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Comparative Analysis of Global Standards in Accelerated Carbonation Testing of Concrete

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ABSTRACT

Carbonation is one of the major causes of steel reinforcement corrosion, affecting the durability of concrete. Natural carbonation is a very long process; therefore, to predict the development of concrete carbonation, standards prescribe accelerated carbonation tests, in which specimens are exposed to carbon dioxide (CO_2) in a controlled environment. Although based on the same principle, global standards differ in methodology, e.g., different CO_2 concentrations, relative humidity or size of the specimens. Results of these tests might not be comparable with each other, and therefore, it is difficult to conclude which methodology most accurately predicts long-term carbonation. This diversity in standards highlights the need to study and compare them to identify similarities, differences, and the reasons behind these variations in accelerated carbonation tests worldwide. In this study, 12 standards from various regions were examined for differences in key parameters. Significant variations were found, largely due to climatic differences and testing objectives. A correlation was observed between CO_2 concentration and specimen surface area, and the study also noted that standards specifying higher CO_2 concentrations tend to have shorter test durations compared to those with lower CO_2 concentrations, aiming to accelerate the testing process. The study found that the ISO standard is applicable across diverse climatic conditions, as its flexible temperature and humidity ranges allow adjustment to local environments within the ISO limits.

Keywords: Accelerated Carbonation, Concrete Durability, Global Standards.

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1 Introduction

The durability of reinforced concrete structures is a key factor in ensuring the safety, serviceability, and long-term performance of global infrastructure. Among various degradation mechanisms, reinforcement corrosion is considered one of the most critical, contributing to premature deterioration, increased maintenance costs, and, in severe cases, structural failure [1]. This corrosion is frequently initiated by carbonation, a process in which atmospheric carbon dioxide (CO_2) diffuses into the concrete, dissolves in pore water, and reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$) [2]. This reaction lowers the pH of the pore solution from approximately 12.5 to below 9.0, undermining the passive layer around steel reinforcement and enabling corrosion to commence [3].

Carbonation-induced corrosion is a major durability concern for reinforced concrete structures, particularly those exposed to elevated CO_2 concentrations in urban or industrial atmospheres [4]. In the UK, a 60-year design life for reinforced concrete has been a common, historically rooted specification; however, current Eurocode standards adopt a default design working life of 50 years for ordinary buildings, while longer design lives (e.g. 100 years or more) are increasingly specified for critical infrastructure such as major bridges and nuclear containment structures [5]. As design lives extend and sustainability demands intensify, the accurate assessment of carbonation performance has become increasingly important. Two principal approaches are used to evaluate carbonation resistance: natural and accelerated testing. Natural carbonation provides realistic results under ambient exposure at an average CO_2 concentration of 0.042%, but its progress is slow, often requiring several years, making it impractical for efficient material evaluation or performance-based design [6, 7].

Accelerated carbonation testing has therefore become the preferred method in both research and industry. It exposes specimens to elevated CO_2 concentrations under controlled temperature and humidity, enabling simulation of long-term exposure within weeks or months and allowing for efficient prediction of carbonation depth and durability performance [6, 8]. Over recent decades, numerous international and national standards have been developed for this method. Although these standards share common principles, they differ markedly in pre-conditioning procedures, specimen surface area, CO_2 concentration, exposure duration, and measurement techniques, leading to variability in results and limited comparability between studies [7, 9].

Variations in parameters such as CO_2 concentration, relative humidity, specimen geometry, and preconditioning regime result in substantial variations between test outcomes [10]. For instance, high CO_2 levels can alter the carbonation mechanism [11], while different drying protocols significantly influence carbonation rate [12]. These inconsistencies hinder comparability and create uncertainty in durability-assessment frameworks. The challenge becomes even greater for concretes incorporating supplementary cementitious materials (SCMs), which exhibit distinct hydration and pore-structure development, often yielding inconsistent performance under varying accelerated regimes [4, 13, 14]. Such methodological differences not only limit cross-study comparability but also undermine the reliability of service-life predictions and CO_2-uptake estimations for low-carbon concrete systems. The lack of alignment across accelerated carbonation testing standards represents a critical gap in current knowledge. Therefore, the present study conducts a detailed comparison of major international and national standards to identify their key similarities and differences, and the factors contributing to these variations.

