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Impact of Curing on Structural Performance of Reinforced Concrete members: A Comprehensive Review

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ABSTRACT

Curing is a fundamental process that significantly influences the mechanical performance and durability of reinforced concrete structures. This comprehensive review examines the effects of various curing methods, environmental conditions, and curing durations on the structural behavior of concrete, with a particular focus on the hydration process and its impact on strength development, durability, and crack resistance. Traditional wet curing techniques such as ponding and sprinkling generally provide superior moisture retention and strength gains, while alternative methods like membrane curing and chemical compounds offer viable solutions in water-scarce or extreme climates. The review also highlights the critical role of curing in enhancing the performance of steel fiber reinforced concrete (SFRC) beams, where proper curing ensures effective fiber-matrix bonding essential for improved shear strength and ductility. Environmental factors such as temperature and humidity markedly affect curing efficacy, underscoring the need for tailored practices under varying climatic conditions. Despite challenges related to resource use and environmental dependency, optimized curing remains indispensable for achieving desired concrete properties and ensuring long-term structural integrity. The paper identifies research gaps in curing under irregular and hot environmental conditions and calls for further investigation into sustainable and efficient curing technologies suitable for modern construction demands.

1. Introduction

Curing is a vital process in the development of concrete's mechanical strength and durability [1]. It plays a decisive role in maintaining sufficient moisture and temperature conditions to ensure continuous hydration of cement, especially during the early stages of hardening[2]. Over the past decades, researchers have extensively explored various curing techniques from conventional methods such as water ponding and spraying to more advanced systems like geotextile and self-curing technologies[3].These studies consistently emphasize the strong correlation between curing efficiency and concrete performance indicators, such as compressive strength, carbonation depth, and resistance to chloride ion penetration. Moreover, elevated temperatures, irregular moisture conditions, and climate-specific challenges have been identified as critical variables affecting curing outcomes[4]–[6]. This study reviews and synthesizes a selection of previous studies that examine the effects of different curing methods, environmental conditions, and curing durations on concrete properties. The aim is to identify research gaps, establish a solid foundation for the present study, and justify its focus on curing irregularities in hot and uncontrolled environments.

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2. Concrete Properties and Lifecycle States

Concrete undergoes three distinct states throughout its lifecycle, each playing a critical role in determining the final quality and performance of the material in structural applications[7][8]. These states are as follows:

- Plastic.
- Stiffing/setting and curing.
- Harding/Strength gain.

In each state, concrete has different properties, characteristics or qualities that determine its readiness to ensure the intended end result is achieved. The four main properties of concrete are:

- Workability/Compact ability.
- Cohesiveness.
- Strength.
- Durability.

2.1 Plastic State:

Concrete is plastic during casting and compaction and this is the first state of concrete. Concrete is made of cement, aggregate and water, and all these ingredients are mixed together to create a building material that is like bread dough; it is soft and can be worked or molded into different shapes.

The most important properties of plastic concrete are workability, ability to compact and cohesiveness.

Workability is the relative ease with which a fresh concrete mix can be handled, placed, compacted, and finished without segregation or separation of the ingredients. Good workability is required to produce concrete that is both economical and high in quality.

Concrete with poor workability does not flow smoothly into forms nor does it properly envelop reinforcing steel and embedded items, and it is difficult to compact and finish.

Depending on the application, however, a mix that has good workability for one type or size of element may be too stiff or harsh for another, so the term is relative and each mix must be suitable for its intended use to achieve a balance between fluidity, strength, and economy[9][10].

Cohesiveness is the element of workability which indicates whether a mix is harsh, sticky, and it will not easily segregate or separate.

A harsh mix lacks plasticity and the ingredients may tend to separate. Harshness can be caused by an excess or deficiency of mixing water (high- or low-slump mixes), a deficiency of cement (lean mixes), or a deficiency of fine aggregate particles.

A sticky mix may have high cement content (fat mixes) or large amounts of rock dust, fine sand, or similar fine materials (over-sanded mixes). Sticky mixes do not segregate easily, but because they require a lot of water to achieve even minimal workability, sticky mixes often develop excessive shrinkage cracking[11].

