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Influence of Diurnal Temperature Variation on Concrete Mechanical Properties: Cyclic Effects and Damage Mechanisms—A Review

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تأثير التغير اليومي في درجات الحرارة على الخصائص الميكانيكية للخرسانة: التأثيرات الدورية وآليات التلف ـــ مراجعة علمية

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الملخص:

تتعرض المنشآت الخرسانية بشكل مستمر لتغيرات يومية في درجات الحرارة خلال فترة خدمتها. وعلى الرغم من أن تأثير درجة الحرارة على الخصائص الميكانيكية للخرسانة تمت دراسته بشكل واسع تحت ظروف ثابتة أو درجات حرارة قصوى، إلا أن دراسة تأثير دورات التسخين والتبريد الواقعية الناتجة عن تعاقب الليل والنهار ما تزال غير مكتملة ومجزأة في الأدبيات العلمية الحالية .بناءً على ذلك، تستعرض هذه الدراسة وتجمع نتائج الأبحاث التجريبية والتحليلية التي تناولت تأثير الدورات الحرارية ضمن ظروف التشغيل الطبيعية على:

- مقاومة الضغط،
- معامل المرونة،
- ومقاومة الشد للخرسانة .

تشير الدراسات إلى أن التأثير اللحظي لدرجة الحرارة يختلف بشكل جوهري عن الاستجابة الناتجة عن التكرار الدوري للحرارة. ففي الظروف الحرارية المستقرة، تكون التغيرات في المقاومة والصلابة غالبًا قابلة للعكس. أما عند تكرار فروقات درجات الحرارة بشكل دوري، فإن الضرر التراكمي يبدأ بالتطور تدريجيًا. وينتج هذا الضرر بسبب الاختلاف في التمدد الحراري بين الركام وعجينة الإسمنت، مما يؤدي إلى تولد إجهادات موضعية عند منطقة الانتقال البينية بينهما(Interfacial Transition Zone) ، وبالتالي تشكل شقوق مجهرية تدريجية داخل الخرسانة .وقد تؤدي الدورات الحرارية ذات السعات المتوسطة إلى زيادة مؤقتة في مقاومة الضغط نتيجة استمرار عملية الإماهة (Hydration)، إلا أن هذا التأثير يتراجع مع استمرار الدورات الحرارية، حيث تصبح ظاهرة التدهور الميكانيكي هي المسيطرة .وفي المقابل، ما تزال الأدلة المباشرة المتعلقة بتطور مقاومة الشد تحت تأثير الدورات الحرارية اليومية الواقعية محدودة نسبيًا مقارنة بمقاومة الضغط ومعامل المرونة .بشكل عام، يبدو أن التغير اليومي المتكرر في درجات الحرارة يعمل كعملية تعب حراري–ميكانيكي منخفض الشدة، وليس مجرد ظاهرة مرتبطة بدرجة الحرارة فقط .ولذلك، هناك حاجة إلى إجراء تجارب طويلة الأمد وأكثر دقة تحاكي دورات بيئية حقيقية مدتها 24 ساعة، وضمن مجالات حرارية واقعية تقارب: (10–50 °C) وذلك لفهم التأثيرات الميكانيكية طويلة الأمد لهذه الظاهرة بشكل أوضح.

- **الكلمات المفتاحية:** الخرسانة، الضرر الدوري، منطقة الانتقال البينية، التدهور الميكانيكي، الدورات الحراري

Abstract

Concrete structures are continuously exposed to daily temperature changes during their service lives. While the influence of temperature on mechanical properties has been widely examined under constant or extreme conditions, the study of the effect of realistic day–night heating and cooling cycles remains fragmented in the existing literature. Accordingly, this review synthesizes experimental and analytical studies investigating how service-level thermal cycling influences compressive strength, elastic modulus, and tensile strength.

The literature indicates that instantaneous temperature effects differ fundamentally from the response observed under repeated cycling. Under stabilized conditions, changes in strength and stiffness are largely reversible. When temperature differentials are applied repeatedly, however, cumulative damage begins to develop. The mismatch in thermal expansion between aggregates and cement paste generates localized stresses at the interfacial transition zone, promoting progressive microcracking. Moderate amplitudes may temporarily increase compressive strength due to continued hydration, but this effect diminishes as cycling continues and degradation becomes dominant. In contrast to compressive strength and modulus, direct evidence describing tensile strength evolution under realistic diurnal cycling remains limited.

Overall, repeated daily temperature variation appears to act as a low-level thermomechanical fatigue process rather than a simple temperature-dependent phenomenon. More controlled long-term experiments replicating true 24-hour environmental cycles within realistic temperature ranges (approximately 10–50 °C) are needed to clarify the long-term mechanical implications.

Keywords: Concrete, Cyclic damage, Interfacial transition zone, Mechanical degradation, Thermal cycling.

Introduction

Concrete is one of the most widely used structural materials in construction projects due to its availability, versatility, and mechanical performance (Merbouh et al., 2012). During service, concrete is subjected to changing environmental conditions. Among these, temperature variation—often coupled with moisture changes—strongly influences both material behavior and structural response (Chen et al., 2020; Shoukry et al., 2009).