2 Methodology

A desk-based comparative analysis was conducted on 12 accelerated carbonation testing standards for concrete. The selected standards and their corresponding regions are listed in Table 1. Data were collected from official documents and literature, focusing on six parameters: preconditioning, specimen surface area, CO_2 concentration, environmental conditions, exposure duration, and measurement techniques. The information was tabulated and visually presented to highlight similarities and differences.

Table 1: The chosen standards for the comparison in the research

	Standard	Application area	Reference
1	ISO 1920-12 (2015)	International	[15]
2	EN 12390-12 (2020)	European countries	[16]
3	BS 1881-210 (2013)	UK	[17]
4	RILEM CPC-18 (1988)	Belgium	[18]
5	DIN EN 12390-12 (2020)	Germany	[19]
6	UNI 9944 (1992)	Italy	[20]
7	NT BUILD 372 (1991)	Nordic Countries	[21]
8	AFPC–AFREM (1997)	France	[22]
9	KS F 2584 (2010)	South Korea	[23]
10	JIS A 1153 (2012)	Japan	[24]
11	GB 50082 (2009)	China	[25]
12	IS 516 (2021)	India	[26]
Sum Population			

3 Results and discussion

The comparative analysis revealed notable variations among accelerated carbonation testing standards, indicating differences in testing methodologies and parameters.

3.1. Preconditioning Regimes

Preconditioning is a critical stage in accelerated carbonation testing, as it helps control internal moisture content and ensures more reliable and comparable results [12]. However, the results in Figure 1 reveal significant differences across standards in both duration and environmental conditions.

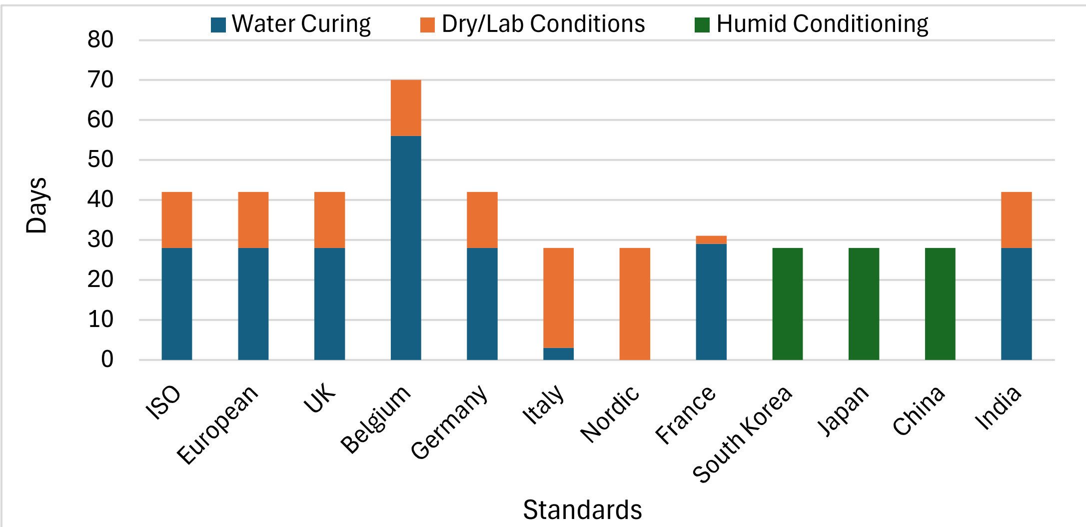

Figure 1: Comparison of Preconditioning duration and type among standards

Most standards specify 28 days of water curing followed by 14 days of laboratory conditioning. Although lab conditions vary slightly, for example, ISO (18–29°C, 50–70% RH), the European standard (18–25°C, 50–65% RH), and the Indian standard (27 ± 2°C, 65 ± 5% RH), the objective remains the same: to achieve full hydration and stabilise internal moisture before CO_2 exposure. These variations reflect the specific environments of each region, with the ISO standard designed to accommodate a wide range of global climates. This helps ensure that the preconditioning process accurately replicates the conditions in which the concrete will be tested and used.

