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Research Article

A field-exposure study on the effects of seasonal temperature variations and curing conditions on concrete strength and density

Rukiye Koçkar Tuğla ^{a,*}

^a Department of Construction, Abana Sabahat-Mesut Yılmaz Vocational School, Kastamonu University, 37970 Abana, Kastamonu, Türkiye

ABSTRACT

The performance of concrete is largely influenced by temperature and curing conditions during the early stages of hydration. While these effects have been extensively investigated under controlled laboratory conditions, field-based experimental evidence remains limited. Therefore, this study investigated the combined effects of seasonal temperature variations and curing conditions on the compressive strength of C30/37 concrete under field conditions. Concrete samples produced at a commercial ready-mix concrete plant were subjected to three curing conditions between March and July: water curing (WC), air curing (AC), and intermittent water curing (IWC). Monthly temperature data were recorded, and the effects of curing conditions and seasonal temperature variations on density and compressive strength were evaluated. The results showed that water curing produced the highest compressive strength (56.36 MPa) and density (2.40 g/cm³), whereas air curing yielded the lowest performance because of greater moisture loss. A negative correlation was observed between temperature and density ($R^2 = 0.87$ for AC and 0.81 for IWC), whereas only a weak relationship was found between density and compressive strength, indicating that density alone is not sufficient to explain concrete strength. In addition, variations in compressive strength under similar curing conditions suggest that early-age temperature exposure has a lasting influence on concrete performance. Overall, the results indicate that seasonal temperature variations influence concrete performance by altering hydration and moisture conditions. The findings provide field-based data that complement previous laboratory studies and contribute to a better understanding of concrete behaviour under practical construction-site conditions.

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1. Introduction

Concrete is a composite construction material generally produced using water, aggregate, and cement, and, where necessary, admixtures. It is initially workable and hardens after setting. Concrete is widely used worldwide due to its durability, workability, and cost-effectiveness (Barbhuiya et al. 2024; Emarah et al. 2025; Haigh and Ameri Sianaki 2025). The mechanical performance of concrete, particularly its compressive strength, is markedly influenced by curing conditions, environmental fac-

tors, and temperature variations (Barbhuiya et al. 2024; Haigh and Ameri Sianaki 2025; Chu et al. 2024; Lin et al. 2023). In addition, previous studies have shown that mixture composition, curing history, and production conditions also contribute to concrete performance (Wang et al. 2023a; Mohe et al. 2022; Mostofinejad et al. 2016; Akeed et al. 2022).

Curing conditions play a decisive role in the strength and durability of concrete (Haigh and Ameri Sianaki 2025; Xu et al. 2023). Proper curing reduces shrinkage and cracking by providing the moisture necessary for hy-

* Corresponding author. E-mail address: rkockar@kastamonu.edu.tr (R. Koçkar Tuğla)

dration (Haigh and Ameri Sianaki 2025; Chu et al. 2024). Traditional curing techniques primarily encompass practices such as water and air curing (Haigh and Ameri Sianaki 2025), which have long been utilized as conventional approaches to maintain the moisture levels necessary for hydration and strength development (Başyigit et al. 2011). In addition to these standard methods, advanced technologies such as steam and autoclave curing are used to significantly accelerate hydration (Xu et al. 2023). Furthermore, recent innovations have introduced high-efficiency thermal regimes, including microwave and electrical curing, to the precast industry (Dong et al. 2024). These specialised modern regimes, which often include dry-hot, steam and combined curing methods, are particularly effective for optimising the microstructure of high-performance construction materials (Wang et al. 2023a; Wang et al. 2023b).

Water curing is one of the most effective methods as it allows hydration to continue by maintaining moisture within the concrete (Emarah et al. 2025; Haigh and Ameri Sianaki 2025; Neville 2011). In contrast, with air curing, moisture loss increases, particularly under high-temperature conditions, leading to a loss of strength (Haigh and Ameri Sianaki 2025; Başyigit et al. 2011). Periodic curing (controlled moisture and periodic watering), however, lies between these two curing conditions, and partial moisture loss may occur (Emarah et al. 2025).

Cement hydration is highly sensitive to ambient and curing temperatures; indeed, the rate of hydration reactions is primarily controlled by temperature (Chu et al. 2024; Wang et al. 2023a; Kiernożycki and Błyszko 2021). At low temperatures, hydration reactions slow down considerably; this leads in particular to a delay in strength development during the early stages and the formation of a weaker or looser microstructure (Chu et al. 2024; Lin et al. 2023; Xu et al. 2023; Wang et al. 2023b). For example, when the casting temperature falls below the freezing point, the expansion of water within the concrete as it forms ice crystals (ice expansion pressure) can damage the internal structure of the cement paste whilst it is still in the setting stage, thereby reducing its ultimate strength (Wang et al. 2023a; Shi et al. 2019). Conversely, whilst high temperatures accelerate hydration thereby providing high early-age strength, increased evaporation and uncontrolled moisture loss result in a more porous and coarse void distribution within the concrete's internal structure; this situation adversely affects the mechanical properties and durability in the long term (Haigh and Ameri Sianaki 2025; Chu et al. 2024; Wang et al. 2023b; Dong et al. 2024). Consequently, both the slowing of hydration caused by low temperatures and the structural irregularities and porosity triggered by high temperatures can adversely affect concrete performance (Haigh and Ameri Sianaki 2025; Lin et al. 2023; Xu et al. 2023; Başyigit et al. 2011).