Several studies investigated the sensitivity of concrete’s mechanical properties to temperature. For instance, variations in curing temperature and humidity significantly influence strength development, and even moderate reductions in ambient temperature can decrease compressive strength (Farzampour, 2019). Experimental simulations of hot and cold weather conditions further show that early-age environmental temperature affects long-term strength evolution (Ortiz et al., 2005). At elevated temperatures, progressive reductions in compressive strength, tensile strength, and elastic modulus occur due to thermally induced microstructural changes within the cementitious matrix (Krishna et al., 2019; Osuji & Ukeme, 2015). These findings confirm that concrete is inherently temperature dependent.

In practice, thermal effects are widely recognized in design and construction. Mass concrete guidelines recommend pre-cooling and post-cooling to limit thermal gradients and reduce cracking risk (ACI 207), while design provisions address cracking associated with volumetric changes and restrained deformation (ACI 318). Such measures reflect longstanding engineering understanding that temperature is a governing parameter in concrete performance.

Most existing research has focused on controlled curing conditions or extreme thermal events such as fire exposure and freeze–thaw cycles (Son & Hosoda, 2010; Anupama Krishna et al., 2019; Osuji & Ukeme, 2015; Lagrini et al., 2019; Huo et al., 2022). In contrast, concrete structures in service experience continuous seasonal and daily temperature fluctuations. Long-term monitoring of a reinforced concrete building reported daily ambient temperature variations ranging from approximately 12–34 °C in summer and 3–27 °C in winter (Ramírez et al., 2022), while differences of about 20 °C have been recorded in other climatic conditions (Al-Shathr et al., 2018). Day–night air temperature differences approaching 28.5 °C have also been measured in concrete arch bridges (Tang et al., 2018), and coastal environments may experience rapid surface heating and cooling under solar radiation (Qiao et al., 2022). These observations confirm that diurnal temperature variation is a recurring service condition.

Repeated daily heating and cooling induce self-equilibrated thermal stress and impose loading on the interfacial transition zones (ITZs) due to differential thermal expansion between aggregates and cement paste (Pichler, 2023). At the structural scale, diurnal temperature variation acts as a generalized load that redistributes internal forces and neglecting it can lead to discrepancies in load transfer prediction (Huang & Liu, 2014). Collectively, these findings indicate that daily temperature cycles represent a persistent thermomechanical loading condition affecting both material integrity and structural response.

At the structural member level, daily temperature fluctuations produce non-uniform thermal distributions, as surface regions respond more rapidly than the interior. The resulting differential expansion induces restrained deformation and thermal stress (Chen et al., 2024). Tensile stresses may exceed tensile capacity, leading to cracking (Prasanna et al., 2010; Chala & Mourougane, 2015), and numerical simulations confirm that day–night temperature differences generate tensile stress fields consistent with observed cracking patterns in large concrete structures (Li et al., 2021). Over time, these repeated stress cycles indicate that diurnal temperature variation behaves as a recurring low-level thermomechanical load.

Beyond immediate stress development, repeated temperature cycling can contribute to progressive material changes. Cyclic thermal exposure has been associated with microcracking and durability-related effects (Lagrini et al., 2019; Son & Hosoda, 2010). Fluctuating environmental conditions may also increase drying shrinkage relative to steady laboratory environments, with largely irreversible deformation (Al-Shathr et al., 2018). In addition, deterioration processes such as corrosion activity have been shown to follow diurnal temperature patterns (Lyons et al., 2019), underscoring the dynamic interaction between environmental variability and material response.

Despite extensive research on extreme temperature exposure, comparatively limited attention has been directed toward systematic evaluation of daily service-level temperature variations and their influence on intrinsic mechanical properties. Existing data are fragmented and often embedded within broader studies of thermal effects rather than focused specifically on realistic diurnal amplitudes. Consequently, the long-term mechanical implications of repeated daily heating and cooling remain insufficiently consolidated.

Therefore, this study synthesizes available experimental and analytical evidence concerning daily temperature variation and its influence on compressive strength, tensile strength, and elastic modulus. By distinguishing between extreme thermal scenarios and realistic service-level diurnal cycles, this review aims to clarify the current state of knowledge and identify priorities for further investigation.

Literature Search Strategy and Review Framework

This study adopts a structured literature review approach to collect and synthesize available experimental studies concerning daily temperature variation and its influence on the mechanical properties of concrete. The primary objective is to consolidate reported data under service-level thermal fluctuations and to identify gaps and inconsistencies in the existing literature.

Search Sources and Scope

The literature survey was conducted using Google Scholar and the Scopus database, in addition to direct access to peer-reviewed journal publications through major academic publishers, including Elsevier and MDPI. No strict publication restriction was imposed during the search process. However, most of the relevant studies identified fall within the period 2005–2025, reflecting the increasing research attention given to thermal cycling and temperature- dependent mechanical behavior of concrete in recent years.