Some standards adopt different approaches. The standard applied in Belgium specifies the longest regime (56 days of water curing plus 14 days at 60°C) to ensure full hydration and rapid drying [12]. The French standard offers two options: 28 days of water curing or 90 days at 95% RH, followed by vacuum saturation and oven drying to enhance CO_2 diffusivity [27]. The Italian standard uses only 3 days of water curing followed by 25 days of air curing at 20°C and 50% RH. The Nordic standard recommends at least 28 days under controlled conditions (23±2°C, 50±5% RH), aligning more closely with natural exposure environments. These differences often result from national experience, climate, and construction practices [28].

In Northeast Asia, where the climate is humid [29], standards specify 28 days of humid conditioning at 20°C and 95% RH. The second stage varies: the Chinese standard uses 2 days of oven drying at 60°C before testing with 20% CO_2 concentration for 28 days, while the Japanese and South Korean standards apply 28 days of lab conditioning at 20°C and 60% RH before testing at 5% CO_2 concentration for 182 days. These differences reflect distinct testing objectives: faster moisture reduction in the Chinese standard versus a closer simulation of natural carbonation in the Japanese and South Korean standards [12].

These variations reflect two main approaches: one focuses on accelerating testing by quickly reducing specimen moisture through oven drying or elevated temperatures, while the other aims to simulate more realistic exposure conditions using milder, longer conditioning periods. The preconditioning regime represents the first major point of difference among standards, making direct comparison between results difficult and reducing overall test comparability.

3.2. Accelerated Carbonation Exposure Conditions

Accelerated carbonation conditions, including CO_2 concentration, temperature, and relative humidity, strongly influence carbonation rate and depth. As shown in Figure 2, there are clear variations in these parameters among standards.

