology	Physical testing under controlled loading, temperature, and humidity	Mathematical simulation using constitutive laws, viscoelastic theory, algorithms and computational solvers
Data Source	Direct strain/time measurements from specimens (e.g., cylinders, beams)	Input from material properties, empirical models, and calibrated parameters
Creep Mechanism Captured	Includes microstructural effects (hydration, porosity, moisture transport)	Models ageing, viscoelasticity, and drying creep via abstractions and equations.
Time Resolution	Real-time data over months/years; limited acceleration techniques	Adjustable time steps; simulates decades in minutes; extrapolates long-term behaviour
Strengths	Realistic, material-specific insights; essential for model validation	Scalable; enables parametric studies, sensitivity analysis, and design optimisation. Applicable to full-scale elements and complex geometries via numerical models
Limitations	Time- and resource-intensive; limited generalizability across mix designs, Limited to lab-scale specimens; challenging for full-scale structures	Sensitive to assumptions; may overlook microstructural phenomena without coupling
Efficiency	Low; requires long-term monitoring and physical resources	High: simulates decades of deformation in minutes; supports iterative design and optimisation
Applications	Benchmarking, material characterisation, and validation of numerical models	Structural design, life-cycle assessment, performance prediction under varied loads
Integration Potential	Provides an empirical basis for calibration and hybrid modelling	Can incorporate experimental data for hybrid or data-driven modelling approaches

Source: Compiled by the authors based on recent literature on creep testing and modelling (e.g., Rilem TC 107-CSP, 2000; Kazemi et al., 2024; Lu, 2023).

To delineate the methodological and performance-based distinctions between experimental and numerical approaches to concrete creep, **Table 2** presents a comparative summary structured around key modelling parameters. Experimental models offer high-fidelity insights into material-specific behaviour through direct measurement under controlled conditions. These models are indispensable for capturing microstructural phenomena such as hydration kinetics, porosity evolution, and moisture redistribution. However, their scalability and extrapolation capacity are inherently limited. On the other hand, numerical models leverage constitutive laws and computational solvers to simulate long-term deformation across diverse structural scenarios. Techniques from the B3 model, to ML, enable predictive reliability and parametric flexibility, provided adequate calibration is performed. These models abstract creep mechanisms into mathematical formulations, allowing for efficient simulation of service-life behaviour and integration into design workflows.

4. Emerging Trends and Future Directions

4.1. Emerging Trends

Emerging technologies allow for the identification of critical variables affecting creep with unprecedented precision. These advanced predictive models allow for effective control of deflection, ensuring prolonged performance under service loads [14,22,23].

4.1.1. Structural Optimisation

Refined and effective creep modelling directly leads to safer and more efficient structural designs, and design strategies. Predictive models discussed in Section 3.4 have profound implications for structural design in the following areas:

a. In Prestressed Concrete Beams and Composite Structures, understanding long-term deformation is critical for predicting deflections and mitigating stress redistribution over time. Advanced creep-resistant materials like UHPC are increasingly utilised in complex, high-stress engineering applications [83,84]. Generally, optimising design parameters minimises deflection and enhances load-bearing capacity over the long term [85–88].

b. Additionally, for large-scale infrastructure such as High-concrete Arch Dams, accurate creep simulation is crucial for assessing long-term structural stability. Finite Element Analysis (FEA) plays a key role in validating the integrity of these designs, ensuring durability and resilience while effectively balancing safety requirements with cost-efficiency [89]. The authors examined the long-term creep effects on high concrete arch dams, revealing that neglecting creep can lead to substantial inaccuracies in structural modelling, particularly when contraction joints are included. Their findings emphasise the need for updated models in evaluating the structural integrity of older concrete arch dams.

c. Accurate creep modelling enhances durability in applications to Nuclear Reactor containment. Given the critical nature of safety in high-stress scenarios, precision in creep prediction is paramount for ensuring containment integrity under prolonged service conditions [90]. They discussed the damage in prestressed concrete structures due to creep and shrinkage, highlighting the importance of considering these effects in super-tall buildings and nuclear reactor containments. They noted that nonuniformity of creep properties can lead to stress redistributions and deleterious cracking.

4.1.2. Sustainable Practice and Green Innovations

Sustainable materials and techniques are integral to modern engineering. While environmental sustainability is increasingly adopted in modern structural engineering research and practice, innovations in material science are also increasingly geared toward using recycled and low-carbon materials without sacrificing performance. The adoption of recycled aggregates, nano-materials, and supplementary cementitious components reflects a shift towards greener construction. These materials not only contribute to sustainability but also improve durability and long-term performance [90].