Search Strategy

Keyword combinations were developed to capture both explicitly diurnal investigations and broader cyclic thermal studies representative of environmental heating–cooling conditions. Core search strings included:

- “Diurnal temperature variation” AND “concrete”
- “Thermal cycling” AND “compressive strength”
- “Temperature differential” AND “elastic modulus”
- “Cyclic temperature” AND “tensile strength”

Because relatively few laboratory studies explicitly use the term “diurnal,” the search was expanded to include investigations examining repeated heating–cooling cycles within temperature ranges representative of environmental exposure.

Titles and abstracts were screened to assess relevance to mechanical performance under temperature variation. Studies focused exclusively on extreme thermal exposure (e.g., fire conditions exceedingly approximately 200 °C) or freeze–thaw deterioration dominated by phase-change mechanisms were excluded from detailed synthesis, except where such studies provided mechanistic insight into temperature-dependent mechanical behavior. Studies addressing durability transport phenomena without reporting intrinsic mechanical property changes were also excluded.

Inclusion Criteria

Studies were included in the review if they:

- Reported quantitative changes in compressive strength, tensile strength, or elastic modulus;
- Investigated stabilized or cyclic temperature exposure within ranges representative of environmental service conditions (approximately −20 °C to 80 °C);
- Provided sufficient methodological detail to allow interpretation of temperature amplitude (ΔT), number of cycles, and material characteristics.

Analytical Framework

Rather than presenting a chronological summary, the selected studies were synthesized according to three governing parameters:

- Temperature amplitude (ΔT);
- Number of thermal cycles.
- Material composition and microstructural characteristics.

A central objective of this review is to distinguish between reversible temperature-dependent behavior under stabilized exposure and cumulative degradation induced by repeated thermal differentials. This framework enables consolidation of fragmented findings into an amplitude-dependent thermomechanical interpretation relevant to realistic service-level diurnal temperature conditions.

Regional Variability in Diurnal Temperature Amplitude and Implications for Concrete Performance

Concrete structures exposed to ambient environmental conditions undergo repeated daily heating and nighttime cooling driven by solar radiation (Pichler, 2023). The magnitude of these daily temperature fluctuations is not geographically uniform. A global analysis of 1,537 subnational regions reported that low-latitude regions, particularly tropical zones, exhibit greater sensitivity to increased daily temperature variability compared with high-latitude regions characterized by larger seasonal differences (Kotz et al., 2021; Zou et al., 2024). Complementary assessments have identified elevated day-to-day temperature variability in parts of Central and Southern Africa, Central Asia, Eastern Europe, and Russia (Zou et al., 2024), indicating that pronounced daily fluctuations are concentrated in specific climatic zones.

Within-country analyses further demonstrate spatial gradients in thermal variability. In mainland China, intra-annual temperature fluctuations are significantly higher in northern and northwestern regions than in southern areas (Han et al., 2024), illustrating that diurnal variability can differ substantially even within a single national context. From a climatic perspective, the governing mechanisms of daily maximum temperature variability vary across zones, with radiative effects dominating in humid tropical climates and heat advection and land surface heat storage contributing more strongly to dry subtropical and high-latitude regions (Ghausi & Kleidon, 2025). Collectively, these findings indicate that exposure to pronounced daily temperature variation is regionally concentrated rather than globally uniform. For concrete infrastructure located in such environments, sustained diurnal thermal amplitudes may represent persistent thermomechanical loading conditions capable of influencing long-term material performance and structural response.

Microstructural Mechanisms of Mechanical Degradation under Diurnal Thermal Cycling

Concrete structures subjected to daily (diurnal) temperature variation experience repeated heating and cooling cycles that generate cyclic internal stresses. Phase-field fracture modeling has shown that large diurnal temperature ranges can initiate and propagate internal cracking, progressively reducing structural stiffness and load-bearing capacity (Han et al., 2024). Importantly, thermochemical degradation mechanisms in cementitious materials occur only at elevated temperatures significantly exceeding service-level environmental conditions (Zeng et al., 2022). Therefore, mechanical deterioration observed under moderate thermal cycling is attributed to cumulative thermo-physical damage processes rather than hydration phase decomposition (Zeng et al., 2022). Experimental investigations further demonstrate that thermal strain incompatibility between aggregate and cement paste generates interaction stresses concentrated at the interfacial transition zone (ITZ), where microcracks preferentially initiate and correlate quantitatively with reductions in compressive strength and elastic modulus (Zunino et al., 2015; Chen et al., 2020).

Thermo-Physical Damage under Service Temperature Ranges

Thermochemical transformations in cementitious materials occur at temperatures significantly higher than those associated with daily environmental exposure (Zeng et al., 2022). Therefore, reductions in mechanical performance observed under moderate thermal cycling (e.g., 5–45 °C) cannot be attributed to hydration phase decomposition. Instead, repeated thermal strain reversals generate cyclic internal stresses that progressively accumulate damage.

Under such cycling conditions, decreases in strength and hardness correlate with increased microcrack width, length, and density, as well as pore coarsening (Zeng et al., 2022). Similar reductions in compressive strength, splitting tensile strength, and elastic modulus with increasing cycle number have been reported for high-performance concrete subjected to thermal cycling, accompanied by microcrack generation and interconnection (Chen et al., 2020). Temperature differential cycling has likewise been shown to reduce dynamic elastic modulus and compressive strength while promoting internal crack evolution (Tao et al., 2025). Together, these findings indicate that mechanical degradation under service-level temperature fluctuations is driven by progressive microcrack development rather than chemical phase alteration.