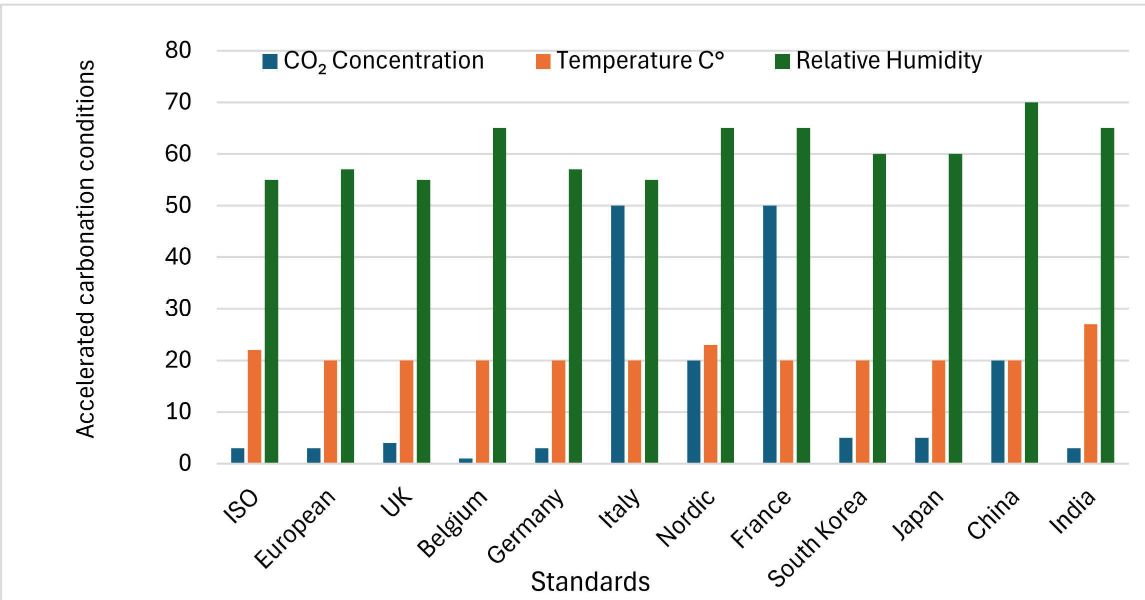

Figure 2: Comparison of Environmental conditions parameters across standards

3.2.1. CO_2 concentration

Most standards, including ISO, European, UK, German, Indian, South Korean, and Japanese, specify moderate CO_2 levels between 3% and 5%. These concentrations aim to balance test acceleration with a realistic simulation of natural carbonation, thereby improving the reliability of durability predictions [30].

The standard applied in Belgium specifies approximately 1% CO_2, which probably reflects a conservative testing philosophy. Lower concentrations allow more gradual carbonation, enabling detailed observation over time. Several studies recommend using low CO_2 concentrations to avoid exaggerated carbonation rates and preserve microstructural accuracy [10].

The French and Italian standards specify very high CO_2 concentrations of 50%, while the Nordic and Chinese standards use 20%. This higher level is intended to accelerate testing, but studies have shown that concentrations at or above 20% may begin to alter the carbonation mechanism, potentially affecting microstructure and CO_2 diffusion [11]. In addition, high CO_2 levels raise safety concerns in laboratory settings [9].

The variation in CO_2 concentrations across standards reflects differing priorities; some aim to accelerate testing, while others focus on closely simulating natural carbonation. Since there is still no agreement on the ideal CO_2 concentration [9], some standards are currently being revised to adjust their parameters. RILEM Technical Committee 281-CCC recommends using a CO_2 concentration between 1% and 3% to better reflect natural carbonation mechanisms [7]. However, further investigation is still needed to validate this range and determine its suitability for different concrete types and exposure conditions.

3.2.2. Temperature

Temperature plays a critical role in carbonation testing, as higher temperatures generally result in deeper carbonation by accelerating reaction kinetics and influencing CO_2 solubility in pore water [10, 31]. In addition, high temperatures increase the risk of microcracking, which can distort test results and compromise long-term durability predictions [32]. Most standards specify a testing temperature near 20°C, which serves as a conventional reference for laboratory-based durability testing. This temperature is selected to ensure consistency and comparability across laboratories, rather than to reflect real-world exposure conditions.

The International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC) have recognised that a single test temperature may not be suitable for all regions. To account for climatic variation, the Committee on Atmospheric Conditions for Testing (ATCO) proposed three reference temperatures: 20°C, 23°C, and 27°C [33]. These values have been adopted by various standards based on regional environmental conditions. For example, ISO allows testing at 22°C to accommodate a broader range of climates, while the Nordic and Indian standards specify 23°C and 27°C, respectively, in accordance with ISO/IEC guidelines and local climatic data.

3.2.3. Relative humidity

Relative humidity (RH) has a direct influence on the degree of pore saturation and the transport of CO_2 through concrete [14]. Most standards specify RH levels between 55% and 65%, reflecting the well-established observation that carbonation rates peak around 65% RH [34]. This explains why many standards adopt values within this range. At low RH values (below 50%), there is insufficient moisture to form carbonic acid, limiting the carbonation reaction. At high RH values (above 70%), excessive pore saturation hinders CO_2 diffusion, reducing carbonation potential [35].

