Comparative Study of Performance of Curing Methods for High-Performance Concrete (HPC)

Sandesh S. Barbole, Bantiraj D. Madane, and Sariput M. Nawghare

Abstract In this paper, the results statistical and graphical analysis of a comparative study of curing methods for high-performance concrete is discussed. The results are obtained from an experimental investigation carried out on concrete cubes. Mainly, two experiments were conducted: concrete cube strength test using a Compressive Testing Machine (CTM) and a permeability test. Concrete cubes of M35, M45, M50, M60, and M70 were cast and they were cured for 8 h, 3 days, 7 days, 14 days, 28 days, 56 days, and 128 days by three curing methods, namely, steam curing, water curing and sealing compound curing. By using results obtained from this experimental investigation is compared to find out the strength of concrete at the age of all curing periods mentioned above for individual grades of concrete. In addition, a comparison of the compressive strength of concrete with the early strength of concrete across all grades is investigated. Furthermore, a study on the percentage change in strength w. r. t. water is also conducted.

Keywords Steam curing · Water curing · Compound curing · Compressive testing machine (CTM) · Permeability test

1 Introduction

The quality, strength, and durability of concrete completely depend on the efficient continuous curing method. The method of curing depends on the nature of concrete,

S. S. Barbole (✉)
P.G. Diploma in Rail & Metro Technology (PGDRMT), College of Engineering Pune (COEP), Pune, India
e-mail: barboless19.pgdrmt@coep.ac.in

B. D. Madane
Maharashtra Metro Rail Corporation Limited (Maha-Metro), Pune, India
e-mail: bantiraj.madane@mahametro.org

S. M. Nawghare
College of Engineering Pune (COEP), Pune, India
e-mail: smn.civil@coep.ac.in

M. S. Ranadive et al. (eds.), *Recent Trends in Construction Technology and Management*, Lecture Notes in Civil Engineering 260,
https://doi.org/10.1007/978-981-19-2145-2_7

properties of concrete, application of concrete, the surrounding temperature, and relative humidity. It is essential to keep concrete moist and stop the loss of moisture from it, while it is gaining strength through the hydration process. There are many methods of curing, which are depending on site conditions and the requirement of construction. There are many arguments on which method of curing concrete gives good strength, therefore this topic has gained wide scope for research and application in the construction industry. There was much research conducted to find effective curing and the effect of type of curing on curing properties. Common properties of concrete, which are measures, are strength and permeability. Very few studies had been conducted on curing oh High-Performance Concrete (HPC). Site constraints restrict the curing by a conventional method, hence there is a need to explore and establish modern curing for high strength and performance of concrete.

The application of steam curing at atmospheric pressure to the curing chamber is one of the oldest and most widely used methods of accelerated curing of concrete. Under ideal conditions, the curing of concrete by steam at atmospheric pressure (low-pressure accelerated) has the advantage over other methods of accelerated curing in that the curing environment of the concrete is near saturation in regards to moisture. Evaporation of water from the products is minimized, which is especially important where products like block, pipe, etc. are involved. Although the steam curing of masonry units, pipe, and precast or prestressed concrete products follows the same basic rules, curing procedures are different for each. Heat transfer and evaporation will be fast. Pipe and precast products may be cured in a form where evaporation is minimum or may be of such large mass that heat transfer is slow, and large temperature gradients and resultant stresses may exist between the centre and the outside of the mass [1]. Steam curing has been used for many years. It is used to speed up the strength development of concrete products. With an increase in curing temperature, the rate of hydration of cement also increases. Therefore, the speed of strength gain of concrete can be increase with the help of steam curing [2]. The curing temperature has a huge influence on the strength development rate of concrete.

One of the major challenges is the lack of availability of Indian standard codes suitable for Indian climatic conditions for steam curing and compound curing. In order to study across all three methods, i.e., water curing, steam curing, compound curing we have referred IS 456(2000) for water curing, ASTM C 309 for compound curing, and ACI SP-32 for steam curing. Synchronization and simulation of practical conditions was the biggest challenge faced by us. This research will help in the standardization of Indian codes for steam and compound curing.

2 Literature Review

The following are the previous research reviews based on the effect of various curing methods on concrete properties.