2.2 setting State

The setting and curing phase represent a critical stage in the life cycle of concrete, directly influencing its strength, durability, and long-term performance. This phase begins after the concrete has been placed and compacted, marking the transition from a plastic state to a hardened state. It is during this period that concrete undergoes significant chemical and physical changes essential for achieving its designed properties. Setting refers to the initial stiffening of the concrete mixture when it loses its malleability and begins to harden. Setting occurs after compaction, as the cement particles start reacting with water, leading to the formation of hydration products. The process of setting is crucial because it establishes the ability of the concrete to resist deformation and remain in the desired shape during finishing operations. Curing, on the other hand, involves maintaining the proper moisture and temperature conditions for an extended period to allow the cement hydration process to continue. Proper curing ensures that the concrete gains strength and achieves the necessary durability. Without sufficient curing, concrete is susceptible to surface defects like scaling and abrasion, which can compromise the aesthetic and structural integrity of the concrete surface.

The curing period is typically recommended to last 28 days to allow for complete hydration of the cement particles, although this can vary depending on environmental conditions, concrete mix proportions, and the intended strength requirements. During this time, the concrete must be kept moist, and the temperature should be maintained within a range that supports optimal hydration. Without adequate curing, concrete can suffer from reduced strength, increased porosity, and a greater likelihood of cracking. Therefore, curing is essential for achieving the desired properties of concrete, ensuring its long-term performance, and extending the lifespan of concrete structures[12][13].

2.3 Hardening State

After concrete has set it begins to gain strength and harden which is what most people associate with when thinking about concrete. The properties of hardened concrete are strength and durability. Hardened concrete will have no footprints if walked on.

A hardened concrete must possess the following, properties:

Strength is defined as the resistance of a hardened concrete to rupture under different loadings and is designated in different ways i.e. tensile strength, compressive strength, flexural strength, etc. A good quality concrete in hardened state must possess the desired crushing strength for its intended use.

Durability is defined as the period of time up to which concrete in hardened state withstands the weathering effects satisfactorily. This property is mainly affected by the water cement ratio denseness or it must be impervious in other words nothing should be able to pass into the concrete and cause damage from inside over a longer period. A good quality concrete in hardened state must be durable.

3. Curing of Concrete

Curing is one of those activities that every civil engineer and construction worker has heard about, but in reality, does not worry about much. Many publications lead with statements about how curing is critically important, yet in practice curing is often low on the list of priorities on the construction site [12] [14]. The aim of this section is to understand why curing is important, that it is indeed possible and worth the effort, and to show how it can best be carried out. The basic need for curing of concrete is very simple. Cement hydration is a chemical process that requires the presence of water over a relatively long period of time at a reasonable range of temperatures. Curing is defined as action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop [15]. In other words, Curing is the work we do to encourage concrete hydration until we get the properties that we want in the mixture [13].

Concrete Curing refers to the maintenance of adequate moisture and temperature conditions after the placement of concrete to ensure proper hydration of cementitious materials within the mixture. During the curing process, the hydration process continues as cement particles react with water to form chemical bonds that bind the aggregates, i.e., fine sand, gravel, crushed rocks, etc., together[16]. Concrete sets and hardens as a result of a chemical reaction between cementitious materials and water. This process is called hydration. Curing is the process of maintaining satisfactory temperature and moisture conditions in concrete long enough for hydration to develop the desired concrete properties. The potential strength and durability of concrete will be fully developed only if concrete is properly cured[17]. Curing is the name given to the procedures used for promoting the hydration of the cement, and consists of a control of temperature and of moisture movement from and into the concrete[12]. Curing allows continuous hydration of cement and consequently continuous gain in the strength, once curing stops strength gain of the concrete also stops. Proper moisture conditions are critical because the hydration of the cement virtually ceases when the relative humidity within the capillaries drops below 80%. With insufficient water, the hydration will not proceed and the resulting concrete may not possess the desirable strength and impermeability. The continuous pore structure formed on the near surface may allow the ingress of deleterious agents and would cause various durability problems. Moreover, due to early drying of the concrete micro-cracks or shrinkage cracks would develop on surface of the concrete. When concrete is exposed to the environment evaporation of water takes place and loss of moisture will reduce the initial water cement ratio which will result in the incomplete hydration of the cement and hence lowering the quality of the concrete. Various factors such as wind velocity, relative humidity, atmospheric temperature, water cement ratio of the mix and type of the cement used in the mix. Evaporation in the initial stage leads to plastic shrinkage cracking and at the final stage of setting it leads to drying shrinkage cracking [18][13]. Nowadays construction is rapidly increasing and as concrete is inherent material for construction so its performance also very important for life of structure and it depends on the various parameters [12]. One of the most important parameters is Curing. Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. This can be achieved by various methods like; continuously wetting the exposed surface thereby preventing the loss of moisture from it, spraying the surface with water, leaving formwork in place, covering the concrete with an impermeable membrane after the formwork has been removed, by the application of a suitable chemical curing agent (wax etc.) and using chemicals as internal curing or by a combination of such methods. In order to obtain good quality concrete, an appropriate mix must be followed by proper curing in a suitable environment during the early stages of hardening. Also, for durability as well as performance of structure proper and homogeneous curing is necessary [7][13] [19].

