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AN ANALYTICAL REVIEW ON EXTERNAL AND INTERNAL CONCRETE CURING MECHANISMS

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Abstract - *Concrete is the most frequently used material in the building sector, but it also uses a lot of water in its manufacturing, necessitating urgent study to reduce the amount of water used in concrete production. Construction and chemical industry advancements have cleared the ground for the development of new curing procedures. A lot of study has been done to see how successful curing is and how it affects different concrete qualities. The key to high-quality concrete is efficient, continuous curing. Concrete curing is critical for achieving design strength and maximum durability. Curing is determined by the needed qualities of concrete, the intended use of the concrete, and the surrounding environment, which includes temperature and relative humidity. Curing is primarily intended to keep the concrete moist by limiting moisture loss from the concrete during the strength-building process. Curing can be done in a variety of methods, and the best method for curing may be determined by the site or construction method. The purpose of this research is to assess the efficacy of various curing processes as well as to investigate the impact of climate on concrete strength.*

Key Words: Concrete Curing, Relative Humidity, Internal Curing, Compressive Strength, Durability

1.INTRODUCTION

Concrete is a common building material that is utilized in a variety of applications. Concrete's strength and durability determine its quality. Concrete's compressive strength is one of the most essential and helpful parameters for determining its quality. The hydration of cement in the mix must be complete for concrete to achieve the requisite strength. Cement that has been properly hydrated produces high-quality concrete with sufficient strength. Fresh concrete must be put in a favourable environment for optimal hydration to occur. Cement hydration is a set of chemical processes that take place over a long length of time and necessitate a sufficient supply of water and the right temperature (Taylor 2014).

Curing is defined as activities taken to maintain moisture and temperature conditions in a newly installed cementitious mixture so that hydraulic cement hydration and possibly pozzolanic reactions can occur and the combination's potential qualities can develop (ACI 2013). Curing refers to the techniques for promoting the hydration of the cement, which include temperature management and moisture transfer out of and into the concrete. Curing provides for continuous cement hydration and, as a result, continual strength increase; however, once curing is stopped, the concrete's strength gain stops as well. When the relative humidity within the capillaries falls below 80%, the hydration of the cement nearly stops. If there is insufficient water, the hydration will not proceed, and the resulting concrete may lack the desired strength and permeability. The continuous pore structure generated on the near surface could allow harmful chemicals to enter and cause a variety of durability issues (Dnyanoba and Madhukar 2020). Memon et al (2018), asserts that the use of light weight aggregates in concrete production increases the odds for concrete's self-curing potentials, through the storage and subsequent use of moisture in concrete pores.

Curing mechanisms are mainly grouped under external and internal approaches (Kovler, 2012, Ghourchian *et al*, 2013). External methods are commonly used to cure conventional concrete. External curing keeps the surface from drying out, keeps the mixture warm and moist, and keeps the cement hydrated (Taylor 2014). Internal curing is a relatively new technology for extending cement hydration by creating internal water reservoirs in a concrete mixture that have no negative impact on the concrete's fresh or hardened physical qualities. The demand for more lasting structural concretes that were resistant to shrinkage cracking prompted the development of internal curing (Babcock and Taylor 2015) Water/cement (w/cm) ratio plays a vital role in the hydration and permeability properties of concrete. Low w/cm ratio in concrete mix, with w/cm ratios less than 0.42, have less water for hydration than required (Neville 1996). Water in the capillary pores is consumed as the cement in a concrete mixture hydrate. This process reduces the relative humidity of the mixture while also increasing internal tensions, increasing the likelihood of drying shrinkage and cracking (ACI 2013). It is vital to control the drop in relative humidity in the mixture during hydration to reduce the risk of drying shrinkage and cracking (Bentur et al. 2001). External curing does not meet this requirement since water cannot permeate the entire length of the element and is confined to a thin surface layer of around 25.4mm (Babcock and Taylor 2015). Additionally, it's an acceptable knowledge that limiting w/cm ratio, enhances the strength and stability potentials of concrete, on the very important assumption that relative humidity within the concrete matrix can be maintained through the hydration cycle of the concrete.

Meeks et al. (1999) related the durability and strength of high-performance concrete with the interaction between the constituents of the concrete as well as the curing potentials of the concrete. An interesting phenomenon is that high performance concrete is conventionally of decreased permeability, necessitating the prolonged durability, which goes to show limitations in the use of external curing techniques (Powers et al. 1959).