Thermomechanical Incompatibility and ITZ-Dominated Crack Initiation

The heterogeneous nature of concrete amplifies thermally induced strain incompatibility. Differences in coefficients of thermal expansion and elastic moduli between aggregates and cement paste produce localized interaction stresses during heating and cooling. Micromechanical modeling combined with fluorescence microscopy has shown that these stresses concentrate preferentially at the ITZ (Zunino et al., 2015). Experimental thermal cycling investigations on high-performance concrete likewise report that repeated heating–cooling cycles induce microcracks predominantly within the ITZ due to thermal expansion mismatch between the cement matrix and coarse aggregate, leading to progressive interfacial deterioration (An et al., 2020.

Thermally exposed specimens exhibit microcracks predominantly distributed around coarse aggregates and aligned with the ITZ, consistent with tensile stress fields predicted by two-phase modeling (Zunino et al., 2015). Backscattered electron imaging under controlled thermal cycling further confirms that these ITZ microcracks expand and increase in density with increasing cycle number (An et al., 2020) .Reductions in compressive strength and dynamic Young's modulus were statistically correlated with calculated thermal interaction pressure and radial matrix strain parameters, establishing a quantitative link between interfacial microcracking and macroscopic degradation (Zunino et al., 2015). Nanoindentation measurements additionally demonstrate that micromechanical degradation is more pronounced within the ITZ than in the surrounding cement matrix during thermal cycling (An et al., 2020). Additional thermal cycling studies report deterioration of micromechanical properties within both the cement matrix and ITZ due to incompatible deformation between phases (Chen et al., 2020). The repeated identification of interfacial damage across independent investigations supports the interpretation that the ITZ serves as a primary initiation zone for thermally induced cracking under repeated temperature variation.

Crack Propagation, Connectivity, and Macroscopic Property Reduction

Microcrack initiation alone does not fully explain mechanical degradation. Progressive crack growth and connectivity govern the macroscopic response. In cement-based materials, interconnected bond cracks at the aggregate–paste interface significantly increase crack volume fraction and density, with permeability rising as connectivity develops (Wong et al., 2009). Although examined under drying conditions, the principle that bulk behavior depends more on crack connectivity than total porosity provides insight into thermally induced cracking.

In thermally cycled systems, increases in microcrack density are consistently accompanied by reductions in compressive strength, elastic modulus, and dynamic mechanical performance (Chen et al., 2020; Tao et al., 2025; He et al., 2025). Detailed microstructural observations show that ITZ microcracks generated during thermal cycling progressively propagate into the cement matrix, intersect, and form microcrack clusters, which correspond with measurable reductions in mechanical properties (An et al., 2020). In pavement concrete subjected to alternating temperature and loading, macroscopic property reductions were directly associated with microcrack accumulation and ITZ deterioration (Yang et al., 2021). These observations indicate that progressive interfacial cracking disrupts stress transfer pathways, reduces the effective load-bearing cross-section, and lowers stiffness and strength.

Damage Accumulation under Diurnal Temperature Variations

Computational fracture modeling further supports this mechanistic interpretation. A thermomechanical phase-field approach applied to concrete subjected to large diurnal temperature ranges demonstrated that increasing temperature amplitude reduces the number of cycles required for crack initiation and accelerates crack propagation, ultimately reducing structural stiffness and load-bearing capacity (Han et al., 2024). Although such models do not provide direct microstructural imaging, their predictions align with experimental observations that cyclic thermal stress alone can induce progressive internal cracking under service conditions.

Integrated Multi-Scale Mechanism

Synthesizing the available evidence, a consistent damage pathway can be identified for concrete exposed to daily temperature variation:

1. Cyclic thermal expansion and contraction generate internal stress.
2. Thermal strain mismatch between constituents produces ITZ stress concentration.
3. Microcracks initiate preferentially along the aggregate–paste interface.
4. Repeated cycling promotes crack propagation and connectivity.
5. Increasing crack density reduces strength and stiffness.

The damage pathway described above is summarized schematically in Figure 1.

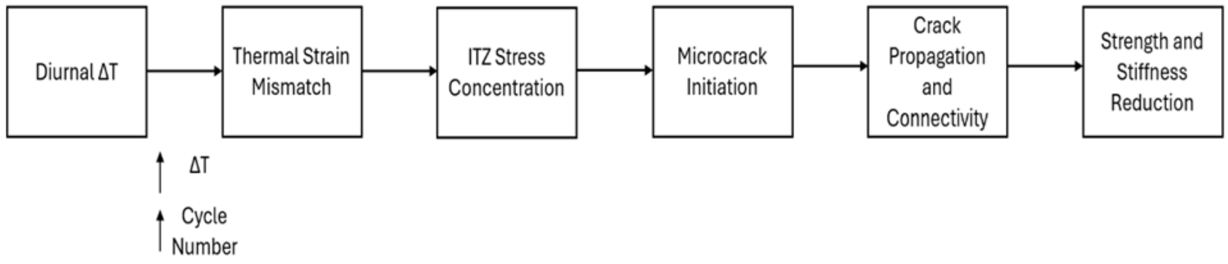

Figure 1: Conceptual schematic of thermomechanical damage evolution in concrete under repeated diurnal temperature variation. Increasing temperature amplitude (ΔT) and cycle number are associated with accelerated ITZ-dominated crack initiation and connectivity, contributing to progressive reductions in strength and stiffness.