3.1 State of Development

The curing process plays an important role in developing the strength and durability of concrete. Curing occurs immediately after concrete is casting and finished, and involves maintaining the desired moisture and temperature conditions, both at depth and near the surface, for extended periods of time. Properly cured concrete contains sufficient moisture to sustain hydration and develop strength, volume stability, freeze-thaw resistance, and resistance to abrasion and scaling [18]. The duration of adequate curing depends on the following factors:

- Mixture proportions.
- Specified strength.
- Size and shape of concrete member.
- Ambient weather conditions.
- Future exposure conditions.

The concrete curing process maintains satisfactory moisture content in the concrete in its early stages in order to develop the desired properties. In the 21st century, cities as well as the country building process are expanding rapidly and concrete is the most widely used building material. In recent years, different types of concrete have been developed such as high-performance concrete, fiber reinforced concrete, early strength concrete, recycled concrete, self-compacting concrete etc. [19].

3.2 Method of Curing

“Curing techniques and curing duration significantly affects curing efficiency” Various degree of efficiency can be achieved by various in situ-curing methods. The effectiveness of the concrete curing method depends on the material used, method of construction and the intended use of the hardened concrete. Techniques used in concrete curing are mainly divided into two groups namely, Water adding techniques and Water- retraining techniques. Reliability and effectiveness of such curing methods are still under debate. Classification of membrane forming curing compounds as per [20].

The curing techniques that were applied are:

1- Shading concrete work: The object of shading concrete work is to prevent the evaporation of water from the surface even before setting. This is adopted mainly in case of large concrete surfaces such as road slabs [7][18] [21].

This is essential in dry weather to protect the concrete from heat, direct sun rays and wind. It also protects the surface from rain. In cold weather shading helps in preserving the heat of hydration of cement thereby preventing freezing of concrete under mild frost conditions. Shading may be achieved by using canvas stretched on frames. This method has a limited application only[18], as illustrated in Figure 1.

Figure 1. shading curing

2- Ponding method: This is the best method of curing. It is suitable for curing horizontal surfaces such as floors, roof slabs, and road and air field pavements. The horizontal top surfaces of beams can also be ponded. After placing the concrete, its exposed surface is first covered with moist hessian or canvas. After 24 hours, these covers are removed and small ponds of clay or sand are built across and along the pavements [18].

In ponding method, as shown in Figure 2, small rectangular or square artificial ponds are built with using bunds of clay or lean mortar or sand across and along the concrete surface. Water is filled in small rectangular or square ponds two or three times per day depending upon the atmospheric conditions. This method is very efficient but the more amount of water required is huge. Further, ponds can easily break and water may flow out resulting in loss of curing and water both.

It is a probably better than other concrete curing methods but also the hardest to perform correctly. Hence, following precautions are necessary:

- Water should be continuously replenished to avoid dryness because ponded water gets lost due to evaporation.

Figure 2. ponding concrete method

- All the corners and edges of the entire surface should be covered by ponding water uniformly to avoid dry spot, i.e. the last point also needs to be covered without fail.
- Water used for curing should have identical properties as that of water used for the manufacture of concrete, i.e. it should be potable water.
- Water and materials used for bonding should be free of substances that will stain or discolor the concrete surface.
- The difference in the curing water temperature and ambient temperature should not be more that 11°C to prevent thermal stresses that could result in cracking.
- Sufficient amount of water should be available at the site throughout the curing period of 7 to 14 days.
- Bunds of impervious clay or cement mortar to retain water should be maintained throughout the curing period and should not get disturbed due to movement of worker managing it.
- The height of the bunds and area of the concrete surface which is to be ponded must be selected in such a way that there is at least about 25 mm of water ponded on the highest surface [18].