For instance, Eco-Friendly Materials such as recycled aggregates (RAC) and supplementary cementitious materials like Ground Granulated Blast-Furnace Slag (GGBFS) not only reduce environmental impacts but also improve the mechanical performance against creep. GGBFS is a supplementary cementitious material widely used in concrete to enhance its properties. Additionally, GGBFS contributes to sustainability by reducing the carbon footprint of concrete production. It is derived as a by-product of the iron and steel industry. GGBFS is obtained by rapidly cooling molten slag, which is then ground into a fine powder. It offers several benefits, such as improved durability, reduced permeability, and enhanced resistance to sulfate attack [35].

In Green Engineering and Carbon-Neutral Materials, sustainability-driven research efforts are focused on developing carbon-neutral binders and incorporating recycled materials to meet global environmental targets without compromising structural integrity [77]. Incorporating eco-friendly practices, such as using recycled aggregates and reducing cement consumption, not only reduces environmental impacts but also lowers creep susceptibility. Research into sustainable and innovative concrete materials that exhibit reduced creep behaviour can lead to more durable and environmentally friendly structures. The integration of sustainable practices is critical for aligning modern infrastructure with global sustainability goals [15,19,65].

4.1.3. Smart Infrastructure and Real-Time Monitoring

Advancements in sensor technology and the Internet of Things (IoT) have enabled the implementation of real-time monitoring systems to track creep development. The integration of sensor networks and IoT technologies is revolutionising engineering research [91], including structural health monitoring. Real-time environmental Monitoring and Smart Structures will play a pivotal role, with the deployment of distributed sensor networks enabling continuous tracking of structural health. These systems will dynamically adjust parameters within computational models as conditions evolve, ensuring more accurate and reliable creep predictions. Embedded sensors in concrete enable continuous monitoring of variables such as strain and stress, facilitating timely maintenance and extending service life [31,32].

This real-time monitoring is achievable in two ways. The First is the use of Embedded Sensors that are deployed within concrete structures, which enables real-time tracking of changes in strain, variations and creep development. This proactive approach facilitates adaptive maintenance strategies and early risk mitigation. Embedded sensors effectively facilitate proactive maintenance strategies and early risk mitigation, ensuring structural integrity under dynamic loading conditions [37,38].

The second approach is the integration of AI-enhanced data Analytics. By coupling sensor data with machine learning models, predictive frameworks can be continuously updated. These models allow structures to self-monitor and adapt intelligently throughout their lifecycles, providing improved accuracy and reliability in creep prediction [92].

4.2. Future Directions

The future trajectory of creep research lies in the convergence of advanced computational tools, sustainable practices, smart infrastructure technologies and multidisciplinary collaborations.

a. **Machine Learning and AI-driven innovations:** AI-powered and ML models have significantly advanced creep prediction by enhancing sensitivity analysis and improving predictive accuracy, and promise to revolutionise prediction methods by leveraging deep learning models and extensive datasets. These models are becoming increasingly sophisticated, and their integration into structural monitoring and modelling workflows would account for a multitude of variables, including environmental conditions, material heterogeneity, and complex stress states, all in real time [93].

b. **Sustainable Materials:** The integration of sustainable concrete materials, such as those discussed in section 4.1, represents a critical frontier in creep research. These materials offer reduced carbon footprints and enhanced durability, but their long-term deformation behaviour remains complex and often undercharacterised. Therefore, future research should focus on standardised creep testing for these advanced and sustainable mixes, supported by modelling frameworks that reflect their viscoelastic and microstructural traits. Multi-scale simulations and validated numerical approaches can clarify their long-term performance under sustained loads and environmental factors, which is crucial for aligning eco-efficient design with structural resilience.

c. **Long-Term Monitoring and Structural Diagnostics**: The integration of long-term monitoring systems is essential for validating creep models and ensuring structural reliability over time. Embedded sensors, strain gauges, and IoT-enabled platforms allow for continuous tracking of deformation, environmental exposure, and stress redistribution in concrete structures [91]. These systems support real-time calibration of predictive models and facilitate early detection of creep-induced serviceability issues. Future research should focus on coupling sensor data with AI-driven analytics to enable adaptive model refinement and predictive maintenance. Digital twins and cloud-based diagnostics can further enhance lifecycle management, allowing the simulation, monitoring, and response to creep behaviour dynamically. This convergence of monitoring technology with computational modelling will be critical for resilient infrastructure in variable service environments.

d. **Integrated Models and Multidisciplinary Collaborations:** Collaborations between material scientists, structural engineers, and data analysts are paving the way for holistic solutions, as seen in **Figure 5**. Integrating field measurements with laboratory data enhances model reliability and applicability[93–97]. In addition, interdisciplinary Integration and combination of different types of models (e.g., mechanical, chemical, and thermal) into integrated frameworks can provide a more comprehensive understanding of creep deformation[98–105].

