Concrete Hydraulic Curing Under Different Moisture Conditions

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Abstract The temperature and humidity conditions are extremely important for the normal reaction of cement hydration and concrete structure formation. Due to the fact that the influence of temperature in the literature has been considered in some detail and that it has less significance on changes in water tightness and concrete strength, the contribution of moisture conditions on the formation of concrete properties is considered in the article. The research was carried out both in the laboratory and on the building site.

Keywords Watertightness · Concrete · Strength · Normal conditions · Air-dry conditions

1 Introduction

Portland cement belongs to the hydration group of binders. The structure formation is due to the interaction of minerals in portland cement with water and their subsequent binding into insoluble crystalline hydrates. For most of the currently used concrete, the amount of mixing water in excess is sufficient for complete hydration of cement (if mixing water ratio more than 0.38), provided that part of it will not evaporate. In practice, however, as the concrete curing process is usually prolonged, evaporation from the concrete surface will occur when ambient moisture falls below 80%. Therefore, concrete should be cured in conditions that prevent the evaporation of water from the concrete body [1–3].

Normal and water-curing conditions are commonly used for concrete specimens. For precast structures and products heat and water curing are used (mainly reinforced concrete pipes and tunnel segments). In the case of cast-in-place concrete, curing compounds are used that prevent the evaporation of water. All these conditions have in common the fact that they aim to retain the concrete's own water in its body (with the exception of autoclave curing, where water is pressed through) [4].

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A. Mottaeva (ed.), *Technological Advancements in Construction*, Lecture Notes in Civil Engineering 180, https://doi.org/10.1007/978-3-030-83917-8_42

2 Normal Conditions

Normal conditions for concrete are considered: 95 ± 5% humidity and 20 ± 20 °C ambient temperature. Often normal conditions are created in special storage chambers for samples with the possibility of controlling the temperature and humidity of the environment. Since the air in the normal curing chamber is saturated with water vapor, there is no evaporation from the samples. Curing under normal conditions is regulated in a number of standards: GOST 10180, BS 1881-111, AASHTO T23.

3 Hydraulic Setting

Hydraulic setting of concrete is stipulated in the European standard EN 12390. The water temperature must be 20 ± 20 °C.

Once the concrete specimen has been stripped and placed in the water, the water protects the specimen from moisture loss. During the initial period, it is not possible to add water into the specimen, as the capillaries of the concrete are occupied by the concrete's "own" water. The water action of the pores then fills them during curing, due to cement setting and the creation of a vacuum in the contracting pores, in contrast to normal conditions where the contracting pores are filled with air. As for the capillary pores, the latter are filled with water from outside in an amount equal to the volume of water displaced into the contractile pores. The opinion of some experts about complete water saturation of concrete samples curing in water is erroneous, since the ambient water can penetrate into the sample only at higher pressure, as well as in the presence of free volume [5–10].

To study influence of humidity conditions on water impermeability, concretes with cement content 200–500 kg/m^3, curing under normal conditions ($T = 20 \pm 2$ °C, $\phi = 95 + 5\%$), in water ($T = 20 \pm 2$ °C, $\phi = 100\%$) and in air at $T = 20 + 5$ °C, $\phi = 30$–40%, where T—temperature, ϕ—humidity of environment were tested.

The following materials were used in this study: 5–20 mm basalt crushed stone from Yeghegi (Armenia), washed river sand (Plastic big bag = 2.6) and CEMII/A-P 42.5N Portland cement (Ararat factory). The basic composition of concrete: CS = 1110 kg/m^3, S = 740 kg/m^3, C = 360 kg/m^3, W = 0.64 (according to variation of cement consumption, the composition of concrete was changed correspondingly), where CS—Crushed stone, S—sand, C—cement, W—water. In all cases mobility of concrete mixtures was 20–21 cm.

4 Methods

For each cement consumption 9 cylinder specimens were made, 3 of which were cured in water, 3 under normal conditions and 3 in air. After curing for 28 days under appropriate conditions, the concretes were tested for water penetration depth. The water tightness grade, water penetration rate on the Germann GWT-4000 and water absorption of the concrete were also determined. The test results are shown in Tables 1, 2, 3, 4, 5 and in Fig. 1.

Table 1 Results of EN12390-8 water tightness tests on cylinder specimens

Cement consumption, kg/m^3		200	240	280	320	360	380	400	450	500
Water penetration depth, mm	Normal curing	125	123	95	64	61	62	57	59	61
	Hydraulic curing	124	122	75	47	24	30	36	37	38
	Air curing	>150	>150	>150	141	102	104	109	103	113

Notes - Each result is an average of 3 samples
- Result >150 means that signs of filtration were observed on the top end of the samples until 72 h had elapsed.