The Chinese standard specifies an RH of approximately 70%, which has been shown to produce the highest carbonation depth under national test conditions [36]. This illustrates how RH values may be adjusted to reflect regional materials and climate considerations. Some standards also maintain consistent RH levels between the conditioning and testing phases to reduce internal moisture gradients that can develop between the surface and the core during drying. This approach improves reliability by ensuring that carbonation results reflect the intended exposure conditions rather than uncontrolled variations in internal saturation [7]. These differences in RH reflect how each standard tries to balance faster carbonation with realistic testing conditions. Without consistency in how RH is controlled, test results can vary widely, making it harder to compare findings across different standards.

3.3. Specimen Surface Area

Specimen surface area and geometry directly influence carbonation behaviour, primarily by affecting the exposed surface available for CO_2 ingress and the internal diffusion path [7]. As shown in Figure 3, standards vary widely in both specimen shape (e.g., prism or cylinder) and surface area. Cylindrical specimens are specified in several standards, including those of Italy, France, the Nordic countries, and South Korea. Cylinders may exhibit greater carbonation depth due to radial CO_2 diffusion, especially toward the core [10].

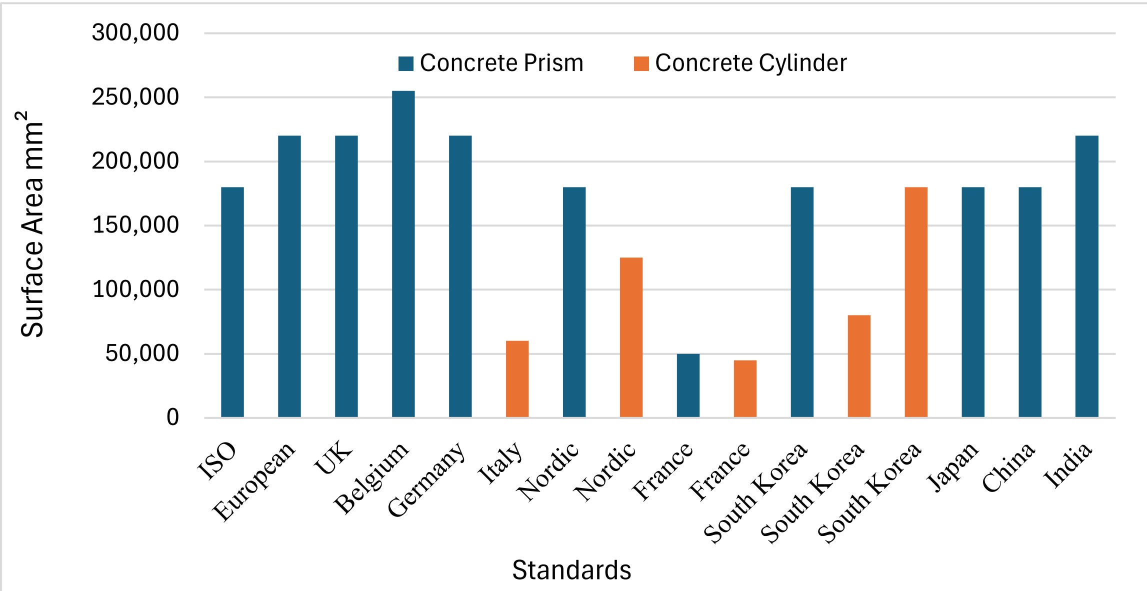

Figure 3: Comparison of Specimen Surface Areas and Shape among Standards

This study identifies a clear relationship between specimen surface area and CO_2 concentration, as illustrated in Figure 4. Standards that use higher CO_2 concentrations tend to specify smaller specimens. In contrast, standards that adopt lower CO_2 concentrations typically use larger specimen geometries, supporting longer exposure durations and more gradual carbonation. For example, the standard applied in Belgium specifies the largest surface area (around 255,000 mm^2) and applies a CO_2 concentration of 1%, reflecting a more conservative testing philosophy. On the other hand, Italy and France specify the smallest specimen surface areas while using the highest CO_2 concentration of 50%. This correlation offers valuable insight into how CO_2 levels and specimen geometry are coordinated in standard design, helping to explain the observed variation in specimen sizes across testing protocols.