One of the most important parameters affecting the pace of strength development is the curing temperature. Ordinary concrete loses strength at high temperatures due to the creation of cracks between two thermally incompatible elements, cement paste and particles. When concrete is cured at a high temperature, it usually develops a higher early strength than concrete that is created and cured at a lower temperature, although the strength is usually reduced after 28 days. According to laboratory testing, concrete cured in a dry atmosphere can lose up to 50% of its potential strength compared to equivalent concrete cured in a damp environment (ACI, 2009). The above is however logical for Normal Weight Aggregate (NWA) concretes; where no trapped moisture is available to be desorbed into the cement matrix. The case is however different for LWA concretes.

Internal curing can be given by highly absorptive materials that easily desorb water into the cement pore structure, according to Byard and Schindler (2010). This reduces capillary strains and adds water to the cement hydration process. Light Weight Aggregates (LWA), super absorbent particles (SAP), perlite, and wood pulp are some of the materials that can be employed for internal curing. LWA provides structural capability to the concrete mixture, but SAP, perlite, and wood pulp do not (Byard and Schindler 2010).

2.0 MECHANISM OF CONCRETE CURING

Strength and durability properties of concrete are set by the chemical reactions of the various components during the hydration process, (Dnyanoba and Madhukar (2020), as such, there are three key factors to proper curing.

- ✓ Moisture – Having sufficient moisture to ensure the hydration process continues
- ✓ Temperature – Maintaining a sufficient temperature (≥10°C) to ensure that the chemical reaction continues
- ✓ Time – Maintaining both the moisture and temperature requirements for a minimum period of time (3 – 7days – See CSA A23.1 – Table 20) for adequate growth of the concrete's durability potentials.

It is essentially noteworthy that the key answer to why we cure concrete, is to enhance the development of the calcium hydrate silicate gel (cement main binder compound) as wells as moderate the effect of temperature and moisture gradient within the concrete during the hydration process for internal shrinkage, stress and crack control, by maintaining sufficient relative humidity within and without the concrete.

2.1 Concrete Ponding

Ponding curing mechanism is the most conventional curing mechanisms particularly for low volume works. It entails complete submersion of the concrete surface in clean water for a specific period (mostly 28days). Pavements and floors are good examples of flat surfaces that can be ponded for curing purposes. In most cases, earthen materials are layed over the flat surface and saturated with water to enhances a ponded surface over the concrete for the specific curing period. The curing water should not be more than about 11°C (20°F) cooler than the concrete to prevent thermal stresses that could result in cracking (Dnyanoba and Madhukar 2020). The most thorough method of curing with water consists of total immersion of the finished concrete element. This method is commonly used in the laboratory for curing concrete test specimens.

Table-1: Concrete curing mechanisms (Kovler, 2012, Ghourchian *et al*, 2013)

MECHANISMS OF CONCRETE CURING				
External Curing		**Internal Curing**		Other Methods
Water Curing	Sealed Curing	Internal Curing	Internal Sealing	
Ponding	*Water-proof paper*	*Light Weight Aggregates (LWA)*	*Water soluble chemicals*	*Oven Curing*
Spraying	*Plastic Sheeting*	*Super Absorbent Polymers (SAP)*		*Hot mix Concrete*
Fog Misting	*Curing Membranes*	*Water Saturated Normal Weight Aggregate (NWA)*		*Natural Curing*
Saturated Coverings		*Wood derived products*		*warm water /accelerated Curing*
		Heat extraction curing		*Steam curing*

Raza et al (2020) affirms that ponding is the most strength effective means of water based external curing techniques. However, external water-ponding mechanism is limited to 1-inch penetration depth around the surface of the submerged concrete (Guo et al 2020, Babcock and Taylor 2015).

Fig - 1: Ponded concrete surface (Structural Guide 2021)

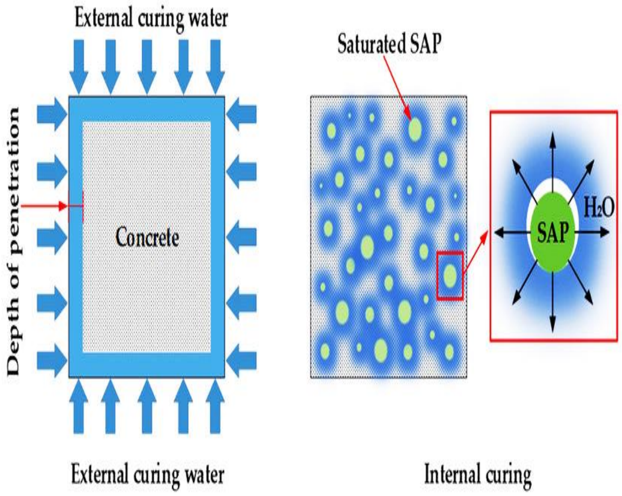


Fig - 2: Different mechanisms between external and internal curing methods. (Guo et al 2020)