Density is an important indicator of the internal structure and quality of concrete (Emarah et al. 2025). High density generally implies a compact structure containing fewer voids, and this is associated with higher mechanical performance (Barbhuiya et al. 2024; Emarah et al. 2025; Haigh and Ameri Sianaki 2025). However, the relationship between density and compressive strength is

not always direct; it is influenced by numerous parameters, such as curing conditions, temperature history, and degree of hydration (Emarah et al. 2025; Lin et al. 2023; Xu et al. 2023).

Much of the research on the effects of temperature and curing on concrete is limited to laboratory conditions, where variables can be precisely controlled (Chu et al. 2024; Wang et al. 2023a). However, in field conditions, concrete is exposed to various seasonal and regional factors, particularly from the moment of pouring through the curing period. These uncontrolled environmental factors can directly affect the internal homogeneity, hydration process and safety of the concrete (Wang et al. 2023a; Başyigit et al. 2011). Particularly in high-altitude regions or areas subject to substantial temperature fluctuations, concrete is exposed to accelerated moisture loss and temperature fluctuations during its early stages of curing. This can lead to a phenomenon known as 'ageing' in the microstructure or to permanent damage to the pore structure, thereby markedly reducing its mechanical performance (Chu et al. 2024; Huang et al. 2025). Although several studies have investigated the effects of temperature and curing under laboratory conditions, relatively few have evaluated concrete performance under actual field conditions (Chu et al. 2024; Wang et al. 2023a). Existing field studies have mainly focused on specific harsh environmental conditions, such as high-altitude exposure (Chu et al. 2024), whereas the combined influence of seasonal temperature variations and practical curing conditions under typical construction-site environments remains insufficiently investigated.

On construction sites, the neglect of concrete curing during building inspections, together with seasonal temperature variations, is a critical factor contributing to deviations from the concrete's design strength (Emarah et al. 2025; Kiernożycki and Błyszko 2021). According to the standard, the strength of properly produced and formed concrete will decrease by approximately 30–40% if it is not cured in accordance with the environmental conditions after reaching its initial strength (Başyigit et al. 2011). In particular, it is difficult to standardise the manual sprinkling method used under site conditions. However, this situation prevents the concrete's microstructure from improving. On construction sites, concrete samples inspected by building inspectors are stored in unsupervised locations, under unsuitable weather, and without ideal curing conditions (Başyigit et al. 2011; Yılmaz et al. 2019). As factors such as ambient temperature and humidity vary when construction inspectors take samples, considerable deviations from the concrete's actual performance are observed (Chu et al. 2024; Yılmaz et al. 2019).

A clear gap still exists in the literature between results obtained in laboratory conditions and the actual performance observed in field applications. In this study, unlike traditional laboratory studies, concrete samples were collected from a ready-mix concrete plant over 5 months and subjected to 3 different curing conditions. The concrete samples were evaluated at natural ambient temperatures and in the direct site environment. The primary objective of the study is to quantitatively demonstrate the combined effect of seasonal temperature variations and curing conditions on the compres-

sive strength and density of concrete under uncontrolled environmental conditions. Unlike previous field-exposure studies that focused on concrete performance under specific environmental scenarios, such as high-altitude exposure (Chu et al. 2024), the present study evaluates concrete produced at a commercial ready-mix concrete plant under naturally varying seasonal conditions. By monitoring concrete over five consecutive months under three practical curing conditions, the study provides field-exposure experimental evidence of the combined influence of seasonal temperature, curing condition, density, and compressive strength under typical construction-site conditions. The findings provide prac-

tical guidance for evaluating concrete quality under typical construction-site conditions and may help improve curing practices in construction.

2. Materials and Method

2.1. Materials

The type of cement used in this study was CEM II/A-M (V-L) 42,5 R. The chemical and physical characteristics of the cement, which comply with TS EN 197-1 (2012), are given in Tables 1 and 2, respectively.

Table 1. Chemical characteristics of cement.

	MgO (%)	SO ₃ (%)	Cl (%)	Na ₂ O (%)	K ₂ O (%)	Loss on ignition (%)	Undissolved residue (%)
Cement	1.98	3.07	0.01	0.24	0.76	9.18	1.67

Table 2. Physical characteristics of cement.

	Specific surface area* (cm ² /g)	Specific gravity (g/cm ³)	Fineness (32 micron) (%)	Fineness (40 micron) (%)	Initial set (minute)	Final set (minute)	Volumetric expansion (mm)
Cement	4004	3.04	7.8	4.2	211	292	1

*Blaine method

Crushed aggregate in three different sizes (0–5 mm, 5–11 mm and 11–22 mm) was used in the production of the concrete. The specific gravities of fine (0–5 mm) and coarse aggregates (5–11 mm and 11–22 mm) are 2.62 g/cm³ and 2.64 g/cm³; the water absorption values of the aggregates are 1.33%, 1.08%, and 0.86%, respectively. During concrete production, aggregate moisture was routinely monitored at the ready-mix concrete plant, and the mixing water was adjusted accordingly. The aggregate grading is shown in Fig. 1.