Tan and Zhu [3] have studied the influence of curing methods and mineral admixtures on the strength and chloride permeability of concrete is discussed. Analysis was conducted by using results obtained from the experimental analysis. The chloride permeability of concrete was measured using rapid chloride ion penetration tests (ASTM C 1202). The results obtained by tests show that the compressive strength of plain concrete is decreased by 11% by steam curing. The reason for this decreased in strength was the use of slag, fly ash, and silica fume. However, after using autoclave, the strength of concrete surpasses 80 MPa. Compared with normal curing methods, steam and autoclave curing increases the electric charge passed through plain cement concrete by 110 and 224%, respectively.

Yazıcı and Arel [4] have investigated the effect of steam curing on mortar. Mortar includes mineral admixtures with 3, 1, and 0.5 of aggregate, binders, and water ratios are adopted. In mortars 0, 10, 20, and 30% of fly ash or 0, 5, 10, and 15% of silica fumes were used. 24, 48, and 72 h strength of concrete cubes were measured. This discussed accelerated curing temperature and early strength time is discussed according to compressive strength test results.

Mahmet Gesog Lu has discussed the influence of steam curing on the compressive strength, ultrasonic pulse velocity, water sortivity, chloride ion permeability, and electrical resistivity of metakaolin and silica fume blended concrete. Various combinations of Portland cement, silica fumes, and metakaolin are studied with constant water or binder ration. The use of silica fumes and metakaolin shows a decrease in water sorptivity and chloride ion permeability of concrete.

3 Methods of Curing

3.1 Water Curing

Water curing is the oldest and most common method of curing. In this method, concrete cubes are submerged in water for a designed period. We have done water curing has been done as per IS 456:2000. This method is commonly used in a laboratory. The main purpose of water curing is to continuously keep concrete in a moist environment. Another purpose of water curing is to maintain water temperature. Water curing plays a key role in the promotion of hydration, elimination of shrinkage, and absorption of heat of hydration. The temperature of the water should not decrease by 5 °C than the temperature of concrete. In water curing, cold water should not be used as it may give a thermal shock, which might lead to cracking. On-site, water curing is done by various methods like ponding, immersion, water spraying, wet covering, etc. Precast concrete structures are commonly immersed in water is adopted. The curing of vertical structures is usually conducted by spread curing. Wet curing is done by using gunny bags, hessian bags, jute matting, etc.

3.2 Compound Curing

Compound curing involves the application of the liquid sealing compound to the hardened concrete. It restricts penetration of liquids and gases, which might cause reinforcement corrosion, acid attack, and damages to concrete. There is a variety of curing compounds available on market. With the curing compound, conventional curing is also important. It forms a protective layer of moisture-retentive film over the concrete. Curing cannot be avoided with curing compounds. Curing compounds increase the durability of concrete. This curing compound must not be used over paint, additional concrete layer, or tiles. This method of curing is used at the site where there is a shortage of water. As Indian standards for compound curing are not yet been thoroughly defined, we have done compound curing as per ASTM C 309.

3.3 Steam Curing

Currently, the use of steam curing in the construction industry is increasing with the demand for rapid and speedy construction. The need for early and high-strength concrete is completed by this method of curing. It is mostly adopted for precast members where early high strength is required. It is executed by using water vapor at atmospheric or high pressure. Pressure is approximately between 40 and 70 °C (100–160 °F). In the steam curing procedure, it is suggested that to start the curing procedure a few hours after casting. This period is called as pre-steaming period, which can be from 2 to 6 h. Initial steam curing temperature starts with 10–20 °C and the maximum curing temperature permitted is 85–90 °C. Steam curing is very advantageous in a cold-weather environment. It is done with help of canvas covering or sheets to cover the structure and inside the covering, steam curing is taken place. As Indian standards for compound curing are not yet been thoroughly defined, we have done compound curing as per ACI SP 32 (Figs. 1 and 2).

4 Material Used for High-Performance Concrete (HPC)

The details of concrete mix design are given in Table 1.

Table 2 represents the properties of Fine Aggregates.

Table 3 represents the properties of Fine Aggregates.

Table 4 represents the properties of Cement.