2.2 Water Sprinkling/Spraying

To prevent the concrete surface from getting dry due to the evaporation. Continuous spraying/sprinkling of water at a constant rate and uniformly is another effective mode of water curing. The objective of sprinkling is to ensure the moisture level does not reduce from the required level. This method becomes relatively easy with the help of calibrated sprinklers.

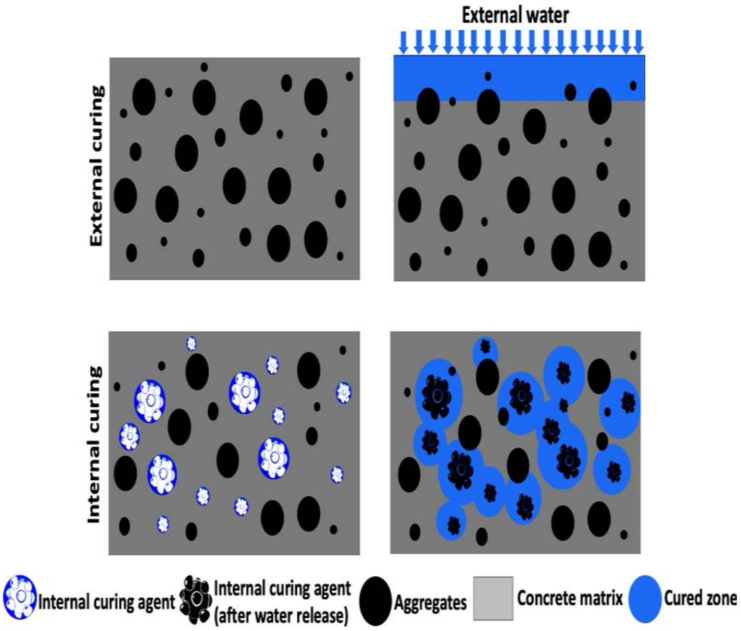


Fig - 3: Internal and external curing mechanism (Danish et al 2020, Memon et al 2018)

Fig - 4: Water Sprinkling concrete curing mechanism (Structural Guide 2021)

2.3 Wet Membrane Covering

With the same objective of keeping the surface constantly moist as in the case of water sprinkling curing mechanism, the use of wet membrane curing technique maintains the surface moisture level by placing materials like hessian or earthen materials. Use of gunnery bae is also common. These covering materials are placed on the hardened concrete surface and consistently kept wet through to enhance a constant temperature and moisture gradient particularly at the surface of the concrete. Other membranes used primarily to prevent moisture.

Fig -5: Wet Membrane Covering concrete curing mechanism (Structural Guide 2021)

2.4 Heat Extraction Mechanism

For high grade concretes used in the production of massive structures such as damns, the rate of hydration is relatively intense and generates massive amount of heat with the potentials for enormous internal stresses and cracks. As such the use of hollow pipes situated at around the middle of the structure's thickness, allows for the constant passage of water to absorb the generated heat within the region and transfer it out through the water medium. However, these methods shall be used with much care as the sudden change in the temperature could cause cracking in the concrete. Continuous monitoring of the temperature of the water provides an idea about the internal temperature. Base on the observations, the flow rate can be adjusted.

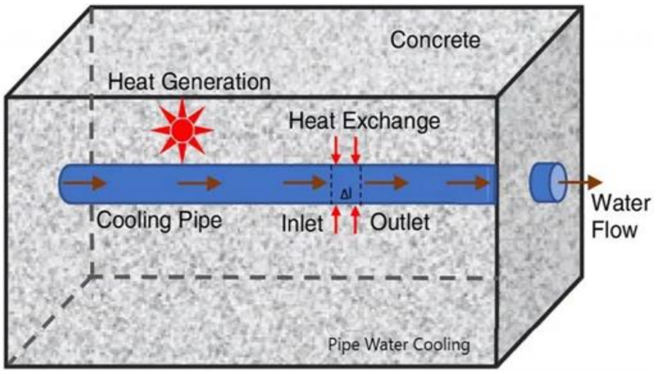


Fig -6: Heat extraction concrete curing mechanism (Structural Guide 2021)