A commercial chemical admixture was used at a dosage of 1% by weight of cement. The technical properties of the chemical admixture, data taken from the

manufacturer's product data sheet, are presented in Table 3.

The target water/cement (w/c) ratio for all concrete mixtures was 0.53. However, during concrete production in July, an additional 5 L of water per m³ was added to maintain workability under elevated ambient temperatures. Consequently, the effective water/cement ratio of the July mixture increased from 0.53 to approximately 0.545. This modification should be considered when interpreting the July test results, as the increased water content may have influenced the mechanical properties in addition to the environmental exposure condition. Detailed mixture proportions are presented in Table 4.

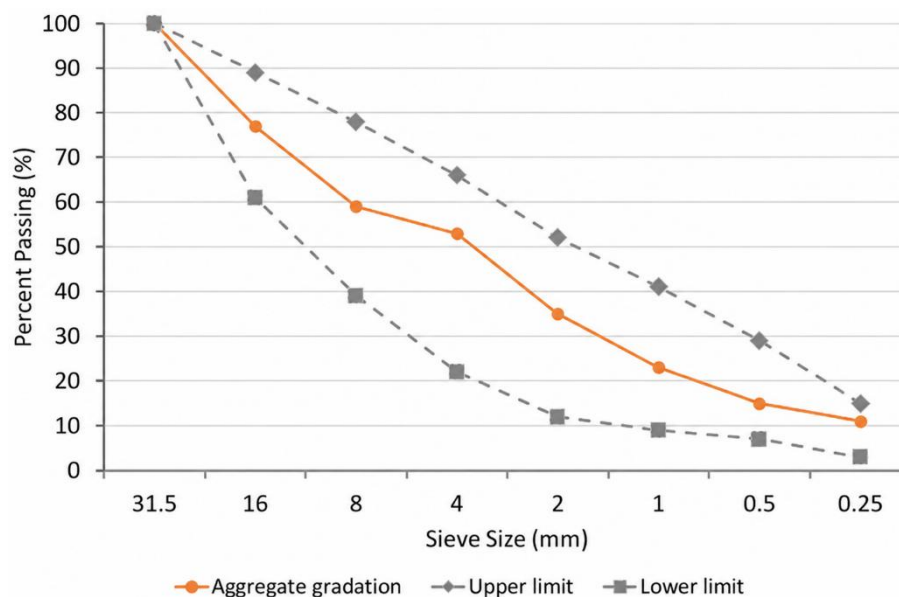


Fig. 1. Particle-size distribution of the combined aggregate, together with the specification limits.

Table 3. The technical properties of the chemical admixture (Sika Türkiye 2024).

Chemical admixture properties	Value
Admixture type	High-range water-reducing superplasticiser
Chemical base	Polycarboxylate-based
Standard classification	TS EN 934-2
Recommended dosage	0.8-1.5% by weight of cement
Density (20°C)	1.0602 g/cm ³
pH	4.82
Solid content	22.46%
Chloride content	0.0570%
Alkali content (Na ₂ O equivalent)	0.31%
Corrosion behaviour	No corrosion effect

Table 4. Mixing proportions and material amounts (kg/m³).

Mixture	Months	Cement	Sand	Crushed aggregate	Admixture	Water	W/C
The concrete samples	March-June	330	1006	830	3.3	175	0.530
	July	330	1006	830	3.3	180	0.545

2.2. Specimen preparation and curing conditions

The concrete mixes used in this study were prepared at a ready-mix concrete plant in Kastamonu. The batching, mixing, and production processes under real-world conditions were carefully executed to ensure precise composition and thorough homogenization of the concrete specimens at a ready-mix concrete plant (Fig. 2). The essential components of C30/37 concrete, including coarse crushed aggregate, sand, cement, a chemical admixture, and water, were systematically and automatically introduced into the mixer in accordance with the TS EN 206 +A2 standard. The mixing process followed a structured protocol to achieve a uniform, well-integrated mixture of all concretes each month. The concrete produced at the concrete plant was placed in 150 × 150 × 150 mm cube moulds in accordance with the TSE EN 12390-2 standard. The concrete in the formwork was compacted using a vibrating table to ensure a void-free and homogeneous structure. The concretes were placed in cube moulds under ambient conditions and demoulded after 24 hours; each specimen was then placed under the specified curing conditions. The concrete samples used in the study were produced over five periods in 2025—March, April, May, June, and July—to assess the effects of seasonal temperature variations. For each month, nine cube specimens were produced and divided into three different curing conditions (Fig. 3). Each curing group consisted of three specimens. The concrete specimens in each curing group were kept in the same place throughout 28 days. Compressive strength values are reported as the mean of three measurements.