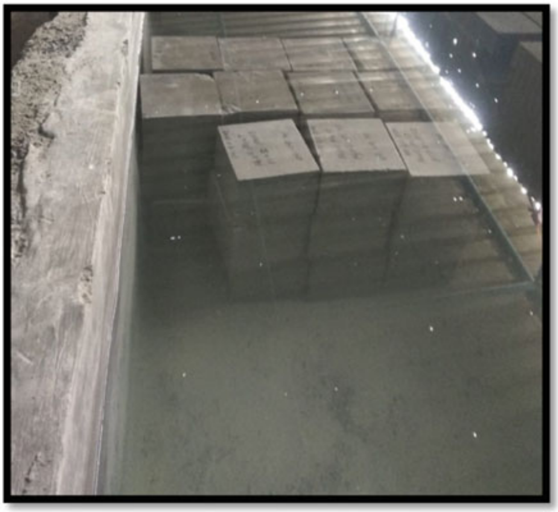


Fig. 1 Water curing by ponding

Fig. 2 Compound curing

5 Methodology for Concrete Mix of HPC

1. Identification of site for raw materials—various sites in the vicinity of the Pune area of Maharashtra, India are visited for suitable raw materials. While deciding on the suitability of raw materials following points are mainly considered.

    i. Availability of enough requirement of quantity required for research.
    ii. Materials having required properties as per IS2386.

Table 1 Material used for high-performance concrete (HPC)

Ingredients	Grades of concrete (N/mm^2)				
	M35	M45	M50	M60	M70
Cement OPC53	215	250	430	440	465
GGBS	215	230	70	35	NA
Microsilica	NA	NA	NA	25	35
20 mm down aggregate	814	758	782	788	778
10 mm down aggregate	349	357	368	371	366
Crusher sand	1006	832	832	832	827
Admixture dosage (%)	1.2	1.2	0.8	1.1	1.1
W/C ratio	0.40	0.36	0.29	0.28	0.29

Note Ingredient's weights are in kilogram (kg/m^3)

Table 2 Properties of fine aggregates

Sr. No.	Properties	Values
1	Bulk density (loose) (kg/m^3)	1650
2	Bulk density (compacted) (kg/m^3)	1770
3	Specific gravity	2.87
4	Water absorption (percentage)	3.12

Table 3 Properties of course aggregates

Sr. No.	Properties	Values
1	Bulk density (loose)	1678
2	Bulk density (compacted) (kg/m^3)	1800
3	Specific gravity	2.98
4	Water absorption	1.06

Table 4 Properties of cement (PPC)

Sr. No.	Properties	Values
1	Consistency (percentage)	28
2	Initial setting time (min)	135
3	Final setting time (min)	195
4	Compressive strength (MPa)	33
5	Fineness (m^2/kg)	290
6	Soundness (mm)	0.8
7	Density (g/cc)	3.14

   iii. Materials and water are free from impurities as well as located close to each other in order to reduce transportation costs to a lab

2. Based on the above factors site at Talegaon, Pune, Maharashtra India has been selected.
3. Raw materials, i.e., coarse aggregate, fine aggregate collected and tested as per IS 2386 for properties such as flakiness index, elongation index, sieve analysis for gradation of aggregates similarly cement is tested for soundness, Initial setting time, final setting time, etc.
4. Proportioning of aggregates on maximum density approach as per IS 2386. Admixtures and other materials are tested for the properties at the time of procurement from the vendor.
5. Now, for finalization of design mix, design is done according to IS10262 for grades M35, M45, M50, M60, and M70 at the same time relevant international codes such as ACI are referred for design. Trial mixes are carried out at the lab according to the design accordingly, mix design is finalized as per getting satisfactory results.
6. Both W/C ratio and Plasticizer dosage are finalized on the basis of mix design and trail mixes carried out consequently to get desired strength, i.e., M35, M45, M50, M60, and M70. Also, the study has been done on industrial practice which is currently being used for W/C ratio and Plasticizer dosage in the heavy civil industry to make the study practically viable.
7. Standard sized cubes are casted, i.e., 1 M $\times$ 1 M $\times$ 1 M. 80 no's of cubes are cast for each grade i.e., a total of 500 cubes are cast for grades M35, M45, M50, M60, and M70. The intention behind huge sampling was to reduce possible errors due to site handling and bring uniformity to the data.
8. Casting of samples is done at three different curing conditions, i.e., Steam curing, curing by using curing compound, and water curing.
9. Calibration of testing apparatus, i.e., Compression Testing Machine (CTM) is done before going for cube tests.
10. Testing of samples at age of 8 h, 3 days, 14 days, 28 days, 56 days, 90 days, and 180 days is performed as shown in the figure on CTM. Strengths got across different concrete grades and different curing conditions are will be discussed and interpreted further in this paper.
11. It is to be noted here that weather conditions are jot down at the time of casting of the cube, testing of cube whenever felt necessary to eliminate variations on the readings.