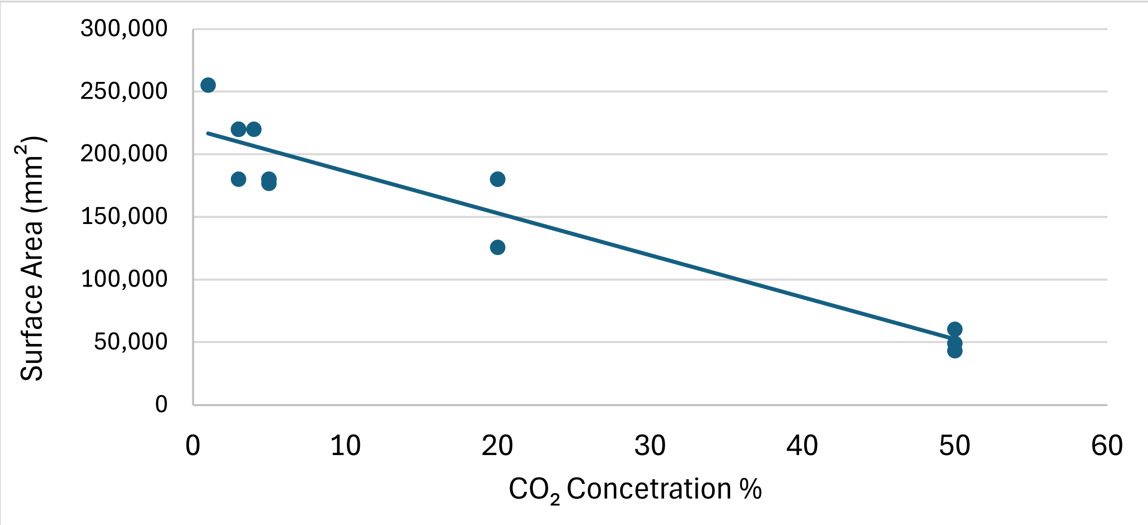

Figure 4: A correlation between CO2 concentration (%) and specimen surface area

3.4. Accelerated Carbonation Test Duration

Exposure duration is another important parameter in accelerated carbonation testing, as it directly influences carbonation depth and rate. As shown in Figure 5, there is considerable variation in exposure times across standards.