3- Sprinkling of water (SC): -Sprinkling of water continuously on the concrete surface provides an efficient curing. It is mostly used for curing floor slabs. The concrete should be allowed to set sufficiently before sprinkling is started [18]. Sprinkling of water is an excellent method of curing. Soaker hoses can be used on vertical surfaces. Alternate wetting and drying are not an acceptable curing practice [22] [23].

4- Covering concrete surfaces with hessian or gunny bags: This is a widely used method of curing, particularly for structural concrete. Thus, exposed surface of concrete is prevented from drying out by covering it with hessian, canvas or empty cement bags as shown in Figure 3 [18].

Figure 3. Covering concrete surfaces with hessian

5- Steam curing: Steam curing and hot water curing is sometimes adopted. With these methods of curing, the strength development of concrete is very rapid. These methods can best be used in pre-cast concrete work. In steam curing the temperature of steam should be restricted to a maximum of 75°C as in the absence of proper humidity (about 90%) the concrete may dry too soon. In case of hot water curing, temperature may be raised to any limit, ay 100°C. After the specimens have been made, they shall be left to stand undisturbed in their molds in a place free from vibration at a temperature of 27+ 2oC for at least one hour, prior to immersion in the curing tank. The time between the addition of water to the ingredients and immersion of the test specimens in the curing tank shall be at least 1hour 30 minutes but shall not exceed 3hour and 30 minutes [18]. Steam curing and hot water curing is sometimes adopted. With these methods of curing, the strength development of concrete is very rapid. These methods can best be used in pre-cast concrete work as shown in Figure 4. In steam curing, the temperature of steam should be restricted to a maximum of 75^0C as in the absence of proper humidity (about 90%) the concrete may dry too soon. In case of hot water curing, temperature may be raised to any limit, ay 100^0C. At this temperature, the development of strength is about 70% of 28 days strength after 4 to 5 hours. In both cases, the temperature should be fully controlled to avoid non-uniformity. The concrete should be prevented from rapid drying and cooling which would form cracks [24].

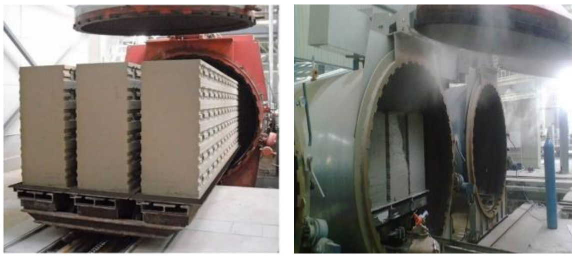

Figure 4. Steam Curing

6- Membrane curing: The method of curing described above come under the category of moist curing. Another method of curing is to cover the wetted concrete surface by a layer of water proof material, which is kept in contact with the concrete surface of seven days. This method of curing is termed as membrane curing [18]. The method of curing described above come under the category of moist curing. Another method of curing is to cover the wetted concrete surface by a layer of water proof material, which is kept in contact with the concrete surface of seven days. This method of curing is termed as membrane curing. A membrane will prevent the evaporation of water from the concrete. The membrane can be either in solid or liquid form. They are also known as sealing compounds. Bituminized water proof papers, wax emulsions, bitumen emulsions and plastic films are the common types of membrane used. Whenever bitumen is applied over the surface for curing, it should be done only after 24 hours curing with gunny bags. The surface is allowed to dry out so that loose water is not visible and then the liquid asphalt sprayed throughout. The moisture in the concrete is thus preserved. It is quite enough for curing. This method of curing does not need constant supervision. It is adopted with advantage at places where water is not available in sufficient quantity for wet curing as shown in Figure 5. This method of curing is not efficient as compared with wet curing because rate of hydration is less. Moreover, the strength of concrete cured by any membrane is less than the concrete which is moist cured. When membrane is damaged the curing is badly affected[24].