Fig. 3 Cube casting

6 Statistically and Graphical Analysis

6.1 Methodology

1. Compressive strength after 7, 28 days is plotted against M50, M60 design mix, respectively.
2. Results are compared with the target strength equation given by IS 10262:2019.

$$f''_{ck} = f'_{ck} + 1.65 \times S$$

where f'_{ck} = target mean compressive strength at 28 days, in N/mm^2;
f_{ck} = characteristic compressive strength at 28 days, in N/mm^2;
S = standard deviation (5 N/mm^2).

3. Finally, the graphical analysis is done (Figs. 3 and 4).

6.2 Results and Interpretations

6.2.1 Compressive Strength of Steam Curing, Water Curing, and Compound Curing

The compressive strength of M35, M45, M50, M60, and M70 of steam curing, water curing, and compound curing are given in Table 5.

Fig. 4 Cube testing

Comparative Interpretation Across the Different Grades

Table 5 and Graphs 1, 2, 3, 4, and 5 demonstrate strengths of concrete subjected to different methods of curings, i.e., water curing, steam curing, and curing using curing compound.

Horizontal Interpretation for All Grades for Early Strength

Early Strength (i.e., 8 h) achieved by steam curing varies between 32.12 and 19.61% (grades M35–M70). As grade of concrete is increased from M35 to M70 variation in the achievement of the early strength achievement decreases, i.e., difference between hydration of concrete decreases as the grade increases. When same conditions and grades are repeated for comparison of compound curing with water curing is found that early strength (8 h) found in the experimental test varies between 12.25 and 10.59% between grades M35 and M70. Here it can be deduced that early strength achieved by using steam curing is higher for all grades (Table 6) after which compound curing is found effective and water curing at last. This might be due to tricalcium aluminate (it has potential capacity to yield a high early strength.) formation reaction speeds up by steam curing due to steam temperature and ability to penetrate the concrete pores and carry out early hydration. In case of curing compound, reasons might be attributed to chemical properties of curing compound penetrate the concrete and speed up hydration of reaction forming tricalcium aluminate which in turn ends up adding to early strength of concrete [1–5].

Table 5 Compressive strength of concrete

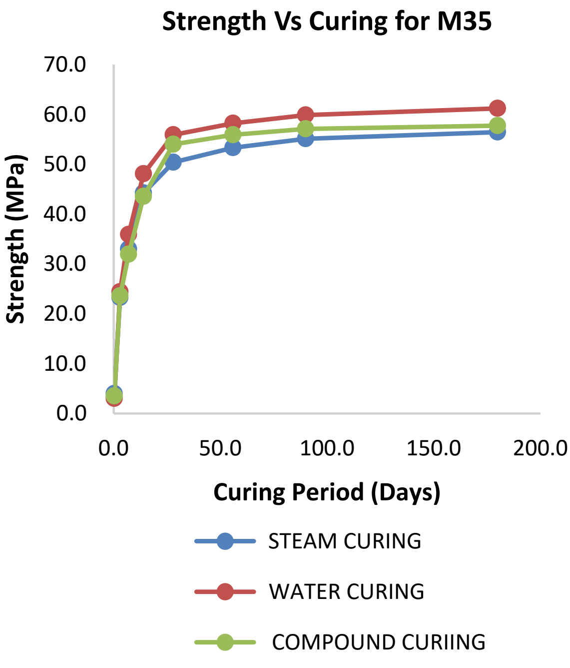
Grade of concrete	Curing in days	Compressive strength (MPa)		
		Steam curing	Water curing	Compound curing
M35	0.33 (8 h)	03.50	03.02	03.06
	3	23.27	24.40	23.58
	7	33.00	30.89	31.94
	14	44.25	40.10	43.53
	28	50.37	53.89	53.97
	56	53.30	58.20	55.89
	90	55.11	59.85	57.09
	180	56.46	61.20	57.74
M45	0.33 (8 h)	03.77	03.27	03.59
	3	31.88	33.30	20.77
	7	45.20	49.91	28.13
	14	60.61	59.60	38.33
	28	69.00	72.67	47.53
	56	73.01	80.22	49.23
	90	75.48	81.99	50.28
	180	77.34	83.91	50.85
M50	0.33 (8 h)	04.47	03.90	04.21
	3	33.15	38.5	33.10
	7	47.01	52.88	44.84
	14	63.03	69.35	61.10
	28	71.76	79.80	75.77
	56	75.93	83.90	78.46
	90	78.50	85.57	80.14
	180	80.43	87.19	81.05
M60	0.33 (8 h)	05.25	04.30	04.89
	3	34.13	42.81	36.77
	7	55.13	59.16	49.81
	14	76.13	78.16	67.87
	28	81.67	86.28	84.16
	56	83.87	93.40	87.15
	90	87.16	95.04	89.02
	180	88.88	96.43	90.03
M70	0.33 (8 h)	06.10	05.10	05.64
	3	42.70	45.14	44.60