2.5 Concrete Hot Mixing/Curing Mechanism

It is evident that the rate of hydration is a circle of heat generation and strength gain. Wedatalla et al (2019) as well as Pawar and Kate 2020, investigated on Hot curing mechanisms via oven and steam approaches. It was gathered that steamed curing was consistently more strength effective as compared to the conventional ponding technique or oven curing technique. Structural Guide (2021) asserts that rising the concrete's temperature could enhance its strength by 10% to 20%. Pawar and Kate (2020) called their technique 'Accelerated Curing' technique, in which, concrete specimens were completely submerged in a hot water for a period of 19 hours 50minutes after which they were cured in a room temperature water for another 1 hour and tested almost immediately for strength. By this method they were able to reduce the long wait for strength development due to conventional hydration at the detriment of 3.32% and 1.45% losses in 28day conventional strengths for grades M20 and M40 concrete's respectively. Structural Guide 2021 further asserts that by heating the aggregates prior to mixing, heating the mixing/curing water or injecting steam into the concrete, hydration process can be raised exponentially (Structural Guide, 2021). The technicalities of this process my encourage more of precast concrete structures as compared to onsite concrete construction. Additionally, the effect of temperature gradient post curing period on drying shrinkage has not been comprehensively studied as it relates to the durability and long-term penetration resistance of the concrete.

2.6 Natural Curing

Natural curing is predominantly the most obtainable concrete curing technique in the construction industry. This is not in itself a technique as it is not a designed approach, however, it is responsible for majority of internal stresses, drying shrinkages and cracks in concrete structures. This is obtainable particularly in dry atmospheres were evaporation effect initiates dryness on the surface and within the concrete matrix and reduces the relative humidity to levels below 80%; a level was less than 5% of absorbed water alone is available for hydration (Babcock and Taylor 2015).

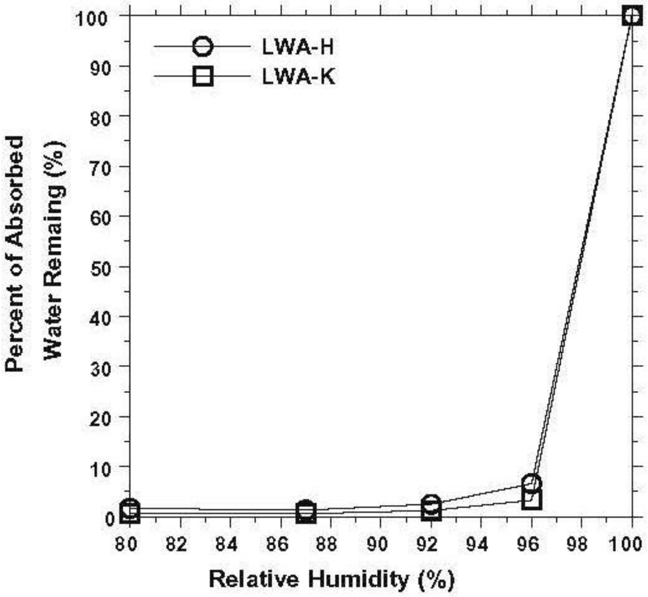


Chart -1: Percent of absorbed water available for hydration as a function of relative humidity (Babcock and Taylor, 2016)

3.0 MATERIALS AND METHODS

We begin by recalling that the lower the w/cm ratio, the higher the strength for both air-entrained and non-air entrained concrete structures, Amhudo et al (2018). Also, it is beneficial to recall further that the very benefit of air entrainment in concrete is to allow for temperature gradient without exceeding the elastic limits of concrete. As such, whilst it is desirable to limit w/cm ratio, it should be noted that w/cm ratios less than 0.42 doesn't possess sufficient water for hydration (Neville 1996). Ultimately, the logical theory behind self-curing/ internal curing mechanism is the use of water absorbent aggregates or admixtures in the production of concrete which allows for the reduction of w/cm to the acceptable minimal while nursing the potential to desorb sufficient water necessary for internal hydration (Delatte and Cleary 2008). In comparison to air entrainment approach, internal curing sufficiently maintains the relative humidity of the concrete internally to allow for hydration and drying shrinkage management and as such eliminates the need for additional pores as it pertains to freezing and thawing management for crack control.