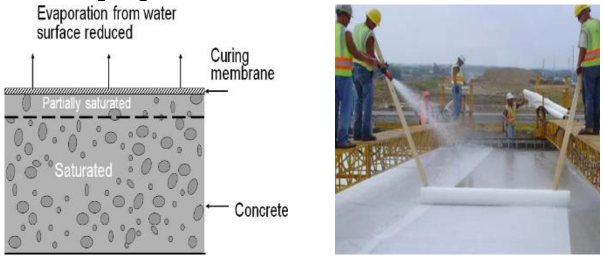

Figure 5. Membrane curing method

7- Chemical curing compounds: Membrane forming curing compounds is of two general types; clear or white pigmented. Clear curing compounds may contain a fugitive dye (usually red) that makes it easier to visually check for complete covering of the concrete surface when the compound is applied. The dye will fade after several days. White pigmented curing compounds have the added benefit of light reflectivity to aid in keeping the concrete cool improving the hydration process [25]. Figure 6 shows the chemical curing.

Figure 6. Chemical compound curing

Table 1 presents a summary for the methods of curing and the advantages and disadvantages

Table 1 Methods of Curing[26][27]

Curing Method	Description	Advantages	Disadvantages
Shading	Using canvas or shade to protect from sun, heat, wind, and rain	Simple, protects from rapid drying and heat damage	Limited to certain conditions, not suitable for all climates
Ponding	Creating small water ponds on horizontal surfaces	Highly effective moisture retention, continuous hydration	Requires large water volume, difficult to maintain uniformly
Sprinkling	Spraying water regularly on the surface	Easy to implement, good for slabs and floors	Needs frequent watering, risk of uneven coverage
Covering with Hessian/Gunny Bags	Covering concrete with wet fabric to retain moisture	Cost-effective, simple, good moisture retention	Requires periodic wetting, can be labor-intensive
Steam Curing	Using steam or hot water to accelerate curing	Rapid strength gain, ideal for precast elements	Requires special equipment, risk of thermal cracking
Membrane Curing	Applying waterproof membranes or coatings to seal moisture	Saves water, low maintenance, suitable where water is scarce	Less effective than wet curing, risk of damage to membrane
Chemical Curing Compounds	Spraying chemical compounds that form a moisture barrier	Easy application, reduces water use, reflects sunlight	Additional material cost, possible interaction with coatings

3.3 Objective of curing

The reaction between cement and water is called hydration. It is an exothermic reaction (accompanied by the release of heat) [25]. After adding water to the concrete mixture, hydration begins, which causes concrete to dry faster due to an exothermic reaction. Concrete retains moisture to complete the hydration process and reach its maximum strength faster. The main curing objectives are as follows:

1. It maintains concrete moisture to keep its strength.
2. It delays concrete shrinkage until the concrete is strong enough to resist cracking.
3. Curing improves durability and strength against erosion.
4. It is an essential process to enhance the compressive strength and stiffness of concrete.
5. Concrete retains its functionality and durability.
6. The microstructure of concrete improves by curing.
7. It increases concrete strength against cracks, plant growth, chemical attacks, etc.
8. It is essential for improving concrete's desired properties, such as impenetrability, strength, durability.
9. It prevents concrete from drying prematurely due to wind, sun, etc.

3.4 Benefits of Concrete Curing

Proper concrete curing benefits the construction in many ways, and are explained below:

1- Improve strength: The hydration process is triggered by sufficient moisture content that provokes chemical reactions between cement and water. This process builds strong bonds between the ingredients of concrete, leading to attaining maximum strength [28]. A well-cured concrete has maximum compressive strength that can withstand heavy loads. As illustrated in Figure 7.

2- Appealing Appearance: In addition to strength gain and versatility, curing provides a glossy and perfect finish to the concrete surface. It helps avoid uneven textures, stains, and discoloration. Maintaining a smooth texture and uniform color throughout the surface is an added advantage to the structure proper curing positively influences the overall aesthetics of a building and improves long-term appearance [29].

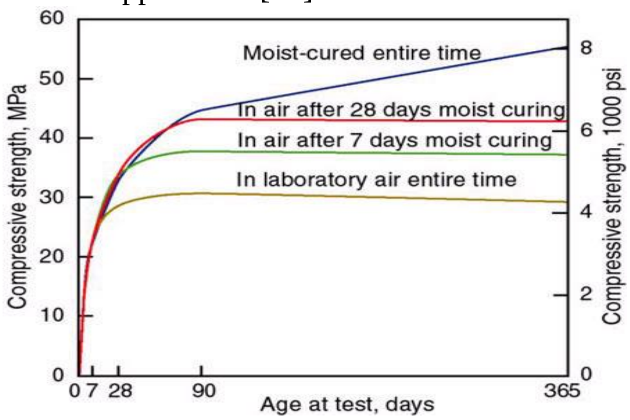

Figure 7. Moist Curing Time and Compressive Strength Gain [30]

3- Enhance Durability: Proper concrete curing enhances durability by preventing water penetration and mitigating risks such as spalling, cracking, and freeze-thaw damage. Well-cured concrete develops a denser and more uniform structure, making the surface less susceptible to wear and tear and thereby extending its service life [30].