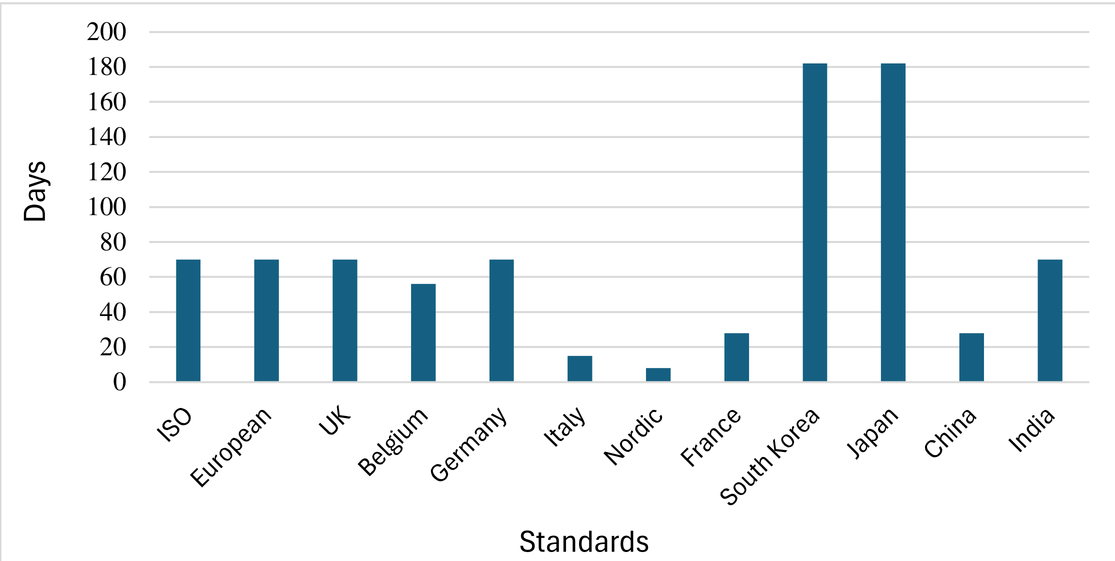

Figure 5: Comparison of Exposure Duration in Chamber among Standards

A clear trend was found from the comparison: standards that adopt higher CO_2 concentrations generally specify shorter exposure periods. This reflects a strategy to accelerate testing while still obtaining measurable results. The duration of the test is strongly influenced by CO_2 concentration, with higher levels promoting faster carbonation [37]. For example, specimens subjected to 10% CO_2 carbonated more quickly than those exposed to 1% or 0.03%. Most standards specify a moderate duration of around 70 days. However, shorter exposure durations are found in standards such as those of China, the Nordic countries, France, and Italy, all of which use relatively high CO_2 concentrations. At the longer end, South Korean and Japanese standards specify exposure periods of up to 182 days, aiming to simulate natural conditions better, even if this approach is more time-consuming [38]. These differences reflect the combined impact of CO_2 concentration and testing objectives, which explain the variations in test duration across different standards.

3.5. Measurement Procedures

Measurement procedures in accelerated carbonation testing differ across standards in terms of timing, frequency, as shown in Figure 6.

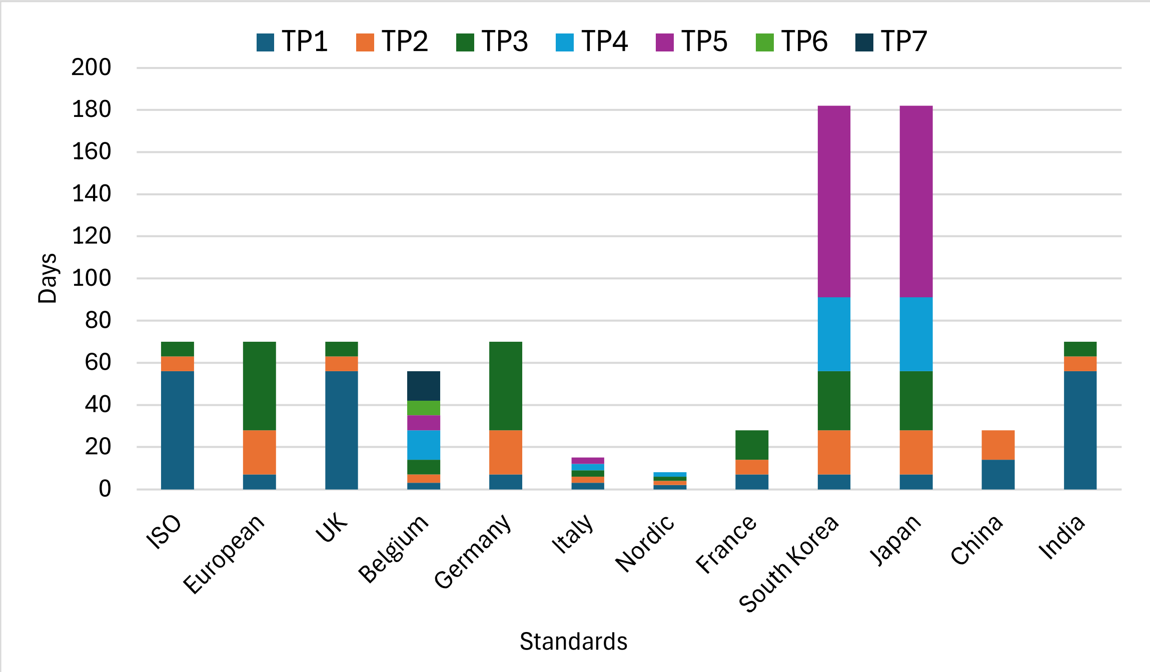

Figure 6: Comparison of Time Points of Carbonation Depth Measurements among Standards