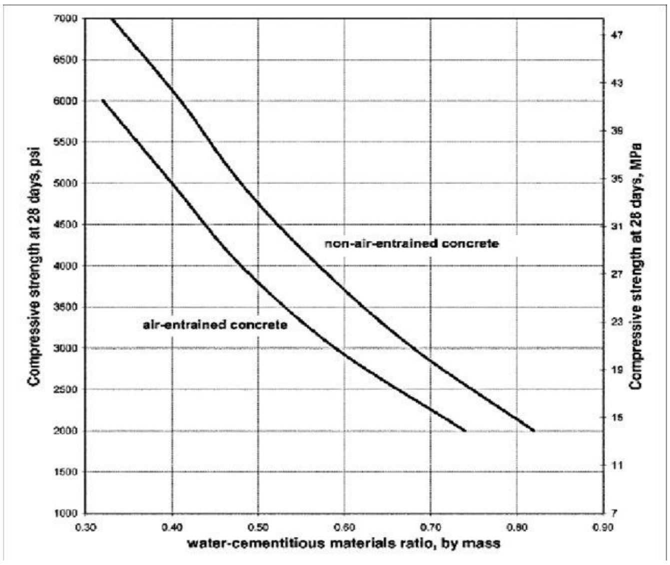


Chart -2: Water-cement ratio vs. compressive strength of concrete (amhudo et al, 2018)

3.1 Light Weight Aggregate

The potentials of internal curing from absorbed moisture in lightweight aggregate (LWA) was identified by pre-stressed concrete researchers in the late 1950s and 1960s, (Campbell and Tobin 1967, Jones and Stephenson 1957, Klieger 1957). The concept of internal curing resurfaced in the 1990s when Philleo (1991) proposed the use of saturated lightweight fine aggregate in concrete mixtures to maintain the relative humidity of hardened concrete for continuous hydration (Philleo 1991). Light wight aggregate is a porous structure of light aggregate, mainly including clay or shale quality materials, which can use their own pores to absorb and preserve water; however, its water absorption capacity is low when compared to other internal curing mechanisms, yet, Byard and Schindler (2010) affirms that of all notable internal concrete mechanisms, only LWA approach maintains the structural integrity of the concrete.

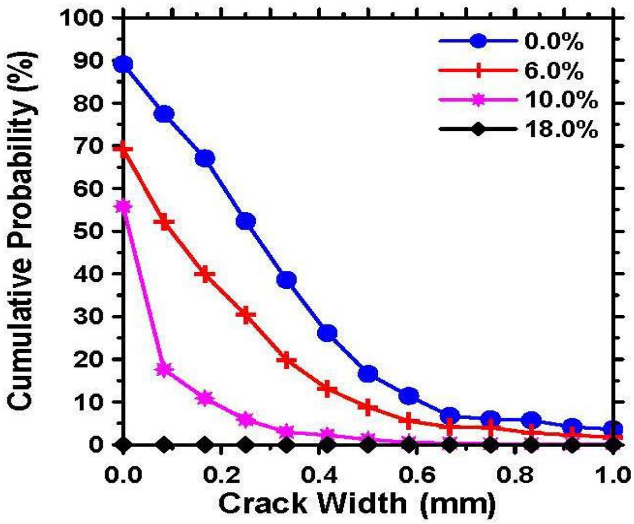


Chart -3: concrete internal crack width as a function of LWA concentration in Concrete (Babcock and Taylor 2015)

3.2 Super-Absorbent Polymer (SAP)

This is a typical functional polymer material with high water absorption potentials; it uses the chemical bond between polymer molecules and water molecules to absorb and retain moisture.

SAPs are 3 dimensional, networks of flexible polymer chains carrying disassociated and ionic functional groups. The origin of SAPs can be traced back to 1970 when they were first prepared and used in various industries like agriculture, healthcare, forestry, etc., (Kiatkamjornwong, 2007). In concrete technology, SAPs gained better attention around early 2000s, (Buchholz and Graham 1998).

Danish et al (2020) added that in concrete, SAPs are used as controllable distribution systems with effectively smart expansion and contraction properties, which are functions of the following;

1. SAP should be chemically stable in ionic solutions
2. SAP should absorb and release water in the concrete under various pressures and temperatures
3. SAP should support the effective distribution of particle size

Contrasting the two most notable Self-curing mechanisms; LWA and SAP, it can be said that whilst mechanical/strength properties are more enhanced by LWA at short durations, SAP will air entrainment as well as explicit hydration potentials is relatively advantageous particularly in frost regions where temperature gradient and drying shrinkage is of greater concern than the mechanical integrity of the concrete structure.