4- Reduce Shrinkage: Curing helps prevent shrinkage, minimizing the risk of cracking in concrete. Choosing a proper curing technique is essential for large structures, particularly in areas with significant temperature fluctuations. Ensure that it creates a denser and impermeable concrete surface, which is less likely to water absorption and staining [29].

5- Save Money: Proper curing practices extend the life of concrete structures, reducing the need for regular or frequent maintenance. It results in increased service life and long-term cost savings. Whether it is a small or large-scale structure, well-planned ideas are needed for proper curing[31].

3.5 Disadvantages of curing concrete:

Curing concrete is essential for achieving desired strength and durability, but it can have some disadvantages or challenges:

1- Time-Consuming: Proper curing requires time, often several days to weeks, which can delay project completion.
2- Labor Costs: Curing methods may require additional labor, increasing overall project costs. Continuous monitoring and maintenance can also add to labor expenses.
3- Weather Dependency: Curing is affected by environmental conditions. Hot, dry, or windy weather can increase evaporation rates, while cold weather may slow curing. Adjustments may be needed based on weather, complicating the process.
4- Water Usage: Traditional curing methods often involve significant water use, which can be a concern in areas with water scarcity.
5- Surface Issues: If not done properly, curing can lead to surface defects, such as efflorescence or scaling, especially if water is not uniformly applied or if curing compounds are not used correctly.
6- Chemical Interaction: Some curing compounds can react with other materials or coatings applied later, potentially affecting adhesion and performance.
7- Cost of Curing Compounds: While curing compounds can be effective,

they may add to overall material costs, especially for large projects.

8- Limited Effectiveness in Certain Conditions: In extremely hot or windy conditions, some curing methods may not be effective, leading to potential issues like cracking or reduced strength.

Despite these disadvantages, the benefits of curing typically outweigh the challenges, as it is crucial for ensuring the performance and longevity of concrete structures[7].

3.6 Specific Factors Influencing the Concrete Curing:

1- Temperature control

Maintaining curing temperature between 10 °C and 24 °C (50 °F–75 °F) is critical. Outside this range, hydration slows (below ~10 °C) or accelerates too rapidly (above ~24 °C), which can lead to micro-cracking or reduced ultimate strength (ACI 308R-16, Sec. 4.2)[7].

2- Relative Humidity and Moisture Availability

A minimum of 85 % relative humidity at the concrete surface must be sustained to prevent premature drying. Low ambient humidity increases evaporation rates, interrupting hydration and causing plastic shrinkage cracks; conversely, misting or ponding maintains moisture for continued cement reaction [7].

3- Section size and geometry

Thick or complex shapes develop moisture and thermal gradients. As Neville (2011) [9] explains, larger cross-sections lose heat more slowly but suffer internal thermal stresses, while thin sections dry out rapidly unless curing is adjusted [9].

4- Timing of subsequent operation

Form removal, finishing, or surface treatments (e.g. painting or sealing) must be delayed until concrete attains sufficient compressive strength—typically at least 70 % of design strength to avoid surface damage or bond failures [7].

Anwar et al. (2022)[32] investigated the impact of curing techniques air curing, ponding, polythene sheeting, and boiling—on the compressive strength of Portland cement concrete in Lahore, Pakistan. Their study used a 1:1.5:3 mix ratio with a 0.5 water-cement ratio, testing specimens at 3, 7, 14, 21, and 28 days. Results showed that water-submerged curing (ponding) achieved the highest 28-day strength (41.42 MPa) due to sustained hydration, while air curing performed moderately, influenced by ambient humidity. Polythene sheeting yielded the lowest strength, likely due to inadequate moisture retention and suboptimal sheeting thickness. Accelerated curing by boiling, though useful for rapid lab predictions, was deemed impractical for field use due to micro crack risks. The study highlighted ponding as the most effective method, balancing strength and feasibility, but noted limitations such as uncontrolled slump variations and lab-field disparities. These findings offer practical guidance for curing practices in similar climates, though further research under stricter controls is recommended to validate the results.