To evaluate the variability and reliability of the experimental results, the standard deviation (SD) and coefficient of variation (CV) were calculated for each curing condition.

The different curing conditions used in this study:

- Water Curing (WC): The concrete samples were cured

by being fully immersed in water tanks under controlled conditions at approximately 20 ± 2°C for 28 days, in accordance with TS EN 12390-2. This method was considered the “reference curing condition”.

- Air Curing (AC): The concrete samples were stored in direct exposure to outdoor ambient conditions, without a moisture supply, and in fixed positions. They have been exposed to the normal weather conditions of the relevant month outdoors, including temperature, solar radiation, and wind, etc. This condition represented the actual environment on construction sites, which are typical conditions for construction.
- Intermittent Water Curing (IWC): The concrete samples were stored under natural ambient conditions and in fixed positions. Until every part of their surface was wet, they were sprayed with water (approx. 3 L) once daily in the evening, when there was no sun exposure. This method was chosen as a practical curing approach that can be easily implemented on a construction site.

The three curing methods were selected because they represent the most common curing conditions encountered during concrete production and quality control in construction practice in Türkiye. Water curing was used as the reference curing method, air curing represented the absence of curing under field conditions, and intermittent water curing simulated the manual water spraying practice commonly applied on construction sites.

All curing conditions were maintained for 28 days. Ambient air temperature (AT) data were recorded during the study period. However, relative humidity (RH) was not measured directly at the experimental site. RH values presented in this study were obtained from the Turkish State Meteorological Service database and used solely to describe the general environmental conditions during the testing period, March to July in 2025. Therefore, RH was not included in the quantitative regression analyses.



Fig. 2. Production of concrete samples in a ready-mix concrete plant.

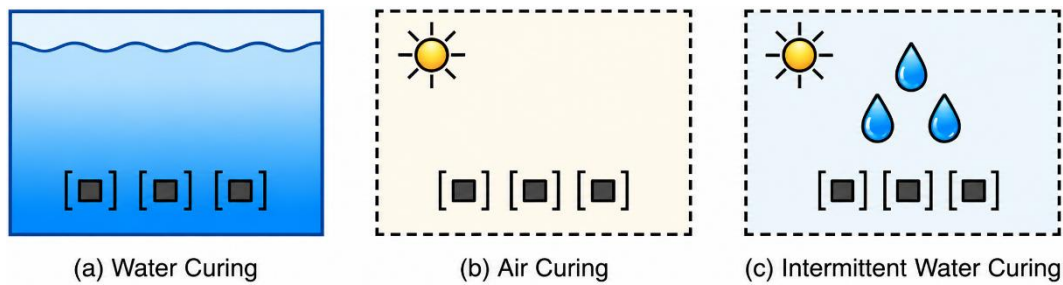


Fig. 3. The scheme of the different curing conditions.

2.3. Testing of fresh and hardened concrete

For each concrete sample, a slump test was carried out in accordance with TS EN 12350-2, and workability was checked to ensure consistency in the fresh concrete properties. The measured slump values were 20, 22, 23, 23 and 23 cm for March, April, May, June and July, respectively.

The density values were calculated at the age of 28 days using the specimen mass measured immediately before the compressive strength test. The apparent density was determined by dividing the specimen mass measured immediately before the compressive strength test by the nominal specimen volume.

At the end of the 28-day curing period, compressive strength tests were performed on all specimens in accordance with TS EN 12390-3. The tests were conducted on a calibrated hydraulic pressure press with a maximum capacity of 2000 kN (Fig. 4). The load was increased continuously at a constant rate until the specimen failed, and the maximum load was recorded. The compressive strength was calculated as the breaking load divided by the specimen's cross-sectional area. The average compressive strength and standard deviation values were determined for each curing group and casting period.

3. Results and Discussion

In this study, the compressive strength (CS) of concrete samples with a design CS of C30/37 was investigated under different curing conditions. The experimental data obtained have been analysed; compressive strength, density and ambient temperature conditions have been evaluated together. The parameters affecting concrete strength and their relationships are presented in detail in this section.

Concrete samples (AC and IWC) were exposed to outdoor curing conditions at the same location during March, April, May, June, and July. The recorded temperature data for each month are presented in Table 5. According to the first-day measurements, April was the coldest month, while July had the highest temperatures. Furthermore, the average temperature values calculated for 7-day and 28-day periods indicate a consistent increase from March to July, reflecting seasonal variations. The relative humidity in Kastamonu gradually decreases from approximately 70–75% in March to 55–60% in July, suggesting a higher potential for evaporation during the summer period. Since these RH values were obtained from meteorological records rather than direct field measurements, they are presented only to describe the general environmental conditions.



Fig. 4. The photograph of the compressive strength testing press.

Table 5. Variation of minimum ($T_{\min}$), maximum ($T_{\max}$), average temperatures (T_{avg}) ($^{\circ}\text{C}$) and relative humidity (RH) during the curing period.