This mechanism is supported by microstructural characterization, micromechanical modeling, transport measurements, mechanical testing, and fracture simulations (Zeng et al., 2022; Zunino et al., 2015; Chen et al., 2020; Wong et al., 2009; Tao et al., 2025; He et al., 2025; Yang et al., 2021; Han et al., 2024). The absence of hydration phase decomposition under service temperature ranges further confirms that diurnal thermal cycling induces cumulative mechanical damage rather than thermochemical degradation.

Accordingly, macroscopic property reductions observed under daily temperature variation can be mechanistically attributed to progressive ITZ-dominated microcracking and subsequent crack network evolution. The ITZ emerges as a critical microstructural region influencing long-term mechanical performance under environmental thermal cycling, supporting the premise that even moderate diurnal temperature fluctuations can produce measurable degradation over time.

Mechanical Property Evolution under Daily Thermal Cycling

Concrete exposed to daily temperature variations does not experience a single temperature state but undergoes repeated heating and cooling over its service life. This distinction is important because instantaneous temperature effects differ fundamentally from the cumulative damage induced by thermal cycling.

Compressive Strength under Diurnal Thermal Cycling

Under stabilized temperature exposure, compressive strength generally decreases as the temperature increases. Experimental conditioning between −20 °C and 60 °C showed a clear inverse relationship between temperature and compressive strength (Jiao et al., 2014; Shoukry et al., 2009). Within this range, strength reductions exceeding 30% have been reported as the temperature approaches 60 °C. Merbouh et al. (2012) further identified a behavioral threshold around 40 °C, beyond which deterioration becomes more pronounced. Importantly, the sensitivity is not uniform; aggregate mineralogy significantly influences performance, with silica- and clay-containing mixtures exhibiting greater degradation than calcareous aggregates (Merbouh et al., 2012). These studies describe the instantaneous thermomechanical response under steady-state conditions rather than damage accumulation.

However, when temperature variations are applied cyclically, a different pattern emerges. Across normal-strength, high-performance, and ultra-high-performance concretes subjected to differential cycling, typically between 20 °C and 60–65 °C, the compressive strength frequently follows a non-monotonic trend (Tao et al., 2023; Tao et al., 2025; An et al., 2020; Ma et al., 2024). During early cycles—often within the first 60–120 cycles—moderate strength increases ranging from approximately 10% to 25% have been reported. This temporary enhancement has consistently been attributed to thermally stimulated hydration and microstructural densification. Similar early-stage strengthening has also been observed in seawater sea-sand concrete exposed to moderate daily-type amplitudes (25–60 °C), where strength gains of up to 12.5% were measured (Qiao et al., 2022).