(continued)

Table 5 (continued)

Grade of concrete	Curing in days	Compressive strength (MPa)		
		Steam curing	Water curing	Compound curing
	7	61.01	70.36	60.42
	14	81.80	84.93	82.33
	28	96.13	99.10	102.10
	56	103.70	114.40	105.70
	90	105.20	116.10	108.00
	180	107.61	117.40	109.20

Graph 1 Strength versus curing for M35

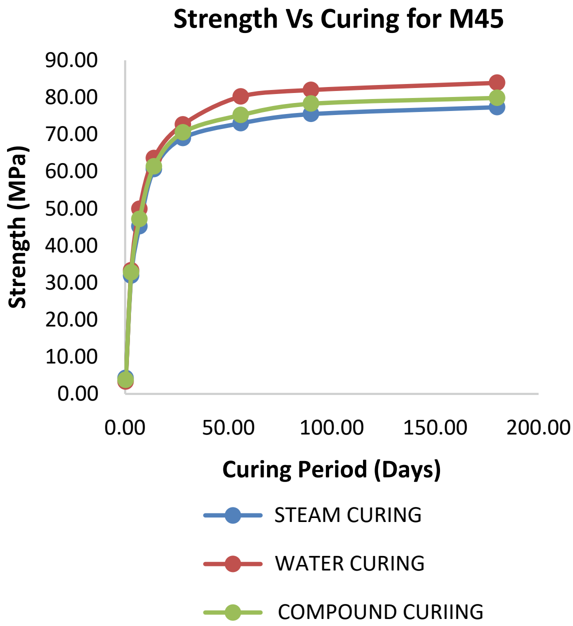


Hence, from above it can be deduced that early strength of concrete varies mentioned in the following order: **Steam curing > Compound curing > Water curing**.

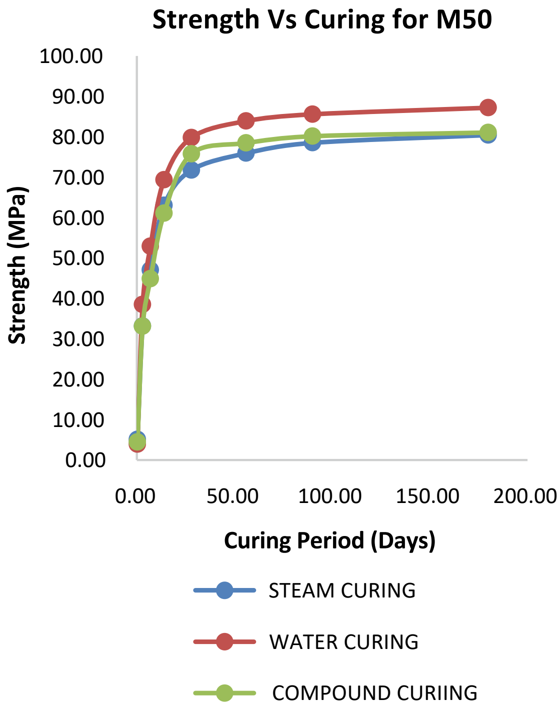
Horizontal Interpretation for All Grades for 28 and 180 days Strength