Months	Curing period	First day for concrete			Average 7 day			Average 28-day			Relative humidity*
		$T_{\min}$	$T_{\max}$	T_{avg}	$T_{\min}$	$T_{\max}$	T_{avg}	$T_{\min}$	$T_{\max}$	T_{avg}	
March	28-day	2	13	7.5	-2.4	9.3	3.5	1.5	13	7.3	70–75
April	28-day	-1	8	3.5	3.7	10.7	7.2	2.9	17.8	10.4	65–70
May	28-day	8	25	16.5	6.7	20.7	13.7	7.5	23.1	15.3	65–70
June	28-day	7	23	15	10.1	27.1	18.6	13.3	30.7	22	60–65
July	28-day	21	37	29	19.0	35.1	27.1	18.9	34.7	26.8	55–60

*Data was taken from the Turkish State Meteorological Service.

The data on the weight, density and compressive strength of the concrete samples are presented in Table 6. The results show that curing conditions affect concrete performance. The variation of density values under different curing conditions is presented in Fig. 5. The results show that specimens subjected to water curing (WC) consistently exhibit higher density than those subjected to air curing (AC) or intermittent water curing (IWC). A general decrease in density with increasing temperature is observed, particularly under AC and IWC conditions. This behaviour is primarily attributed to increased evaporation and moisture loss under higher temperatures. Moisture loss limits the availability of water required for continued cement hydration and contributes to the formation of a less compact internal structure, particularly under insufficient curing conditions. However, a slight increase in density was observed for the AC specimens in July compared with June, despite the higher ambient temperature. This deviation may also be associated with the additional 5 L/m^3 of mixing water introduced in the July mixture, which slightly increased the effective water/cement ratio. Therefore, the July density values should be interpreted with caution, as they reflect the combined influence of environmental exposure and the slightly increased water/cement ratio. In contrast, water-cured specimens exhibited higher apparent density values. This may be attributed to both improved in-

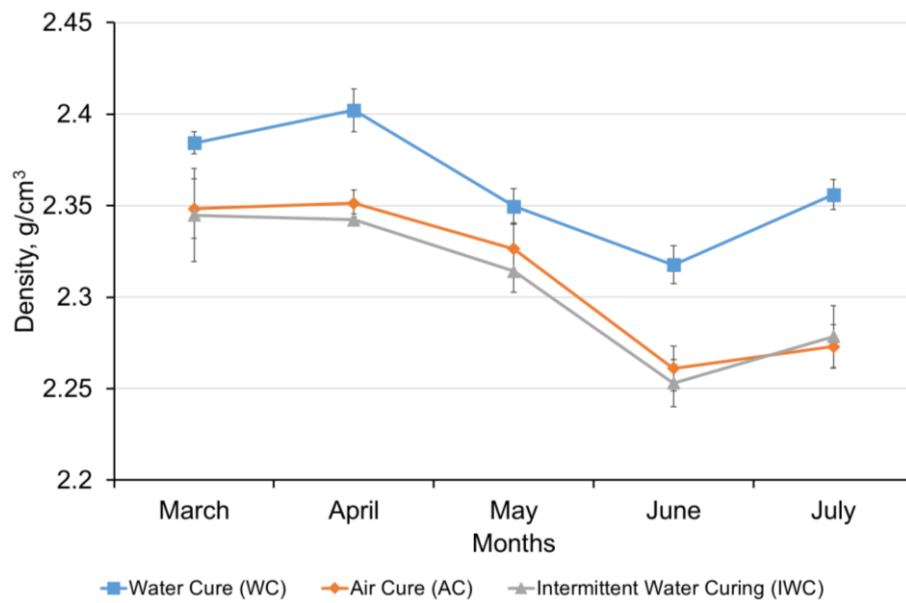
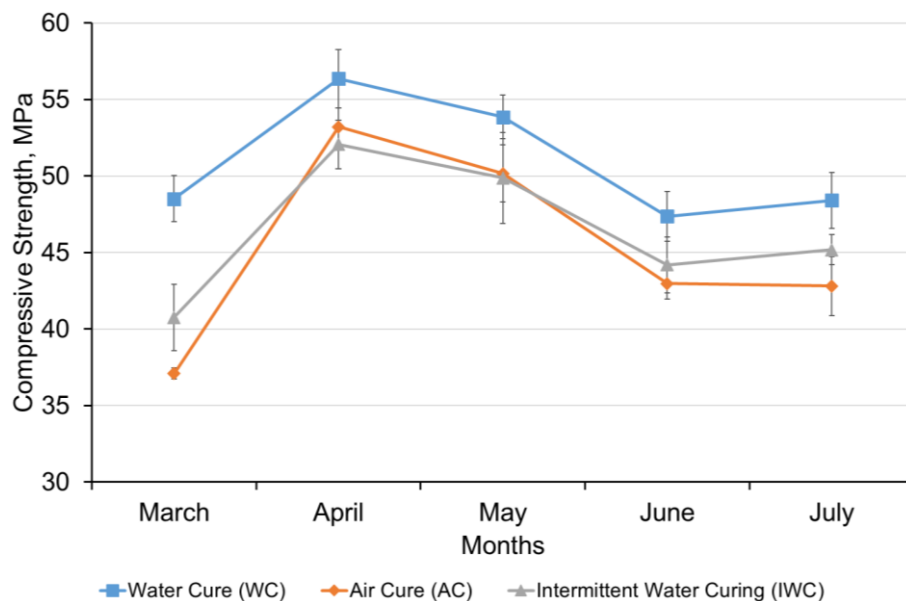
ternal compactness resulting from continuous hydration and the higher moisture content of the specimens at the time of testing. Consequently, density changes observed under field conditions should be interpreted as the combined outcome of hydration progress, moisture condition at testing, and environmental exposure rather than solely as an indicator of internal compactness. These findings are in strong agreement with previous studies (Emarah et al. 2025; Haigh and Ameri Sianaki 2025; Chu et al. 2024; Başıyigit et al. 2011).