4.0 RESULTS AND RESPONSE VARIABLES ON CURING MECHANISMS

From Chart-3, it is evident that LWA is very effective in reducing the crack potential of concrete, of which at 18% concentration, the probability of cracking is brought to zero. This is similar to Chart-1, where relative humidity was measured against available water for desorption and as a function of LWA category.

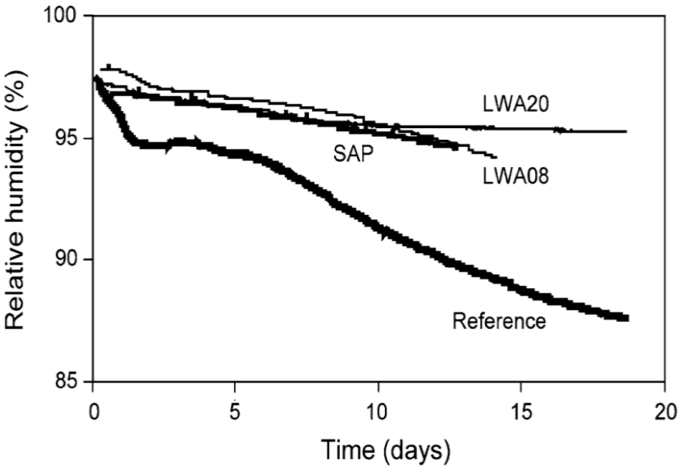
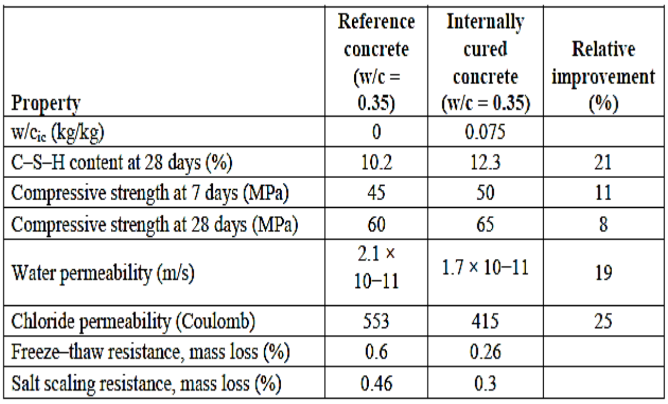


Chart -4: Relative humidity of conventional and internally cured mortar during hydration (Persson and Fagerlund 2002)

Relative humidity (RH) is the core of internal curing mechanism. Persson and Fagerlund (2002), monitored the internal RH of different IC curing methods at incremental ages. Two types of LWA (LWA20 and LWA08), SAP as well as conventional concrete mixes were developed and studied for RH depletion with time (Chart-4). For all concrete types, a gradual reduction in RH was observed, however, a significant variation in favour of SAP, LWA20 and LWA08 was recorded.

Table-2: Selected test results on impact of internal curing properties of high-performance concrete (Cusson and Margeson 2010)



Property	Reference concrete (w/c = 0.35)	Internally cured concrete (w/c = 0.35)	Relative improvement (%)
w/c_{ic} (kg/kg)	0	0.075	
C–S–H content at 28 days (%)	10.2	12.3	21
Compressive strength at 7 days (MPa)	45	50	11
Compressive strength at 28 days (MPa)	60	65	8
Water permeability (m/s)	2.1 × 10–11	1.7 × 10–11	19
Chloride permeability (Coulomb)	553	415	25
Freeze–thaw resistance, mass loss (%)	0.6	0.26	
Salt scaling resistance, mass loss (%)	0.46	0.3	

Cusson and Margeson compared the hydration properties of concretes prepared for internal and external curing. As shown in Table 2, internally cured concrete performed significantly better on all fronts. The 21% relative improvement of C-S-H content is a significant result that reinforces on the advantageous effects and benefits of sustained RH during hydration stage. This is visible on the recorded responses of strength, permeability and durability.

Ye et al (2008) reflected on the findings of Powers 1968 as presented in Figure 12. Careful investigation of the results indicates from figure 11a, increasing solid/void ratio increases the compressive strength of concrete. This is further shown in figure 12b were the percentage of hydration is defined as a function of w/cm ratio and volume of pores available in the mix; increasing the w/cm ratio, potentially increases the volume of pores and ultimately reduces the percentage of hydration products obtainable.