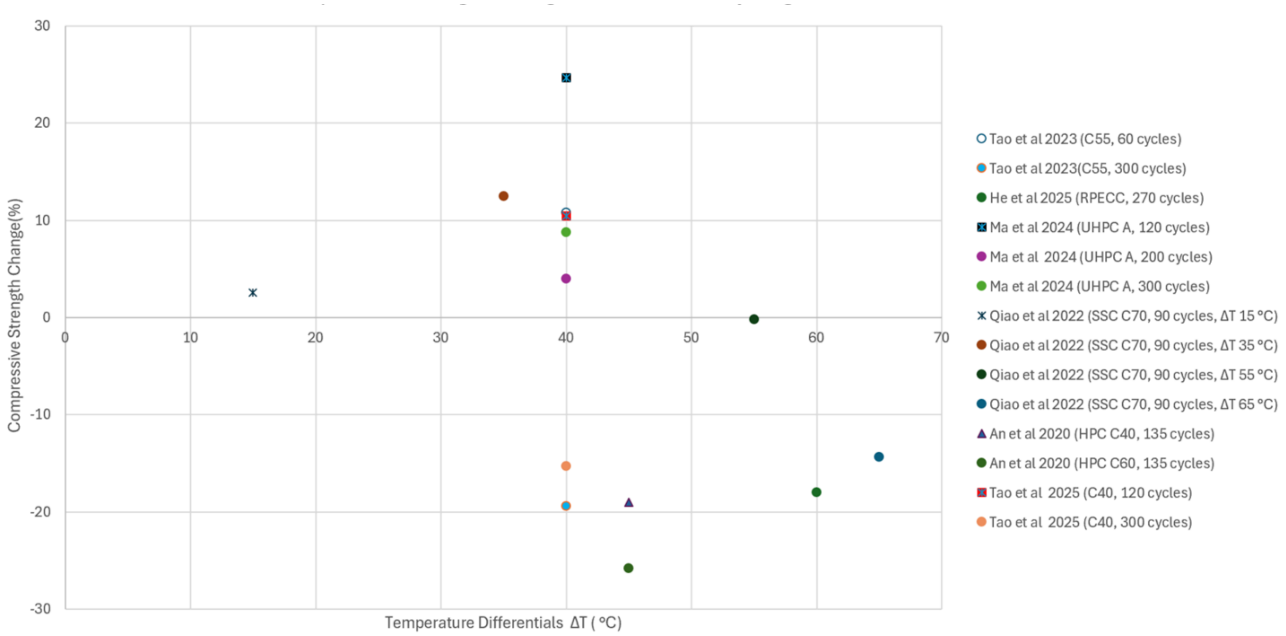

Figure 2: Reported changes in compressive strength (%) of different concrete systems subjected to thermal cycling as a function of temperature differential ΔT (°C). Data compiled from Tao et al. (2023), Tao et al. (2025), Ma et al. (2024), Qiao et al. (2022), An et al. (2020), and He et al. (2025), including normal-strength, high-performance, ultra-high-performance, and fiber-reinforced cementitious composites. Positive values indicate strength increase relative to the reference condition, whereas negative values represent strength reduction after thermal cycling.

With continued cycling, the trend reverses. Beyond a critical cycle threshold—commonly around 100–150 cycles—progressive strength degradation becomes dominant. Reductions of approximately 15–26% after extended cycling have been documented in normal and high-performance concretes (Tao et al., 2023; Tao et al., 2025; An et al., 2020). Even composite systems such as rubber–polyethylene fiber reinforced engineered cementitious composites show comparable deterioration under 20–80 °C cycling, with static compressive strength reductions near 18% after 270 cycles (He et al., 2025). Although the materials differ, a broadly consistent trend can be observed across systems, with repeated thermal expansion–contraction mismatch between aggregates and cement paste inducing cumulative microcracking, particularly at the interfacial transition zone, gradually reducing load-transfer capacity.

Temperature amplitude further controls the balance between strengthening and degradation. Moderate amplitudes (≤60 °C peak) may initially promote hydration, whereas higher peak temperatures within the upper bound of laboratory-applied service ranges accelerate interfacial cracking and physicochemical alteration, leading to net strength loss (Qiao et al., 2022; Merbouh et al., 2012). Concrete grade also influences sensitivity. Higher-strength or denser concretes sometimes exhibit greater degradation under cycling, possibly due to increased restraint and higher internal thermal incompatibility stresses (An et al., 2020).

Taken together, the literature supports two interacting mechanisms governing compressive strength under daily-type thermal cycling:

(1) early-stage hydration enhancement driven by moderate heating; and

(2) long-term cumulative microcracking induced by repeated thermal incompatibility.

The transition between these mechanisms depends on cycle number, temperature amplitude, material composition, and moisture state. This amplitude- and cycle-dependent evolution is consistent with the ITZ-dominated crack initiation and propagation mechanisms discussed in the preceding section**.** However, it should be noted that many laboratory studies apply amplitudes up to 60 °C or higher, which may represent sun-exposed surface conditions rather than typical ambient air fluctuations. Long-term investigations strictly within realistic environmental amplitudes of 10–50 °C remain limited, making precise extrapolation to field performance still uncertain.

Elastic Modulus under Diurnal Thermal Cycling

Concrete stiffness responds to temperature, even in the absence of cyclic exposure. Under stabilized temperature conditions between −20 °C and 60 °C, the elastic modulus decreases almost linearly with increasing temperature (Jiao et al., 2014; Shoukry et al., 2009). Jiao et al. (2014) quantified this relationship as $E_c = -0.125T + 29.13$, while Shoukry et al. (2009) reported approximately 23% modulus reduction over a 70 °C increase. These reductions reflect instantaneous thermoelastic softening rather than accumulated structural damage. At much higher temperatures representative of fire exposure, the stiffness degradation becomes more severe owing to physicochemical transformations within the cement matrix (Krishna et al., 2019). Although such elevated conditions exceed typical environmental ranges, they confirm that the modulus is inherently temperature sensitive.

However, daily temperature variation does not represent a single temperature state but rather a repeated heating–cooling process. Even when laboratory studies do not explicitly use the term "daily temperature variation," cyclic thermal protocols simulate the same fundamental mechanism — repeated expansion and contraction. When a temperature change is applied periodically rather than instantaneously, the stiffness loss becomes cumulative.

In studies involving cyclic amplitudes within moderate environmental ranges (approximately 30–45 °C), modulus reductions on the order of 11–21% have been reported after repeated cycles (Chen et al., 2020; An et al., 2020). Under periodic temperature–humidity cycling with ΔT ≈ 33 °C derived from meteorological data, the dynamic modulus decreased by approximately 11–13% after 15 cycles (Chen et al., 2020). Under controlled thermal cycling with ΔT = 45 °C for up to 135 cycles, static modulus reductions reached 15–21% in high-performance concrete (An et al., 2020). These findings indicate that repeated daily temperature amplitudes within this range can induce measurable stiffness degradation over time.