The compressive strength results under different curing conditions are shown in Fig. 6. The compressive strength of water-cured concrete was 56.36 MPa, and that of air-cured concrete was 53.22 MPa in April (Table 6). It is observed that the compressive strength data of the intermittent water curing (IWC) generally fall between the two types of curing (WC and AC). It is evident that water curing provides the highest strength values across all conditions, while air curing results in the lowest. A general decrease in strength is observed at higher temperatures, particularly under insufficient curing conditions. However, slight deviations are observed in March, where lower temperatures may have slowed hydration and delayed strength development (Fig. 6). These findings highlight the critical role of curing conditions in controlling strength development under varying environmental conditions.

Table 6. Data on the weight, density and compressive strength of concrete samples under different curing conditions by months.

Months	Water curing (WC)			Air curing (AC)			Intermittent water curing (IWC)		
	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)
March	8047	2.38	48.51±1.50	7926	2.35	37.10±0.36	7914	2.34	40.77±2.17
April	8107	2.40	56.36±1.90	7936	2.35	53.22±2.76	7905	2.34	52.06±1.57
May	7930	2.35	53.85±1.43	7851	2.33	50.16±1.87	7810	2.31	49.88±2.98
June	7822	2.32	47.36±1.62	7631	2.26	42.97±1.02	7604	2.25	44.19±1.84
July	7952	2.36	48.42±1.82	7671	2.27	42.82±1.93	7690	2.28	45.19±0.99

*Values are presented as mean ± standard deviation.

**Fig. 5.** Variation of density values under different curing conditions (WC, AC, and IWC) across months.**Fig. 6.** Compressive strength variation of concrete samples under different curing conditions.

Since the WC specimens were cured under a constant water temperature ($20 \pm 2^\circ\text{C}$) throughout the study, only the AC and IWC specimens were considered when evaluating the relationship between ambient temperature and compressive strength (Fig. 7). The highest compressive strength values were observed under the average curing temperatures recorded in April (10.4°C) and May (15.3°C), whereas lower strengths were obtained at both lower and higher temperatures. The present results suggest that the moderate ambient temperatures recorded during April and May provided favorable conditions for compressive strength development, which is consistent with previous studies reporting improved hydration under moderate curing temperatures (Huang et al. 2025; Yilmaz et al. 2019). As expected, WC specimens consistently exhibited higher compressive strength than AC and

IWC specimens because continuous moisture availability allowed cement hydration to proceed uninterrupted and likely promoted a denser microstructure (Emarah et al. 2025). Lower compressive strength values were observed in March because the low ambient temperatures slowed the hydration process, whereas a partial increase was observed in July despite the elevated ambient temperatures (Fig. 7). The partial strength increase observed in July, despite the high temperatures, may be attributed to accelerated early-age hydration (Xu et al. 2023; Wang et al. 2023b). However, considering the increased evaporation and porosity associated with high temperatures, this trend may also have been influenced by early-age curing conditions and mixture parameters (Haigh and Ameri Sianaki 2025; Chu et al. 2024; Wang et al. 2023b).