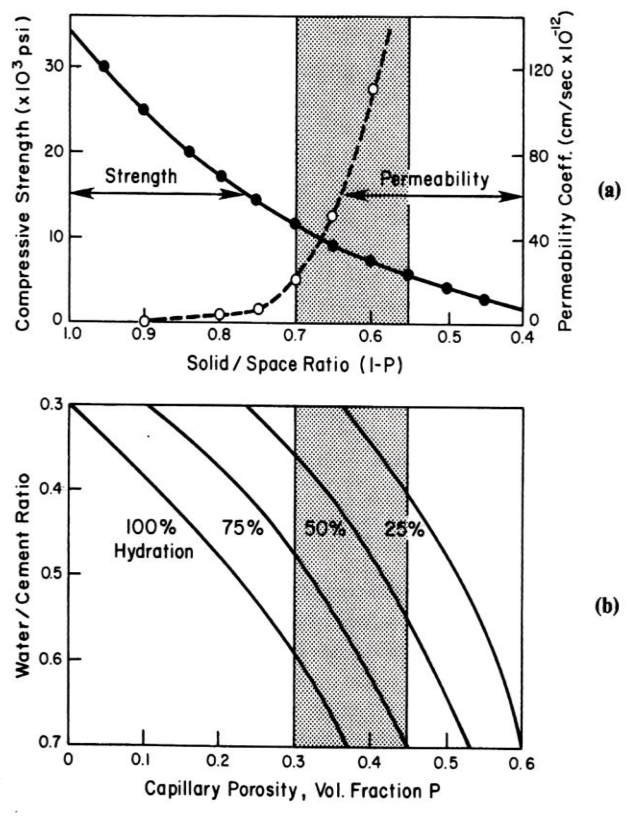


Chart -5: Influence of water/cement ratio, void ratio and degree of hydration on strength and permeability of concrete (Powers 1968, Ye et al 2008)

Raza et al (2020) considered three external curing techniques; ponding, sprinkling and wet covering, from which ponding technique showed slightly superior potentials in compressive strength when compared to the other 2 methods.

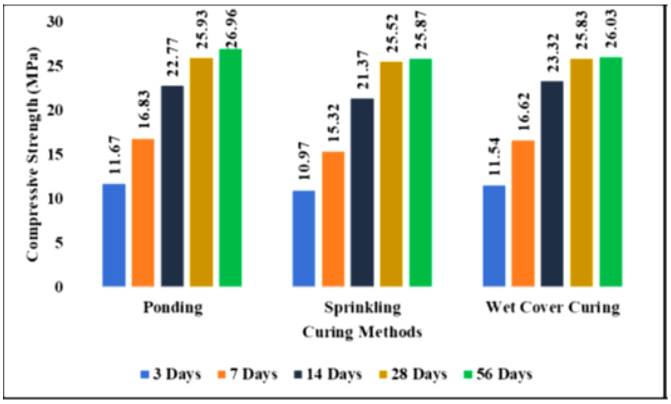


Chart -6: Relationship between curing methods, curing ages and compressive strength of concrete cubes. (Raza et al 2020)

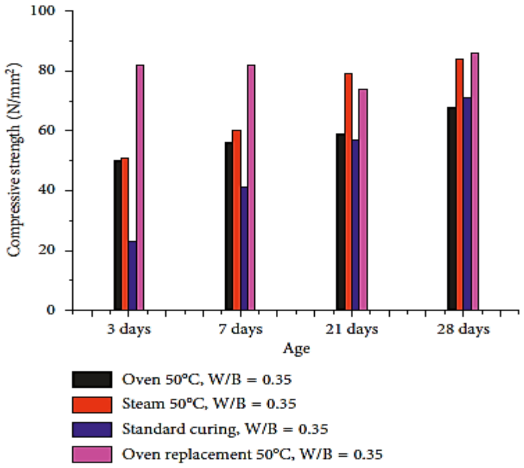
Findings of Pawar and Kate (2020), is in tandem with Raza et al (2020), which shows that curing by ponding is slightly superior in compressive strength to curing by wet covering. The main objective of their work however, is to invest on the possibilities of exponentially reducing the time of hydration by increases its speed using boiling water (55ᵒC) as the curing medium. Indeed, the obtained one day cured compressive strength for the warm water accelerated curing technique was superior to the conventional mixes at 7 and 14 days. However, at 28days a reduction of 3.32% and 1.45% for grades M20 and M40 concretes was recorded. The accelerated cured specimens had acceptable strengths at just 1 day of curing, however, there is a void in knowledge on the effect of temperature gradient beyond the curing period on the durability and strength properties of the concrete.