4. Previous study of the effect of curing on the structural behavior of concrete behavior

Nahata et al. (2014)[33] evaluated the efficiency of various curing methods—water immersion, wet covering, air curing, and membrane-forming curing compounds on the compressive strength of cement mortar. The study used a 1:2.75 cement-to-sand ratio with water-cement ratios (w/c) ranging from 0.45 to 0.60, testing both ASTM-graded sand and locally sourced Sabarmati River sand. Results showed that water immersion and wet covering methods yielded the highest 28-day compressive strengths (50.5 MPa for ASTM sand, 41.8 MPa for field sand at w/c 0.45), while air curing produced the lowest strengths (38.89 MPa and 30.5 MPa, respectively). Among curing compounds, PVA-based (BASF) and wax-based (Pradyuman) compounds performed best, achieving 80–90% of the strength of conventional water curing, with lower water loss (<0.55 kg/m²) correlating to higher efficiency.

The study highlighted discrepancies in results when using Indian field sand versus ASTM sand, noting that field sand led to higher water loss and reduced strength, raising concerns about the applicability of ASTM standards in regional contexts. Nahata et al. (2014) recommended membrane curing for water-scarce areas but cautioned against air curing due to its poor strength outcomes. They also emphasized the need for Indian standards to align testing materials with local practices.

Pannani et al. (2013) [34] investigated the impact of three curing methods—traditional immersion (M3I), wax-based external curing compound (M3C), and internal curing using polyethylene glycol (PEG-600, M3A)—on the compressive strength of medium-strength self-compacting concrete (SCC). The study employed a mix design with a constant water-cement ratio and super-plasticizer dosage (1.1% of cementitious material), testing 150 mm cubes at 3, 7, and 28 days. Results revealed that immersion curing yielded the highest 28-day strength (35.56 MPa), followed by internal curing (33.78 MPa, 5% lower) and external curing compound (32.59 MPa, 9% lower). Notably, internal curing showed slower early strength gain (29% lower at 3 days) but nearly matched immersion curing by 28 days, highlighting its efficacy in water-scarce regions.

The authors emphasized the practicality of curing compounds for SCC, particularly PEG-600, which achieved 95% of immersion-cured strength while conserving water. The study underscored the trade-off between early strength and sustainability, recommending internal curing for projects prioritizing long-term performance and resource efficiency. However, the reliance on laboratory conditions and limited material variability (e.g., single brand of curing compound) suggests the need for field validation.as shown in Figure 8.

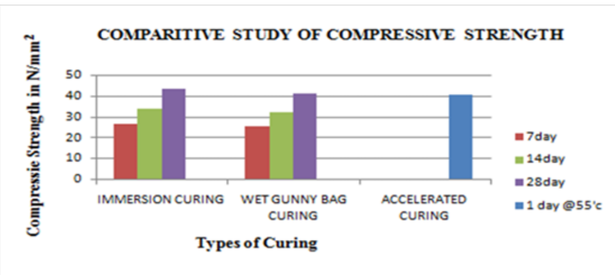

Figure 8. Effect of three types of curing on compressive strength of concrete[34]**.**

Guo et al. (2024)[35] conducted an extensive experimental investigation into the effects of various curing methods specifically air curing, sprinkler curing, geotextile curing, and composite geotextile curing on the mechanical and durability performance of concrete. Their study evaluated parameters including compressive strength, carbonation depth, and chloride ion diffusion coefficient at different ages (7, 14, 28, 56, and 90 days). Results showed that while early-age compressive strengths (7 and 14 days) were relatively similar across methods, longer curing durations significantly influenced both strength development and durability. The composite geotextile method proved most effective, improving water retention, reducing curing frequency, and yielding the highest 28-day compressive strength (55.4 MPa), lowest carbonation depth (2.8 mm), and minimal chloride diffusion coefficient (6.13×10^{-12} m^2/s at 90 days). In contrast, air curing led to reduced hydration, surface drying, microcracking, and the highest degradation in performance over time. The study emphasized that strength alone is insufficient to evaluate curing efficiency, advocating for a combined assessment using mechanical and durability indicators. These findings support the use of composite geotextile systems in environments with high evaporation rates or limited water availability, especially for enhancing the long-term durability of bridge concrete.