Cubes casted as mentioned in methodology, tested in parts according to requirement. 28 days strength of concrete by method of steam curing varies from −9.87 to −3% (−ve sign indicates % strength lower than water) lower than strength achieved by

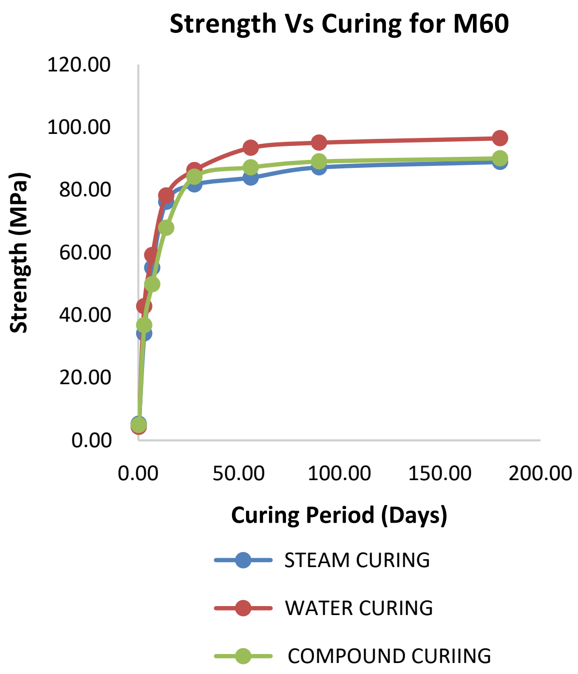
Graph 2 Strength versus curing for M45

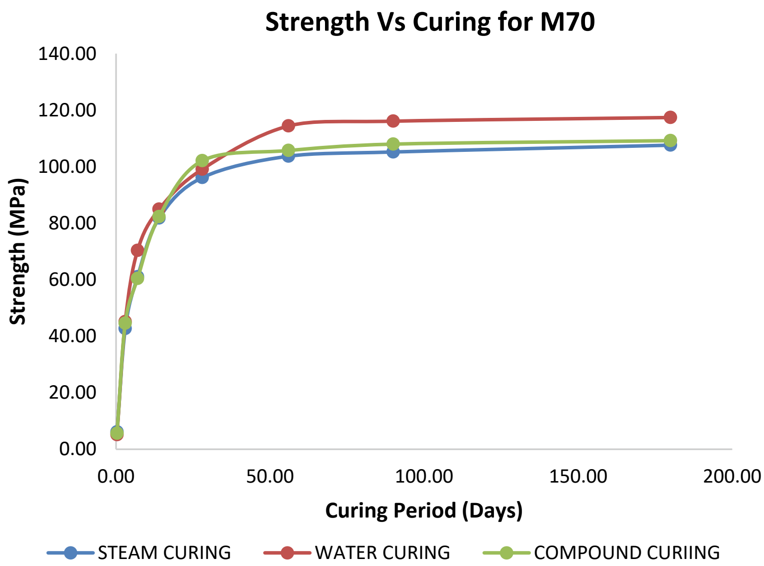


Graph 3 Strength versus curing for M50



Graph 4 Strength versus curing for M60





Graph 5 Strength versus curing for M70

Table 6 Percentage change in strength with water

Curing period	Percentage change in strength with water									
	Water curing versus steam curing					Water curing versus compound curing				
	M35	M45	M50	M60	M70	M35	M45	M50	M60	M70
0.33 (8 h)	32.12	30.28	30.77	22.09	19.61	16.56	15.29	14.54	13.72	10.59
3	−4.63	−4.27	−13.90	−20.29	−5.41	−3.36	−1.60	−14.03	−14.12	−1.20
7	−8.05	−9.43	−11.10	−6.81	−13.29	−10.99	−5.57	−15.20	−15.81	−14.13
14	−8.01	−4.70	−9.11	−2.60	−3.69	−9.51	−3.56	−11.90	−13.17	−3.06
28	−9.87	−5.04	−10.08	−5.34	−3.00	−3.43	−2.93	−5.06	−2.46	3.02
56	−8.42	−8.98	−9.50	−10.20	−9.35	−3.96	−6.23	−6.48	−6.69	−7.59
90	−7.93	−7.93	−8.26	−8.29	−9.39	−4.61	−4.52	−6.35	−6.34	−6.99
180	−7.75	−7.83	−7.75	−7.83	−8.34	−5.65	−4.84	−7.04	−6.64	−6.98

Note −ve sign indicate that strength is lower than strength achieved by water curing

water curing between grades M35 and M70. The reasons can be attributed to the rate of reaction of hydration of compound tricalcium alumina ferrite C3AF is higher in presence of water instead of steam, which in turn adds to later strength of the concrete.