Table-3: Compressive strength results for concrete curved by different curing methods (Pawar and Kate 2020)

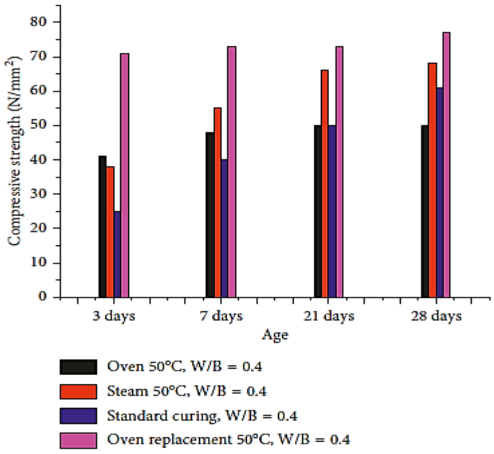
Curing methods		Immersion curing(N/mm²)			Wet gunny bag curing (N/mm²)			Accelerated curing (N/mm²)
Curing(in days)		7	14	28	7	14	28	1
Grade of concrete	M20	13.88	18.67	24.6	12.5	17.7	23.2	22.43
	M40	26.83	33.83	43.6	25.56	32.2	41.3	40.7

Wedatalla et al (2019) experimentally contributed on the concrete curing using steam and oven drying techniques. The impact of hot and dry environments under these curing conditions on the properties of high-strength concrete were studied. The authors also varied the w/cm ratios (0.30, 0.35, and 0.40), and incorporated (30%) fly ash for all mixes, and (0%, 5%, and 10%) silica fume with the binder (450, 480, and 520 kg), respectively. The concrete specimens were cast at a room temperature of 20°C. After casting, the concrete specimens were kept in the laboratory for 24 h until the casting moulds were removed. They were subsequently cured under four different curing conditions; conventional curing (ponding), steam curing at a constant temperature of 30°C or 50°C; Oven curing at 30°C or 50°C; and combined curing where cubes were initially cured for 3, 7, 21, and 28 days by ponding and further cured by oven (oven replacement) for additional 7 days at 30°C or 50°C

At the earliest recorded results (age 3days), oven dried and steamed samples were observed to perform significantly between in strength than the conventionally cured concrete specimens. This trend was not observed to be sustainable as the ages of curing increased to 7 and 28days for al w/cm ratios. All samples were observed to increase in strength with age, however, the effect of oven replacement, was seen to create a surge from as early as age 3 days with significant strength gain, superior to all other curing approaches. This is similar o the observations of Pawar and Kate (2020). However, in this case, it was evidently displaced that the accelerated hydration rate engineering by the combined curing approach, was not seen to depreciate in strength at latter ages, although, a very slight slope of strength gain was observed in compressive strength relative to other curing approaches.



A.



B.

Chart -7: Effect of Accelerated curing methods on long and short term strength of concrete (Wedatalla et al 2019)

3. CONCLUSIONS

Concrete curing mechanisms have been reviewed analytically from which the following conclusions are drawn;

1. Relative humidity is at the core of curing and is responsible for mitigating both autogenous as well as drying shrinkages in concrete
2. Ponding yet remains the most effective external curing mechanism, however, its predominance over other methods is close to insignificant, more so, it is limited to a penetration depth of about 1inch which greatly limits the C-S-H development during hydration.
3. Internal curing mechanisms such as LWA and SAP are more effective in the development of C-S-H gel when compared to external curing approaches.
4. There is need to specify a disparity between internal curing and self- curing concrete as shown by the effects of warm water curing and steam curing. Warm water curing and steam/oven curing cannot be categorized as external curing mechanisms, due to the accelerated development of C-S-H compound, indicating an enhanced internal activity beyond the active boundaries of external curing mechanisms.
5. Whilst self-curing mechanisms can be used to ascribed the desorbtive nature of LWAs, SAPs and other like materials, internal curing mechanisms could be classified as mechanically induced approaches such as warm curing, steam curing, oven curing and combined curing (ponding + steam curing).
6. Effective development of C-S-H compound in concrete expressly implies sound strength and durability properties of the concrete.
7. Further studies on warm water curing, steam curing and combined curing (ponding + steam curing) is recommended, with standard evaluation of development potentials of C-S-H compound over long- and short-term durations.

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