Table 2 Increased permeability of concrete (several times) compared to hydraulic curing (according to Table 1)

Cement consumption, kg/m^3	200	240	280	320	360	380	400	450	500
Hydraulic curing	1	1	1	1	1	1	1	1	1
Normal curing	1.01	1.01	1.27	1.36	2.54	2.07	1.58	1.59	1.61
Air curing	>1.21	>1.23	>2	3	4.25	3.47	3.03	2.78	2.97

Table 3 Results of water tightness tests for cylinder specimens according to GOST 12730.5

Cement consumption, kg/m^3		200	240	280	320	360	380	400	450	500
Water resistance grade	Normal curing	W2	W4	W6	W10	W12	W12	W12	W12	W12
	Hydraulic curing	W2	W4	W10	W14	W16	W18	W18	W18	W18
	Air curing	<W2	<W2	<W2	W2	W6	W6	W6	W6	W6

Note - The series consists of 6 samples

Table 4 Results of Germann GWT-4000 water infiltration rate tests

Cement consumption, kg/m^3		200	240	280	320	360	380	400	450	500
Water infiltration rate, mm/s	Normal curing	1.04×10^{-3}	9.54×10^{-4}	6.40×10^{-4}	4.60×10^{-4}	4.60×10^{-4}	4.56×10^{-4}	4.50×10^{-4}	4.64×10^{-4}	4.65×10^{-4}
	Hydraulic curing	1.01×10^{-3}	9.26×10^{-4}	4.92×10^{-4}	3.94×10^{-4}	2.99×10^{-4}	3.08×10^{-4}	3.12×10^{-4}	3.35×10^{-4}	3.45×10^{-4}
	Air curing	9.44×10^{-3}	9.01×10^{-3}	9.08×10^{-3}	2.26×10^{-3}	7.04×10^{-4}	7.12×10^{-4}	7.95×10^{-4}	7.20×10^{-4}	8.08×10^{-4}

Note - Each result is an average of 3 samples

Table 5 Test results for water absorption of concrete by mass

Cement consumption, kg/m^3		200	240	280	320	360	380	400	450	500
Water absorption by mass, %	Normal curing	5.91	5.85	5.10	3.98	3.92	3.95	3.90	3.94	3.95
	Hydraulic curing	5.84	5.74	4.35	2.94	1.05	1.10	1.32	1.45	1.36
	Air curing	8.05	8.12	7.56	6.54	5.10	5.08	5.78	5.60	5.80

Note - Each result is an average of 3 samples

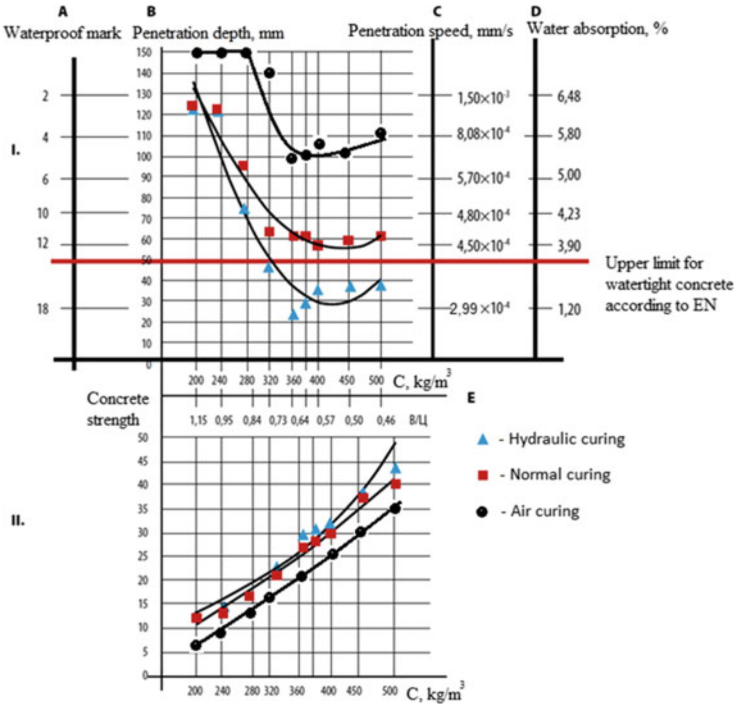

Fig. 1 Change of hydrophysical and mechanical properties of concrete depending on curing conditions. I-Hydrophysical properties of concrete A-E change in concrete waterproof mark, B-E change in water penetration depth, C-E change in Germann water penetration speed, D-E change in concrete water absorption II- change in concrete strength

5 Results and Discussion

It follows from the above results that the curing conditions of concrete have a strong influence on its water tightness. Thus, if we compare the water hardening and curing under normal conditions, it follows that at a cement content of 200–240 kg/m^3 no difference in permeability of concrete is observed. It is obvious that at high V/C relations the capillary sizes are so large that even the water hardening, which predetermines a more optimal regime for structure formation, is not able to reduce the average capillary radius.