From the above it can be deduced that long-term strength, i.e., 28 days is always greater for water curing than the other two methods of the curing, i.e., steam curing and curing by using curing compound. Strength of concrete 28 days varies in the following sequence:

Water curing > compound curing > steam curing

Experimental result at 180 days age of concrete, it is found that strength by using steam curing varies from −7.75 to −8.34% (−ve sign indicates percentage strength lower than water) lower than strength achieved by water curing between grades M35 and M70. In addition, at same conditions strength of concrete by using compound curing varies in the range of −5.65 to −6.98 (−ve sign indicates % strength lower than water) lower than strength achieved by using water curing [6–8].

In case of steam of curing reason for getting 28 days and 180 days strength lower than water curing can be attributed to rate of hydration reaction which forms **tricalcium alumino ferrite** C4AF which intern is responsible for development of later strength in concrete. In case of compound curing 28 days and 180 days strength is lower than strength achieved by water curing under same conditions can be deduced that compound contributing to latest strength of concrete, i.e., tricalcium alumino ferrite is formed at faster rate by water curing than compound curing [9, 10]. The reason might be attributed to continuous contact with water accelerates hydration reaction of formation of all 4 compounds C3S C2S C4A C4AF but steam curing and compound curing affect these rates differently. Compound responsible for early strength of concrete is formed at a faster rate in case steam curing, compound curing, and water curing respectively but as strength achieved over longer period is cumulative of all 4 compounds, which are better formed by water curing (Table 5).

Another notable observation is that strength achieved through experiment for same curing period, i.e., 180 days but across different grades of concrete, i.e., M35, M45, M50, M60, M60, and M70 variation from later strength (180 days) achieved by water curing later strength (180 days) of concrete increases as compared with respective grades of concrete in water curing (Table 5). As exact reason behind this behavior cannot be deduced from available research, it could be a potential gray area of the research.

Summary of Interpretation of All the Results

Water curing always beats the other two methods of curing when it comes to the later strength of the concrete (Tables 5 and 6). Compound contributing to early strength of concrete (**tricalcium alumino ferrite** C4AF) (8 h strength) is hydrated faster in the sequence of steam curing, compound curing, and water curing, respectively. But it is found that trend reverses in case of strength achieved in case of later strength (28, 180 days) in which sequence found to be water curing, compound curing, and stream curing, respectively. Hence, condition where water curing is feasible then the method should be preferred over the other two, i.e., steam curing and compound curing.

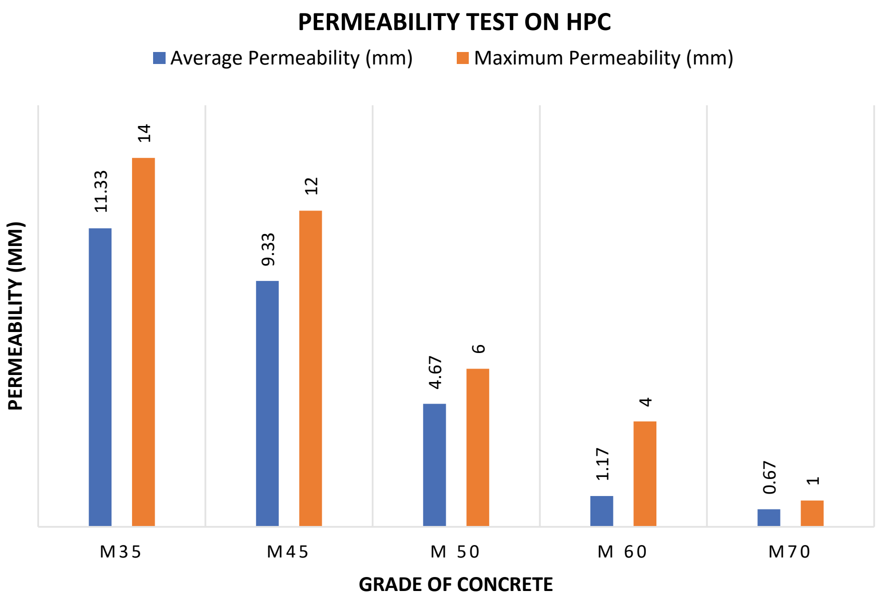
6.2.2 Permeability Test or Water Penetration Test