Future innovations may merge AI-driven data and augmented reality (AR) for real-time visualisation of structural health with Internet of Things (IoT) systems. Such advancements will pave the way for fully interactive and predictive infrastructure management, setting a new standard for smart, self-monitoring structures[103,107,108]. Creep research is a collaborative effort where experimentalists generate data, data scientists build predictive models, material scientists develop improved concretes, and structural engineers apply insights to design. Feedback loops between these fields ensure continuous improvement and real-world relevance.

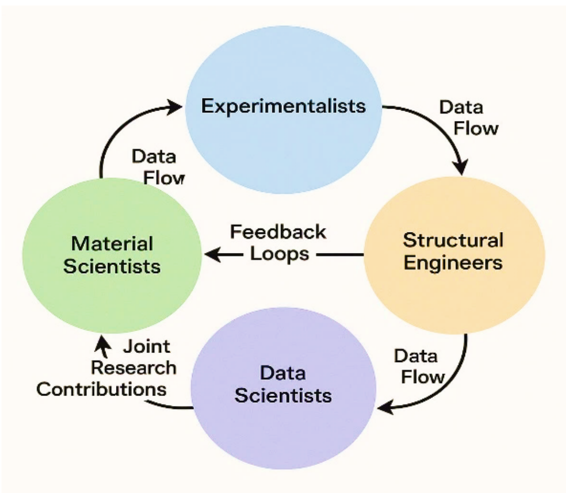

Figure 5. Multidisciplinary Collaboration Network in Creep Research.

These highlighted future directions aim to overcome the current limitations and improve the predictive capabilities of design code models for creep deformation in concrete.

5. Results and Discussions

5.1. Creep Deformation and Implications for Material-Specific Creep

As shown in **Figure 6**, a comparative bar graph presents data on creep deformation (%) for four types of concrete materials previously discussed in Section 3.3. The graph visually compares the creep deformation behaviour of various advanced and modified concrete types, to highlight their performance in resisting long-term deformation. By presenting this data side-by-side, the graph provides an intuitive way to assess which material offers superior creep resistance under specific conditions. The data are derived from previous empirical studies for the period under consideration. They are based on various findings showing the creep performance of each material under similar loading and environmental conditions.

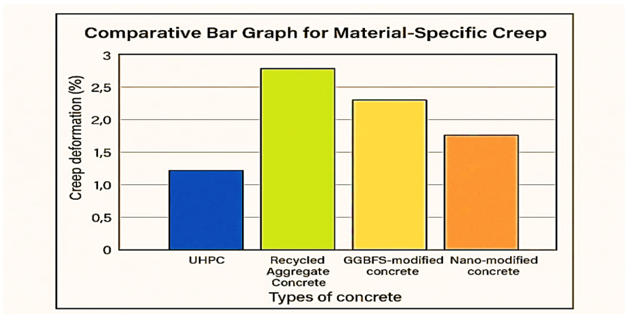

Figure 6. A Comparison of Creep Resistance across Concrete Types.

From the study, Ultra-High-Performance Concrete (UHPC) demonstrates excellent resistance to creep. Its dense microstructure, low water-to-cement ratio, and optimised particle packing contribute to its superior mechanical stability over time, with the lowest Creep Deformation among all types of concrete materials (~1.2%).

Recycled Aggregate Concrete (RAC), on the other hand, exhibits the most significant (highest) creep deformation (~2.8%), primarily due to the lower quality and higher porosity of recycled aggregates. The presence of old mortar and micro-cracks in the recycled content increases long-term strain under sustained loads.

Ground Granulated Blast Furnace Slag (GGBFS)-Modified Concrete has a moderate creep deformation (~2.3%). The addition of GGBFS enhances durability and reduces the heat of hydration, but still allows more creep than UHPC. The slag contributes to later-age strength gain, but the early-age matrix may be less stiff initially.

Finally, the Nano-Modified Concrete provides a Lower-mid (~1.8%) creep deformation. Nano-modification (using nano-silica or other nanomaterials) refines the microstructure and reduces voids, enhancing the material's resistance to deformation. Though not as strong as UHPC, it performs better than recycled and slag-modified versions.