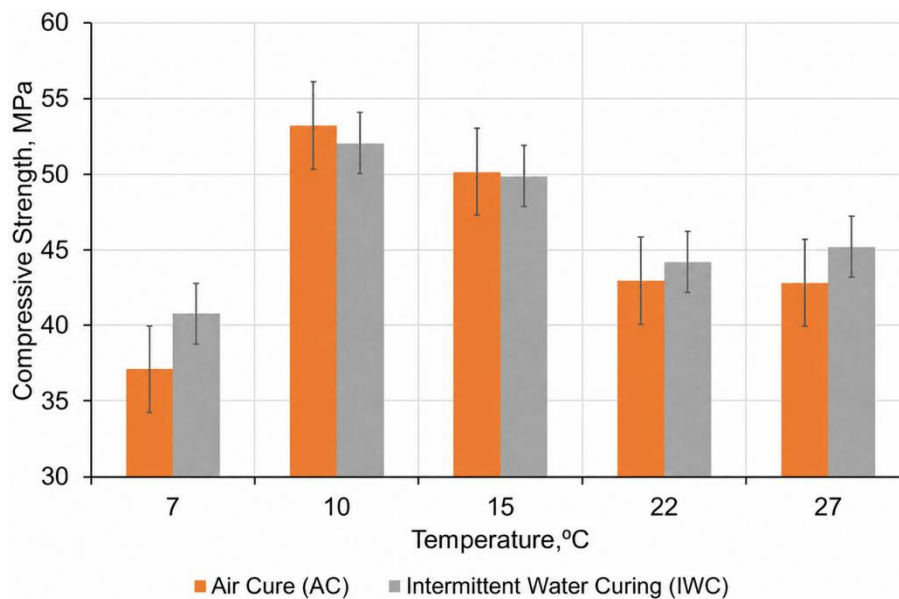


Fig. 7. Relationship between compressive strength and the measured average 28-day ambient temperature for air-cured (AC) and intermittent water-cured (IWC) specimens.

Although an additional 5 L of water per m^3 was introduced during concrete production in July to compensate for the increased water demand associated with elevated ambient temperatures, this amount represented only a minor fraction of the total mixing water. Moreover, the slump value measured in July (23 cm) was identical to those recorded in May and June, suggesting that the additional water mainly contributed to maintaining workability rather than substantially modifying the fresh concrete characteristics. The July results should be interpreted with caution because the additional 5 L of water increased the effective water/cement ratio from 0.53 to approximately 0.545. Consequently, the observed behaviour cannot be attributed solely to elevated ambient temperature and curing conditions. The modified mixture proportion may also have contributed to the measured density and compressive strength values. Therefore, the July results reflect the combined influence of environmental exposure and a slightly increased water/cement ratio.

The coefficients of variation obtained for the compressive strength results ranged from 0.98% to 5.98%,

indicating good consistency among replicate specimens. These relatively low values suggest that the observed differences in compressive strength are predominantly related to curing conditions and environmental exposure rather than experimental variability.

When the relationships among temperature, density, and compressive strength are considered together, it is evident that concrete behaviour is governed by a complex interaction mechanism.

To better understand the influence of temperature, a regression analysis was conducted between temperature and density. The results are presented in Fig. 8. Regression analysis indicated a negative relationship between temperature and density for AC ($R^2 = 0.8696$) and IWC ($R^2 = 0.8075$) (Fig. 8). These results suggest that temperature primarily affects concrete through increased evaporation and moisture loss.

In contrast, the relationship between density and compressive strength was found to be relatively weak. The relationship between density and compressive strength is shown in Fig. 9. Very low correlation coefficients were obtained for air curing ($R^2 = 0.0749$) and in-

termittent water curing ($R^2 = 0.0516$), while a relatively higher, yet still limited, relationship was observed for water curing ($R^2 = 0.3377$). These results suggest that the compressive strength of concrete cannot be explained solely by density and that factors such as curing conditions, ambient temperature, and water content also play important roles. In particular, the fact that different

strength results are obtained for specimens with similar density values indicates that concrete behaviour has a multi-parameter structure. These findings suggest that approaches based on a single parameter may be insufficient when evaluating concrete performance under field conditions, and that multiple parameters must be considered together.

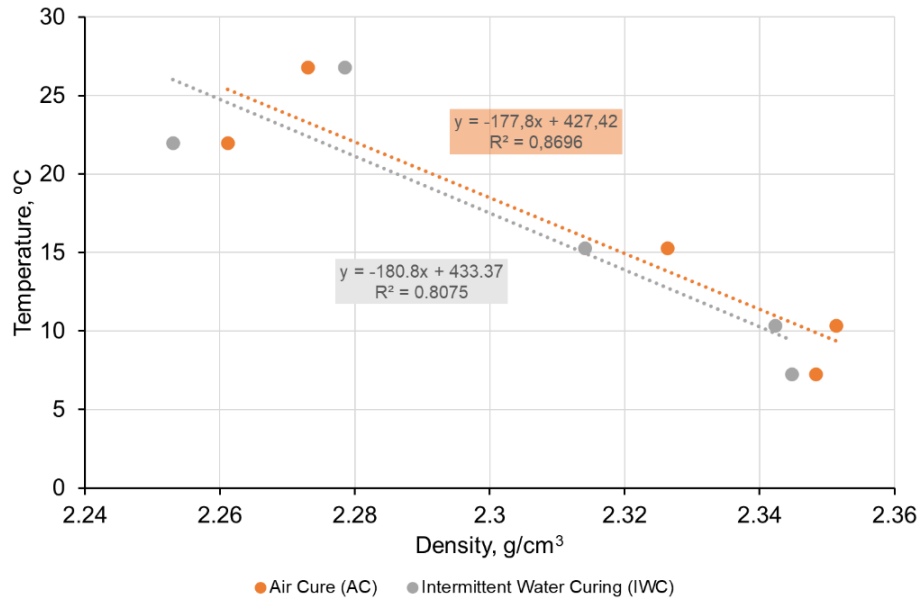


Fig. 8. Relationship between temperature and density for AC and IWC conditions.