The difference between these curing conditions can already be observed from a cement content of 280 kg/m^3. With the appropriate V/C ratio the capillary size decreases and the advantage of aqueous curing becomes evident. With increasing cement content the difference between aqueous and normal hardening increases proportionally. Thus, taking aqueous curing as the basic method, depending on the cement content, the permeability of concrete in normal hardening increases by a factor of 1.27–2.54 and that in air curing by a factor of 3–4.25 (Table 2). As for water impermeability grades it follows that water hardening increases them by 2–3 steps in comparison with normal hardening and by 4–6 steps in comparison with air hardening.

Similar results are observed when testing the water permeation rate and the water absorption of concrete on a mass basis. Thus, the water penetration rate during air curing increases by one order of magnitude in almost all cases compared to water curing and normal curing.

Considering the results of the strength change depending on the curing conditions it follows that the difference between aqueous and normal curing over the whole cement content interval does not exceed 2 MPa (Fig. 1). Consequently, the effect of moisture conditions on the mechanical properties, in contrast to hydrophysical conditions, is minimal. Also a lower loss of strength compared to the water tightness is observed for air-cured concretes.

The water hardening of the samples, however, creates some uncertainty for the evaluation of concretes of real structures. For example, according to the guidelines of the German Reinforced Concrete Committee, concrete is considered water impermeable if the depth of water penetration under pressure (according to EN 12390-8) does not exceed 50 mm. An examination of the data in Table 1 shows that starting from a cement content of 320 kg/m^3, the same concrete, depending on the curing conditions, is considered to be waterproof in one case (water curing) and not waterproof in the other case (normal conditions). As will be shown below, under actual construction site conditions, the moisture conditions are at best close to normal (when properly maintained). This applies in particular in dry, hot climates. The hydro-physical properties of water-curing concrete are therefore not precisely correct.

The above results were obtained by testing concrete specimens curing under laboratory conditions. To investigate the change of properties under real site conditions, the following tests were carried out.

From a production mix of concrete (composition: CS = 1000 kg/m^3, S = 920 kg/m^3, C = 300 kg/m^3, SP-3 kg/m^3, W = 210 l/m^3) were made the samples-cylinders 150 × 150 mm for determination of water resistance and samples-cubes 150 × 150 × 150 mm for determination of strength of concrete from calculation:

- The 3 cylindrical and cubic samples were left in moulds outdoors for 28 days after manufacture, in a dry, hot climate (average daily temperature $T = 30 \pm 2$ °C, humidity $\phi = 30\%$).
- 3 cylindrical and cubic samples were cured under laboratory conditions in water ($T = 20 \pm 1$ °C, $\phi = 100\%$).
- 3 cylindrical and cubic specimens were cured under laboratory conditions under normal conditions ($T = 20 \pm 1$ °C, $\phi = 100\%$).
- 3 cylindrical and cubic specimens were cured in water under construction site conditions ($T = 30 \pm 2$ °C, $\phi = 100\%$). This curing method is used in American concrete quality control practice.

In this study the following materials were used: crushed stone basalt 5–20 mm of Yeghegi deposit, washed river sand (Plastic big bag = 2.6), Portland cement CEMII/A-P 42.5N (Aratarat factory), superplasticizer Rheobuild 561 (based on naphthalene-sulfoformaldehyde). A 600 mm cubic specimen was produced in parallel, the purpose of which was to increase the size (and volume) of the specimen while leaving the surface modulus at the same level. The day after concrete pouring this block was unpacked and cured for 28 days in the open air after which 3 cores 15 and 10 cm in diameter and 30 cm in length were selected from the block in the direction of concreting for testing for water resistance and durability respectively. The cores were then sawn into 15 cm height specimens to test the properties of the top layer, which was directly exposed to the sun, and the inner layer. The watertightness tests for concrete were carried out according to EN 12390-8 and on the Germann GWT-4000 (Fig. 2) [11]. The test results are shown in Table 6.