Olanrewaju et al. (2017) [36]investigated the influence of high curing temperatures on the mechanical properties of concrete, specifically focusing on compressive strength and pullout strength. Concrete specimens were cured at three different temperatures—30°C, 60°C, and 100°C—and tested at 7, 14, and 28 days. The results revealed that higher curing temperatures significantly increased the early-age strength of concrete. At 28 days, the highest strength (24 MPa) was recorded for concrete cured at 100°C, compared to 20.09 MPa and 16.64 MPa for 60°C and 30°C, respectively. However, while elevated temperatures accelerated early strength gain, the authors cautioned that excessively high temperatures could lead to long-term weaknesses due to microstructural changes. Statistical analysis showed that the number of curing days had a more significant impact on strength than temperature alone, with a correlation coefficient of 0.779 ($p = 0.004$). Regression analysis also indicated that every 1°C increase in temperature contributed approximately 0.062 N/mm² to compressive strength. The study concluded that while elevated curing temperatures are beneficial for early strength development, prolonged or extreme heat exposure could negatively affect the durability of concrete over time. These findings are particularly relevant in the context of global warming and the increasing frequency of construction in hot climates.

Steel fibers significantly enhance the shear strength of concrete beams by improving crack resistance, ductility, and post-cracking behavior. The extent of improvement depends on the fiber content, aspect ratio, and beam design. In some cases, steel fibers can partially or completely replace shear stirrups, reducing reinforcement costs and simplifying construction.

Zhang et al. (2020) emphasized that the inclusion of steel fibers significantly enhances the shear performance of high-strength concrete beams, particularly when the fibers are evenly distributed and well-bonded within a dense matrix. Their results indicated that optimized curing contributes to this effect by minimizing voids and improving matrix integrity, which is essential for efficient stress transfer through the fibers[37]. Similarly, Khaloo and Afshari (2005) developed a predictive model for the shear capacity of SFRC beams, noting that the effectiveness of steel fibers in resisting shear is inherently dependent on proper curing to ensure full fiber embedment and matrix consolidation[38].

Narayanan and Darwish (1987) [39] conducted one of the earlier investigations into the shear behavior of SFRC beams without stirrups. Their findings suggested that the presence of steel fibers can partially replace traditional shear reinforcement, provided the concrete is adequately cured to develop sufficient tensile and bond strength. Moreover, inadequate or irregular curing has been reported to result in microcracks, reduced tensile capacity, and premature debonding of fibers, all of which compromise the shear behavior of SFRC elements [40].

5. Conclusion

Curing plays a pivotal role in determining the mechanical strength, durability, and overall structural performance of reinforced concrete members. This comprehensive review highlights that proper curing through the maintenance of adequate moisture and temperature is essential for the complete hydration of cementitious materials, directly influencing critical concrete properties such as compressive strength, tensile capacity, crack resistance, and durability.

- The review has demonstrated that different curing methods, including traditional wet curing techniques (ponding, sprinkling, covering) and advanced methods (membrane curing, chemical compounds, steam curing, and geotextile curing), vary significantly in their effectiveness. Ponding and continuous wet curing generally yield superior strength and durability, especially under controlled environmental conditions. However, in water-scarce or harsh climates, membrane curing and internal curing agents offer practical alternatives despite their somewhat reduced efficiency.
- The impact of environmental factors such as temperature, humidity, and exposure conditions further underscores the necessity of tailored curing practices. Elevated temperatures can accelerate early strength gain but may impair long-term durability if not properly managed. Similarly, irregular or insufficient curing leads to

microcracking, reduced tensile strength, and compromised bonding in steel fiber reinforced concrete (SFRC), diminishing shear resistance and structural integrity.
- In SFRC beams, curing effectiveness is especially critical as it governs the fiber-matrix interaction responsible for enhancing shear strength, ductility, and crack control. The synergy between optimized curing and fiber reinforcement presents opportunities to reduce traditional shear reinforcements and improve structural resilience.
- Despite advances in curing technology and methodology, challenges remain, including labor and water resource demands, weather dependency, and potential chemical interactions. Future research should focus on developing standardized guidelines adaptable to diverse environmental conditions, optimizing curing compounds for sustainability, and exploring curing-fiber interdependencies under field conditions.

Ultimately, ensuring proper and consistent curing is indispensable for maximizing the service life, safety, and cost-effectiveness of concrete structures, particularly in the face of global climate variability and growing construction demands.

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