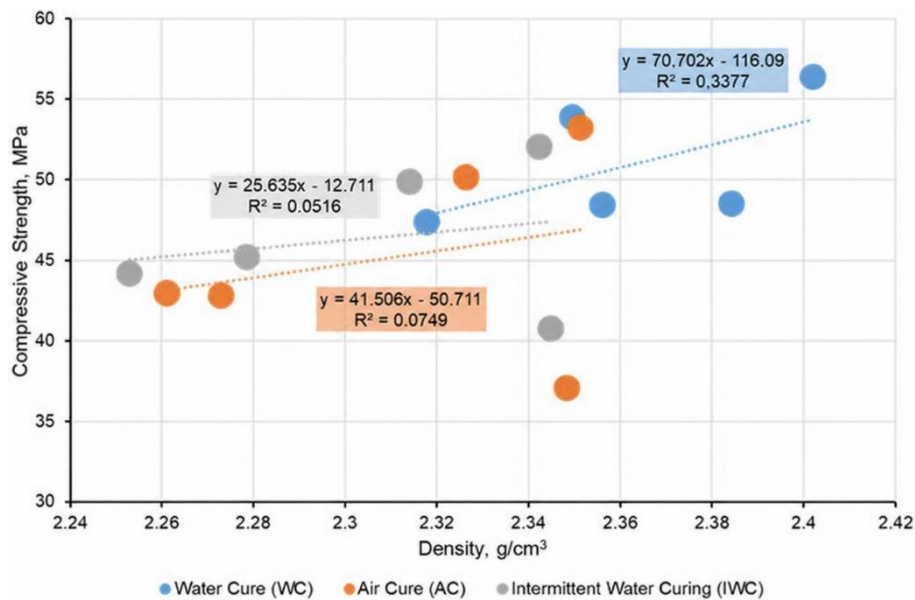


Fig. 9. Relationship between density and compressive strength under different curing conditions.

Overall, the findings demonstrate that the effect of temperature on concrete performance occurs through both direct and indirect mechanisms. Temperature alters the microstructure (represented by density) indirectly, while simultaneously influencing strength development directly through hydration kinetics and moisture loss. Furthermore, when temperature and compressive strength are considered together, a decrease in strength is observed at high temperatures, particularly when curing is insufficient. This indicates

that temperature not only affects density indirectly but also directly influences hydration and moisture loss, thereby affecting the development of strength. These results clearly indicate that concrete performance cannot be explained by a single parameter and that temperature, curing conditions, and microstructural characteristics must be evaluated together. This is particularly critical in field conditions, where the combined influence of these parameters governs concrete's overall behaviour.

4. Conclusions

This study investigated the combined effects of temperature, curing conditions, and density on the compressive strength of concrete under field conditions. Based on the experimental results, the following conclusions can be drawn:

- Curing conditions play a dominant role in concrete performance. Water curing (WC) consistently provided the highest compressive strength and density, while air curing (AC) yielded the lowest performance due to insufficient moisture retention.
- Ambient temperature substantially affects concrete behaviour. Low temperatures, as observed in March, reduced compressive strength due to slower hydration, whereas high temperatures increased moisture loss, negatively affecting both density and strength.
- The comparison between the March and April results suggests that the average temperature during the 28-day curing period may have had a greater influence on compressive strength development than the temperature on the day of casting under the conditions of the present study.
- A negative correlation was found between temperature and density ($R^2 = 0.8696$ for AC and $R^2 = 0.8075$ for IWC), indicating that increasing temperature leads to increased evaporation and reduced density.
- The relationship between density and compressive strength was found to be weak (low R^2 values), demonstrating that compressive strength cannot be explained by density alone.
- The coefficients of variation ranged from 0.98% to 5.98%, indicating good repeatability and consistency of the experimental results.
- Despite identical curing conditions, variations in compressive strength highlight the critical role of early-age temperature conditions prior to curing, indicating that initial environmental exposure has a lasting impact on concrete performance.
- The July results should be interpreted cautiously because the additional mixing water slightly increased the effective water/cement ratio from 0.53 to approximately 0.545. Therefore, the observed performance reflects the combined effects of curing conditions, environmental exposure, and a minor variation in mixture proportion, rather than temperature alone.

Overall, the results show that temperature influences concrete performance both directly (through hydration kinetics) and indirectly (through density changes), and that these effects should be evaluated together rather than independently. This study has several limitations. The experimental program was conducted using a single cement type, a single concrete strength class (C30/37), and concrete produced at one ready-mix concrete plant under local environmental conditions. In addition, the number of specimens was limited, and no microstructural analyses were performed. Therefore, the findings should be interpreted within the scope of the present study and should not be generalised to other concrete types, mixture proportions, or environmental conditions. It is recommended that further research investigate the effects of different field-curing conditions on the compressive strength of concrete, particularly in cold weather, and evaluate other practical curing techniques,

including membrane curing, wet coverings, plastic sheet curing, and sealed curing, to further extend the applicability of the present findings.

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Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, Deeply was used exclusively for language editing and stylistic refinement. The authors take full responsibility for the content, interpretation, and conclusions of the published article.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

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