At lower amplitudes, the response was not strictly degradational. When ΔT remained between 15 °C and 35 °C, slight increases in the static Young's modulus were observed after 90 cycles in seawater sea-sand concrete (Qiao et al., 2022). In that study, moderate thermal cycling (25–60 °C) produced increases of up to 6.8%, whereas higher amplitudes (≥55 °C) resulted in modulus reduction. This suggests that, like compressive strength, there may be a transitional amplitude range in which thermally stimulated hydration temporarily offsets microcrack development.

As the amplitude increased further, the degradation accelerated markedly. Under ΔT = 70 °C, the modulus loss exceeded 40% after 100 cycles in normal- and higher-strength concretes (Peng et al., 2025). Compared with the moderate-amplitude studies cited above, the substantially larger degradation observed at ΔT = 70 °C supports the amplitude-dependent thermal fatigue mechanism. Analytical modeling confirmed that the interfacial tensile stress increases proportionally with ΔT, promoting microcrack propagation and cumulative compliance growth (Peng et al., 2025).

Taken together, the evidence reveals a consistent trend: instantaneous temperature change reduces the modulus reversibly, whereas repeated temperature differentials — analogous to daily heating and cooling — progressively reduce stiffness in an amplitude-dependent manner. Moderate amplitudes below approximately 35 °C may produce negligible changes or slight increases, amplitudes of approximately 33–45 °C induce measurable reductions of approximately 10–20%, and large amplitudes of approximately 70 °C can result in reductions exceeding 40% after extended cycling (Chen et al., 2020; An et al., 2020; Qiao et al., 2022; Peng et al., 2025). Although direct comparison is limited by differences in cycle number and measurement method, the governing parameter across studies is the repeated temperature range rather than the absolute temperature alone.

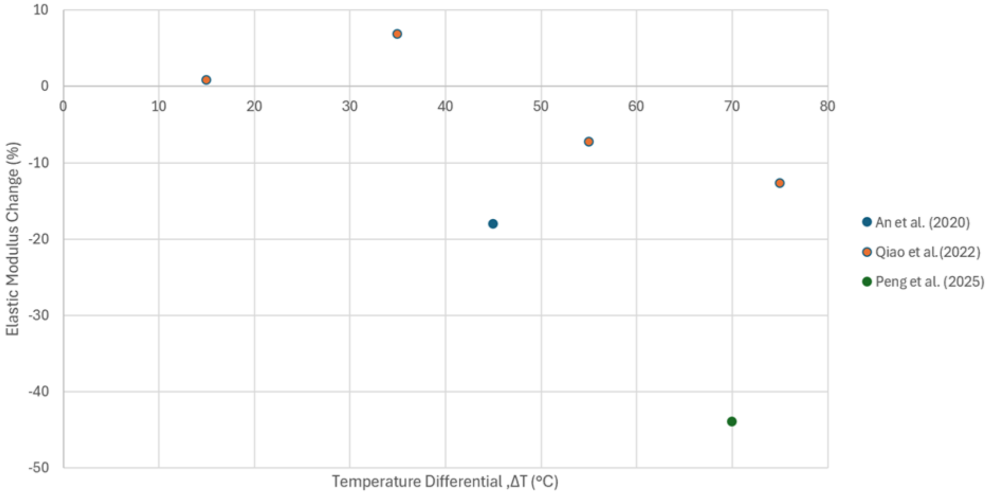

Figure 3: Reported changes in elastic modulus (%) of concrete subjected to cyclic temperature differentials ΔT (°C). Data compiled from An et al. (2020), Qiao et al. (2022), and Peng et al. (2025). Positive values indicate stiffness increase relative to the reference condition, whereas negative values represent modulus reduction after thermal cycling.

Mechanistically, this trend is consistent with composite behavior. The differential thermal expansion between the aggregate and cement paste generates interfacial tensile stresses proportional to ΔT (Peng et al., 2025). With repeated cycling, microcracks are initiated and accumulate within the interfacial transition zone, increasing structural compliance (An et al., 2020; Peng et al., 2025). Because the modulus reflects stiffness rather than ultimate capacity, it often captures early internal damage before significant compressive strength reduction becomes evident. This behavior is consistent with the compressive strength trends discussed in the previous section, where moderate thermal amplitudes may initially promote hydration while continued cycling progressively induces microcracking and mechanical degradation.

It must be emphasized that many laboratory protocols apply amplitudes approaching 60–70 °C, which may represent sun-exposed surfaces rather than ambient air. Controlled long-term studies specifically focusing on realistic diurnal ranges of approximately 10–50 °C remain limited. Although existing cyclic studies provide mechanistic insights, systematic evaluations under standardized daily environmental amplitudes are comparatively scarce.

Overall, while instantaneous temperature influences stiffness reversibly, repeated daily temperature variations govern cumulative modulus degradation. The severity of this degradation depends primarily on the temperature amplitude and cycle repetition, with additional influence from concrete grade, environmental coupling, and testing methodology.

Tensile Strength under Diurnal Thermal Cycling

Comparable to compressive strength and elastic modulus, tensile strength is also sensitive to temperature variation. However, the available literature addressing tensile behavior under daily temperature fluctuations remains comparatively limited.