See Table 7 and Graph 6.

Permeability is directly proportional to the durability of concrete. For low-grade concrete, more water penetration results were obtained and for higher grades almost negligible water penetration shows. This shows that higher grade HPC has more resistance against hydrostatic pressure [11].

Table 7 Permeability test/water penetration text

Sr. No.	Grade of concrete	Penetration in mm	
		Average	Maximum
5	M35	11.33	14
6	M45	9.33	12
7	M50	4.67	6
8	M60	1.17	4
9	M70	0.67	1



Graph 6 Permeability test/water penetration text

7 Conclusion

It is found that early strength (8 h) by steam curing is in the range of 32–19% higher than water curing and early strength (8 h) achieved by curing compound is in the range of 17–11% higher than water curing also. Further, it is observed that 3, 28, and 180 days strength trend said above reverses, i.e., here strengths decrease in the range of 7.75–8.34% for steam curing and −5.65 to −6.98% for compound curing which implies that water curing is best as compared to other two in long term.

Horizontal comparison, i.e., across the grades for same age (M35, M45, M50, M60, M70) showed that achievement of strength varies inversely with the grades, i.e., strength achieved decreases w.r.t water curing as grade of concrete increases irrespective of age of concrete.

It is found that there is a direct correlation between permeability and grade of concrete, i.e., as grade of concrete increases permeability decreases which can be interpreted as concrete which is cured by different methods of curing will have permeability lower for higher grade of concrete which is achieved as per sequence mentioned in results point this paper.

7.1 Potential Applications of the Research Outcomes

1. The industries where achievement of the early lifting strength is important steam curing of the concrete could be done but concrete of higher grade than mentioned should be used in order to avoid effect on ultimate strength or if same grade is being used then it should be made sure that minimum required grade is being achieved for long term according to relevant standard codes at that place.
2. The situations where curing by using steam is not possible compound curing could be done by taking care of things said above.

References

1. Reported by AC1 Committee 5 17. Accelerated curing of concrete at atmospheric pressure-state of the art. Revised 1992
2. Gesoğlu M (2010) Influence of steam curing on the properties of concretes incorporating metakaolin and silica fume. Mater Struct
3. Tan K, Zhu J (2016) Influences of steam and autoclave curing on the strength and chloride permeability of high strength concrete. Springer
4. Yazıcı S, Arel HS (2016) The influence of steam curing on early-age compressive strength of pozzolanic mortars. Arab J Sci Eng
5. ACI Committee 305R-99 "Hot Weather Concreting" Reported by ACI Committee 305. ACI Manual of Concrete Practice (2009)
6. Goel A, Narwal J, Verma V, Sharma D, Singh B (2013) A comparative study on the effect of curing on the strength of concrete. Int J Eng Adv Technol (IJEAT)
7. Lee MG. Effect of steam-curing on the strength of precast concrete. In: Proceedings of the seventh international conference on composites engineering, ICCE, Denver, USA, pp 513–514
8. Singh DN, Pandey SP, Das BB (2014) Influence of initial curing humidity on compressive strength and ultrasonic properties of concrete. Indian Concr J 88(2):48–56
9. Williams RP, Van Riessen A (2010) Determination of the reactive component of fly ashes for geopolymer production using XRF and XRD. Fuel 89(12):3683–3692
10. Olivia M, Nikraz H (2012) Properties of fly ash geopolymer concrete designed by Taguchi method. Mater Des (1980–2015) 36:191–198
11. Lü J, Guan H, Zhao W, and Ba H (2011) Compressive strength and permeability of high-performance concrete. J Wuhan Univ Technol Mater Sci Ed 26