This comparison highlights how material composition and modification strategies directly influence long-term deformation, crucial for selecting the right concrete in high-performance or sustainable applications.

5.2. Multifactor Sensitivity Analysis of Concrete Creep Rate

Concrete creep is governed by a complex effect of environmental, mechanical, and material parameters. To quantify their relative impact, a sensitivity analysis was conducted, as illustrated in **Figure 7**, which assigns normalised influence scores from 0 to 1 for four key variables: temperature, humidity, stress, and material composition on the creep rate of concrete.

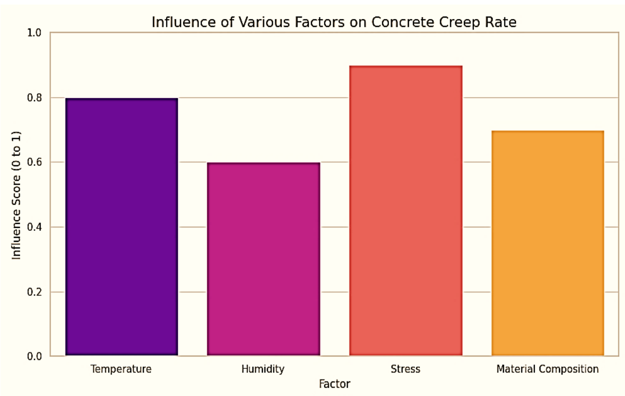

Figure 7. Sensitivity Analysis of Factors Affecting Concrete Creep Rate.

This sensitivity analysis quantifies the relative impact of temperature, humidity, stress, and material composition on creep behaviour. Sustained stress is the most influential factor with a 0.9 score, driving microstructural rearrangement and viscoelastic strain, especially in prestressed systems. Temperature with an influence score near 0.8 accelerates creep via hydration kinetics and matrix softening, requiring thermal-responsive models. Material composition at 0.7 affects creep through mix design, with UHPC showing reduced deformation and RAC exhibiting elevated strain. Finally, humidity with approximately 0.6 modulates moisture gradients and shrinkage effects. These findings highlight the need for stress-adaptive, climate-sensitive, and material-specific parameters in predictive creep frameworks.

5.3. Real-World Case Study: Creep-Induced Deflection in the Alvik Bridge

Figure 8 shows the Alvik Bridge in Stockholm, Sweden, a balanced cantilever box-girder structure, which provides a compelling real-world example of how non-uniform drying creep can compromise long-term structural performance. Post-construction monitoring revealed excessive mid-span deflection, which was not anticipated during the design phase. Investigations attributed this deformation to asymmetric moisture retention, specifically, the top flange of the box girder retained moisture longer than the bottom flange due to limited ambient exposure. This differential drying led to uneven shrinkage and amplified creep strain, resulting in curvature and downward deflection over time.

Figure 8. Creep-Induced Mid-Span Deflection in the Alvik Bridge, Sweden[109].

Finite Element Analyses confirmed that conventional predictive models significantly underestimated the observed deformation. In contrast, more advanced frameworks that incorporate hygro-thermal gradients and time-dependent stiffness evolution yielded results more consistent with field measurements. Notably, some the research have demonstrated that incorporating viscoelastic models with Prony series interpolation into FEM simulations can effectively capture creep-induced deflection in concrete beams and flat slabs[59]. Their findings underscore the importance of integrating time-dependent material behaviour and environmental sensitivity into numerical models. This real-world case[109] also underscores the limitations of standard design codes in capturing environmental sensitivity. Therefore, it highlights the need for refined creep modelling frameworks that integrate early-age calibration, environmental exposure and time-dependent material evolution, especially in prestressed concrete systems with complex geometries.

5.4. Creep Model Selection Framework for Concrete Structures

To support the engineering selection of an appropriate creep prediction model for concrete structures, a structured decision-support framework is proposed. This flowchart synthesises material classification, environmental exposure, and analytical precision into a three-step selection process, ensuring alignment between model complexity and project-specific demands as follows:

Start

- ► Step 1: Identify Concrete Type
  - UHPC / Nano-modified / RAC / Geopolymer
    - Use advanced models (Fractional Calculus, ML, Bayesian, Mesoscopic)
    - Proceed to Step 2
  - Conventional Concrete (OPC, GGBFS blends)
    - Use classical models (B3, EC2, ACI 209, CEB-FIP)
    - Proceed to Step 2
- ► Step 2: Assess Environmental Conditions
  - Variable (humidity, temperature, cyclic loading)
    - Use time-sensitive models (FC, ML, FEA with subroutines)
    - Consider sensor integration for real-time calibration
  - Controlled (lab or stable service conditions)
    - Use empirical models for calibration
    - Proceed to Step 3
- ► Step 3: Define Accuracy Requirement
  - High (design optimisation, life-cycle prediction)
    - Use hybrid models (FEA + ML/FC)
    - Include probabilistic sensitivity analysis (Bayesian)
  - Moderate (preliminary design, academic study)
    - Use calibrated classical models
    - Apply simplified constitutive laws
- ► Output: Recommended Model Type
  - Classical (B3, EC2, ACI 209)
  - Fractional Calculus-based
  - Machine Learning / Bayesian Optimisation
  - Hybrid (FEA + AI/FC)
  - Meso-mechanical / Composite Models

► End

Flowchart Description

Step 1: Identify Concrete Type

For conventional concretes such as Ordinary Portland Cement (OPC) or GGBFS-modified mixes, classical models like B3, EC2, ACI 209, or CEB-FIP are typically sufficient. In contrast, advanced concretes (e.g., UHPC, RAC, nano-modified, or geopolymer systems) exhibit nonlinear, time-dependent behaviour that necessitates the use of more sophisticated frameworks, including Fractional Calculus, Machine Learning, Bayesian optimisation, or mesoscopic composite models.

Step 2: Assess Environmental Conditions

Structures exposed to variable conditions such as fluctuating humidity, elevated temperatures, or cyclic loading require time-sensitive models capable of capturing hygro-thermal gradients and evolving material properties. These may include FEA with custom subroutines or AI-enhanced predictive tools. For structures in controlled laboratory or service environments, empirical models calibrated to standard conditions may be sufficient for reliable performance estimation.

Step 3: Define Accuracy Requirement

Projects demanding high predictive accuracy, such as life-cycle assessments, prestressed systems, or nuclear containment structures, benefit from hybrid models that integrate mechanistic theory with data-driven calibration. These may include FEA coupled with ML or Bayesian frameworks. For preliminary design or academic studies where moderate accuracy is acceptable, calibrated classical models or simplified constitutive laws offer efficient and interpretable solutions.

By progressing through these decision nodes, engineers can select a creep model that balances complexity, precision, and contextual relevance, ensuring that creep behaviour is accurately captured for both conventional and advanced concrete systems under diverse service conditions.

The current work considered the timeline of creep research, which has undergone a notable transformation, as presented in **Table 4**. It details the transition from traditional fixed-parameter models to adaptive, data-driven techniques. Classic empirical frameworks, such as the Bažant and Chern's B3 empirical model, was increasingly replaced by probabilistic tools that leverage Bayesian inference and machine learning. This shift underscores a deeper appreciation of the inherent complexity and variability in long-term material behaviour, enabling more accurate and flexible predictive models.

Table 4. Summary Trends and Observations of Creep Studies.

Trend	Observation	Implications for Engineering Practice
From Empirical to Probabilistic	Shift from fixed-parameter empirical models (e.g., B3) to adaptive probabilistic tools (e.g., Bayesian, ML).	Enables uncertainty quantification, real-time calibration, and improved life-cycle prediction accuracy.
Material Evolution	Progressive integration of eco-friendly materials such as RHA, GGBFS, nano-silica, and RAC reflects growing sustainability.	Requires material-specific creep models and testing protocols; supports low-carbon design strategies.
Environmental Adaptivity	Increased recognition of variables like temperature, humidity, ageing, and shrinkage effects.	Demands climate-responsive algorithms and hygro-thermal calibration in both lab and field simulations.
Modelling Depth	Expanded use of FEA, meso-mechanical, and hybrid numerical techniques.	Facilitates simulation of complex geometries and stress states; supports design optimisation and validation.
Smart Prediction	The 2020s marked the rise of AI and real-time sensor feedback in creep prediction.	Promotes adaptive infrastructure, predictive maintenance, and integration of IoT-based monitoring systems.

Source: The summarised contents were extracted from the following sources- Harapin et al. [1]; Liu et al. [8]; Fanourakis et al. [12]; Usibe et al. [13]; Abadel et al. [18]; Zhou et al. [19]; Gao et al. [20]; Torres et al. [24]; Bazant et al. [27]; Daou et al. [55]; Mondali et al. [56]; Dezheng et al. [57]; Adam et al. [58]; Tran et al. [59]; He et al. [62].