SO, UK, and Indian standards take measurements only near the end of the test (e.g. days 56, 63, and 70 respectively), focusing on the final carbonation depth. In contrast, European and German standards measure at 7, 28, and 70 days, and South Korean and Japanese standards follow a similar approach, but over longer durations. Despite the differences in total test length, these standards gradually increase the interval between measurements to reflect the slowing carbonation rate over time [39]. In short-duration tests, frequent monitoring is applied: the Italian standard specifies measurements every 3 days, and the Nordic standard every 2 days, capturing early carbonation development more accurately. The standard applied in Belgium includes seven measurement points starting from day 3, indicating a comprehensive monitoring approach despite its low CO_2 concentration.

There are also differences in how many points are measured per specimen. ISO, European, UK, German, Indian, and Italian standards specify 20 points; Belgium, South Korea, Japan, and China specify 10. French and Nordic standards do not define the number. Despite this variation, all standards agree on a measurement precision of 0.5 mm and consistently exclude edge readings (e.g., corners, top, and bottom) to minimise edge effects and improve accuracy [10].

3.6. Inconsistent Findings Across Standards

While many aspects of accelerated carbonation testing are broadly harmonised, some procedural differences remain across international standards. One key variation involves the sealing of non-exposed specimen surfaces, which is recommended in several standards (e.g., ISO, UK, India, China, South Korea, and Japan) to ensure unidirectional CO_2 ingress. Most specify paraffin wax, although some permit alternative sealants such as epoxy or foil.

There are also differences in carbonation depth measurement methods. Although all standards use phenolphthalein to identify the carbonation front, only the European standard suggests using a fixing solution to preserve colour changes for later measurement. In contrast, other standards proceed without fixation. Despite this, the depth measurement procedure is generally consistent, with most standards excluding edge values (e.g., corners, top, and bottom) to improve accuracy.

4 Conclusions

4.1. Findings

This study compared 12 standards for accelerated carbonation testing of concrete. It reviewed key parameters such as preconditioning regimes, CO_2 concentrations, environmental conditions, specimen size and geometry, exposure durations, and measurement procedures. The comparison revealed both shared practices and notable differences across standards, which can be summarised as follows:

1- Differences between standards are mainly due to regional climate conditions and testing objectives.
2- Temperature and relative humidity values range between 20°C and 27°C and 50% to 70%, with each standard choosing conditions that suit its region to maximise carbonation depth and simulate natural exposure.
3- There is a clear correlation between CO_2 concentration and specimen surface area: higher concentrations are generally used with smaller specimens, while lower concentrations are paired with larger ones.
4- CO_2 concentrations across standards vary significantly, from 1% to 50%, reflecting different test objectives. Higher concentrations aim to accelerate testing and shorten durations, while lower concentrations provide a closer approximation of natural carbonation and require longer exposure duration.
5- The timing and number of carbonation depth measurements vary depending on whether the standard prioritises final results or process monitoring. However, all standards apply a consistent measurement precision of 0.5 mm.
6- Among the reviewed standards, the ISO standard offers flexibility in temperature and relative humidity, making it suitable for application across a broad range of climatic regions compared with other standards.

4.2. Potential Areas of Research

Based on the findings of this review, several areas for future research and development are recommended to improve the accuracy and consistency of accelerated carbonation testing:

1. Conducting comparative experimental studies to evaluate how effectively each standard predicts natural carbonation performance under real-world conditions.
2. Investigating the possibility of optimising test duration without compromising the accuracy of predictions or the ability to simulate natural carbonation processes.
3. Evaluating the reliability of accelerated carbonation test standards for concretes containing supplementary cementitious materials (SCMs), as their distinct microstructures may influence carbonation behaviour and may require the development of specific testing standards.

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