The results show that outdoor curing of cylindrical and cubic specimens strongly affects the water resistance of concrete, reducing it by more than 3 times compared to water-curing specimens. The loss in strength in this case compared to water-curing specimens is 13% and 7% under normal conditions. For cores taken from a large

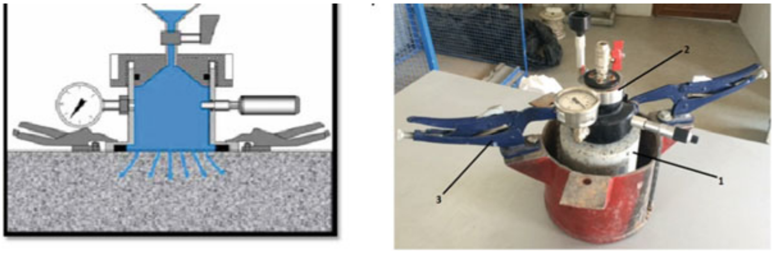

Fig. 2 a) General scheme of the Germann GWT-4000, b) Concrete water penetration rate test. 1-concrete sample, 2-installation GWT-4000, 3-clamps.

Table 6 Test results for hydrophysical and mechanical properties of concrete

Type of samples	Concrete curing conditions	Depth of water penetration under pressure, cm (EN12380-9)	Speed of penetration, mm/s	Water resistance grade	Strength, MPa
Cylindrical and cubic samples	**In the water** T = 20 ± 3 °C (temperature) ϕ = 100% (humidity)	39	3.00×10^{-4}	W16	27.0
	In the water (at the construction site) T = 30 + 2 °C ϕ = 100%	42	4.05×10^{-4}	W16	26.0
	Normal T = 20 ± 2 °C ϕ = 95 + 5%	73	4.11×10^{-4}	W12	25.1
	In outdoor moulds T = 30 + 2 °C ϕ = 30%	128	2.07×10^{-3}	W4	23.4
Cores drilled from a 600 × 600 mm cube curing outdoors	**Top layer 15 cm** T = 30 + 2 °C ϕ = 30%	78	6.03×10^{-4}	W10	21.2
	Bottom layer 15 cm T = 30 + 2 °C ϕ = 30%	52	4.98×10^{-4}	W12	24.9

cubic block, the results for the upper layer of concrete (15 cm) are 200% higher than water-curing specimens and 6% higher than normal curing specimens. For the bottom layer of the block drilled to a depth of 30 cm the permeability of the concrete is 33% greater than that of the samples cured in water and 29% less than that of the samples cured under normal conditions.

When comparing the permeability results between samples and a large block, a large difference is observed, even though the surface modulus is at the same level. It is obvious that the permeability of concrete is not influenced more by the surface modulus, but by the volume of the specimen or structure being manufactured.

As can be seen from the results, the curing environment of concrete specimens has a strong influence on the water tightness of concrete. GOST 18105-2010 "Concretes. Rules of control and estimation of strength" provides curing of test specimens directly in the conditions of construction site in the conditions similar to the conditions of hardening of structures [12–15]. This method is also widely used in American

Fig. 3 Water hardening of concrete specimens under construction site conditions

practice of concrete quality control [16]. Only in contrast to GOST 18105 where the specimens are simply protected from moisture loss, in American practice the specimens are cured in a tank of water (Fig. 3).

On the basis of the results given above, these methods can only be applied for the determination of strength, as they give fairly reliable information. With regard to the water tightness of concrete, this method is not acceptable: specimens that are cured under site conditions (partially protected against moisture loss) have a permeability almost twice as high as real structures, and specimens that are cured in water (under site conditions) show underestimated permeability results [17–20].

Reliable results for the water tightness of concrete are only obtained if the specimens are cured under normal moisture conditions (humidity greater than 95%). In addition, the difference between water-curing and normal-curing results depends on the amount of cement, and the higher the cement content of the concrete, the greater will be the difference from the real permeability value (Fig. 1).

6 Conclusions

- Humid storage conditions have a strong effect on the water resistance of concrete.
- The water-curing concretes have the highest relative density. The permeability of the latter is 1.27–2.54 times lower than that of normal concretes and 3–4.5 times lower than that of air-cured concretes.
- The difference between the strength of concrete curing in water and under normal conditions is negligible.
- Air-dry conditions have a strong effect on the permeability of concrete, increasing it by more than 50% compared to normal-cured concrete.
- The permeability of concrete is strongly dependent on the volume of concrete laid. As the volume increases, the negative effect of the hot climate decreases.
- For checking the permeability of concrete in dry, hot climates, only normal moisture curing of specimens is acceptable.

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