Under stabilized service-level temperature conditions (−20 °C to 60 °C), splitting tensile strength decreases almost linearly with increasing temperature (Jiao et al., 2014). Within this range, tensile strength declined from 5.889 MPa at −20 °C to 2.529 MPa at 60 °C, corresponding to an overall reduction of approximately 57% and exhibiting strong linear correlation ($R^2 = 0.9545$) (Jiao et al., 2014). Merbouh et al. (2012) reported comparable temperature sensitivity for ordinary concretes between −15 °C and 60 °C, with degradation becoming pronounced beyond about 40 °C. The severity of reduction was mixture-dependent: concretes made with clean calcareous sands showed tensile strength losses of up to 60–70% at 60 °C, whereas silica–calcareous–clay sands demonstrated relatively improved retention under the same conditions (Merbouh et al., 2012). Collectively, these findings demonstrate that tensile resistance is intrinsically temperature dependent under stabilized exposure and influenced by aggregate mineralogy (Jiao et al., 2014; Merbouh et al., 2012).

Broader datasets reinforce this trend. A database-based assessment identified temperature as the dominant parameter governing tensile strength variation, showing systematic reduction in normalized tensile strength with increasing temperature (van der Merwe, 2022). At sub-zero conditions, a comprehensive review reported that splitting tensile strength generally increases as temperature decreases, reaching a peak between −30 °C and −70 °C, with moisture condition affecting the magnitude of change (Huo et al., 2022). Although such temperature levels exceed typical diurnal environmental ranges, they further confirm the strong temperature dependence of tensile behavior.

In contrast, evidence directly connecting diurnal temperature variation to tensile strength evolution remains limited. Wang et al. (2022) examined mass concrete exposed to large diurnal temperature ranges (maximum exceeding 23.4 °C) using field monitoring and thermo-mechanical modeling. Increasing the diurnal amplitude significantly elevated thermal stresses, and under an amplified scenario (1.25× the baseline range), the induced tensile stress exceeded the instantaneous tensile strength, indicating cracking risk, particularly at horizontal surfaces (Wang et al., 2022). These findings demonstrate that realistic day–night temperature fluctuations can generate tensile demands approaching or exceeding capacity, even though changes in tensile strength under repeated daily cycling were not directly quantified.

Overall, the literature consistently indicates that tensile strength is highly temperature sensitive under stabilized conditions (Jiao et al., 2014; Merbouh et al., 2012), a trend supported by broader statistical evaluation (van der Merwe, 2022) and low-temperature evidence (Huo et al., 2022). However, direct experimental or numerical investigations quantifying how repeated diurnal temperature variations—or service-level thermal cycling designed to represent daily amplitudes—affect tensile strength over time remain scarce. Consequently, it remains unclear whether daily heating–cooling cycles lead to cumulative tensile degradation or primarily increase cracking risk through elevated thermal stress demand, and this relationship has not yet been clearly established (Wang et al., 2022).

Conclusion

Daily temperature variation should not be viewed as an isolated thermal event but rather as a recurring environmental action that continuously affects concrete throughout its service life. The reviewed literature clearly distinguishes between instantaneous temperature effects and cumulative degradation caused by cyclic heating and cooling. Under stabilized temperature conditions, changes in compressive strength, tensile strength, and elastic modulus are largely reversible and temperature dependent. However, when temperature differentials are repeated, progressive microstructural damage develops and gradually influences macroscopic mechanical behavior.

An amplitude-dependent response consistently emerges across the examined studies. Moderate thermal amplitudes may initially enhance compressive strength through continued hydration and temporary densification. With increasing cycle number, this benefit diminishes as thermomechanical incompatibility between aggregates and cement paste promotes interfacial microcracking, crack interconnection, and stiffness loss. This mechanism appears to govern both compressive strength and modulus evolution under cyclic exposure. In contrast, tensile strength—although clearly sensitive to temperature under stabilized conditions, has been insufficiently investigated under repeated diurnal-type thermal cycling. Most available evidence addresses tensile behavior indirectly through thermal stress development and cracking risk rather than direct evaluation of tensile property evolution.

Another important observation is that many laboratory studies employ temperature amplitudes approaching 60–70 °C, which may represent extreme surface heating rather than typical ambient day–night variation. Systematic investigations designed specifically to replicate realistic diurnal ranges, particularly between approximately 10 °C and 50 °C, remain limited. As a result, extrapolation of laboratory thermal fatigue results to field conditions remains uncertain.

Future research should therefore focus on controlled experimental programs using representative concrete materials subjected to realistic daily temperature variations within the 10–50 °C range. Thermal cycles should ideally follow true 24-hour diurnal patterns to better simulate field conditions rather than shortened laboratory cycles. In addition, compressive strength, tensile strength, and elastic modulus should be evaluated simultaneously over extended cycle numbers to clarify whether daily heating and cooling lead to cumulative mechanical degradation or primarily increase cracking susceptibility through elevated thermal stress demand.

Developing standardized testing protocols that reflect actual environmental amplitudes and cycle durations would improve the reliability of long-term performance assessments for concrete structures exposed to daily thermal fluctuations. Until such systematic data are available, the influence of realistic diurnal temperature variation on intrinsic mechanical properties remains only partially understood and warrants further investigation.

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