There has been a decisive move toward sustainable materials in structural applications. Recent researchers have incorporated eco-friendly components such as Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBFS), nano-silica, and Recycled Aggregate Concrete (RAC). These materials not only align with global environmental priorities but also introduce creep resistance, which in turn necessitates refined modelling and characterisation approaches. The results of a comparative study of creep resistance across different concrete types (**Figure 5**) show the importance of adapting material-specific evolution and integration of advanced materials into structural design and applications.

Post-2017 studies have also demonstrated heightened sensitivity to environmental conditions. Parameters such as temperature fluctuations, humidity, and ageing processes are now routinely embedded into creep assessments. This trend reflects an industry-wide recognition that accurate long-term predictions must consider ambient factors, especially vital for infrastructure operating in diverse climatic zones.

In terms of computational methods, the depth of modelling has expanded significantly. We can now employ the Finite Element Analysis (FEA), meso-mechanical modelling, and hybrid numerical schemes to simulate creep phenomena in concrete materials. These sophisticated techniques facilitate deeper insight into microscale stress redistribution, crack propagation, and the cumulative effects of creep deformation over time.

Finally, the onset of the 2020s has ushered in an era of intelligent material modelling that makes creep predictions more innovative and adaptable. The integration of

Artificial Intelligence and real-time sensor feedback mechanisms has revolutionised how creep is monitored in real-time and predicted. Materials can now be observed in-service, with predictive models dynamically updated based on live performance data, thereby transforming the field of creep rupture studies from static, post-analysis to proactive, data-responsive design of engineering structures.

5.5. Conclusions

Concrete creep remains a critical factor in long-term structural performance, demanding a multidisciplinary approach to creep prediction and mitigation. Therefore, it is a vital area of research to focus on in modern engineering practice. This review has examined the phenomenon of concrete creep and the advancement of its study through three core approaches: Evolution of Predictive Models, Materials Innovation, and their Applications.

Computational models have evolved from empirical frameworks such as the B3 empirical model to advanced techniques, including FEA, Bayesian optimisation, fractional calculus, and machine learning, offering improved understanding and predictive accuracy of concrete creep. However, these advancements still require the integration of adaptability to capture complex creep behaviour under variable conditions, as well as real-time adaptability.

This study reveals that the most significant timeline milestone in concrete creep studies is that of Material-specific evolution, which is consequent on the role it plays in eco-friendly structures and global sustainability goals. Material innovations such as UHPC, RAC, RHA, and nano-modified concretes demonstrate varying degrees of creep resistance, underscoring the need for material-specific formulations that balance mechanical performance with sustainability.

Applications in structural optimisation for prestressed systems, nuclear containment, and smart infrastructure highlight the practical need for accurate creep prediction. Embedded sensors and AI-enhanced analytics are the future approach to reshaping how structures respond to long-term deformation.

While this review synthesises key developments across modelling and materials, it is limited and does not include experimental validation or quantitative benchmarking of model performance. The scope is limited to published literature and conceptual frameworks, and does not address regional variations in design codes or long-term field data from infrastructure projects.

Future research in concrete creep should emphasise multiscale modelling that links microstructural evolution to macro-level deformation, enabling more precise long-term performance predictions. Climate-responsive models that reflect regional environmental variability and ageing effects are essential for resilient infrastructure design. Innovations in metamaterials and architectured concretes offer potential for tunable viscoelastic behaviour, while integrating 3D-printed systems into creep workflows could transform modular construction practices. Additionally, real-time calibration through sensor data and analytics will support digital twins and intelligent diagnostics, fostering adaptive, proactive infrastructure management.

Finally, interdisciplinary collaboration among material scientists, structural engineers, and data scientists will be vital for developing resilient, adaptive, and sustainable solutions to creep-related challenges. The convergence of material-specific design, intelligent modelling, and sustainability-driven engineering would mark a transformative shift in creep research, one that will shape the future of long-term structural performance.

Author Contributions

B.E.U.: Conceptualisation, Methodology, Supervision, Writing—original draft, Writing—review & editing, Data curation; C.C.E.: Writing—review & editing, Formal analysis; N.A.N.: Writing—review & editing, Visualisation; A.I.U.: Methodology, Resources; I.O.I.: Writing—review & editing, Validation; M.B.A.: Writing—review & editing; G.O.I.: Writing—review & editing; O.O.E.: Writing—review & editing; A.O.O.: Writing—review & editing; K.A.: Writing—review & editing; M.E.A.: Formal analysis. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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