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Impact of curing conditions for concrete on its mechanical properties

Joanna Witkowska-Dobrev[1], Olga Szlachetka[2], Paulina Spiek[3]

[1] *Warsaw University of Life Sciences – SGGW;*
Nowoursynowska St. 166 , 02-787 Warsaw, Poland;
joanna_witkowska@sggw.edu.pl iD *0000-0001-6613-5037*
[2] *Warsaw University of Life Sciences – SGGW;*
Nowoursynowska St. 166, 02-787 Warsaw, Poland;
olga_szlachetka@sggw.edu.pl iD *0000-0002-1195-3603*
[3] *Warsaw University of Life Sciences – SGGW;*
Nowoursynowska St. 166, 02-787 Warsaw, Poland;
paulina_spiek@sggw.edu.pl

Abstract: This paper aims to present the results of compressive strength tests of concrete specimens, prepared according to two recipes, after 2, 7 and 28 days of maturing in four different environments. The concrete specimens had the same w/c ratio, the same amount of aggregate of particular fractions, the addition of a superplasticizer, but they differed in the cement type. In one recipe, the Portland cement CEM I 32.5R was used, in the other – pozzolanic ash cement CEM IV/B(V) 32.5R-LH/NA. Concrete specimens with dimensions of 100 x 100 x 100 mm made according to both recipes were placed in individual ripening environments: in cuvettes with water, soaked and wrapped with construction foil, left in room conditions in the laboratory, placed outside the laboratory and being exposed to the atmospheric conditions. The obtained compressive strength results confirmed that the best way of curing concrete is the wet cure (in cuvettes with water). It has been proven that the choice of proper curing method is key in terms of compressive strength.

Keywords: concrete care, compressive strength, Portland cement, pozzolanic cement

1. Introduction

Concrete consists of products of simple physical and chemical structure, however, the course of concrete mix production requires great attention and accuracy [1] [2]. Mistakes made at the initial stage of concrete mix production may have negative consequences at subsequent stages of construction. Therefore, the basic procedure to be performed in the early period of concrete "life" is its maintenance. Its main purpose is to ensure optimal thermal and moisture conditions for the maturing concrete and to protect it from the harmful effects of atmospheric conditions, so as to minimise plastic shrinkage, ensure appropriate strength and durability of the surface zone, minimise thermal stress and protect it from freezing, vibrations, impacts and damage [3].

It is highly recommended to start the process of proper care as early as possible. Otherwise, there will be negative irreversible processes, which the subsequent care will not be able to eliminate (Fig. 1).

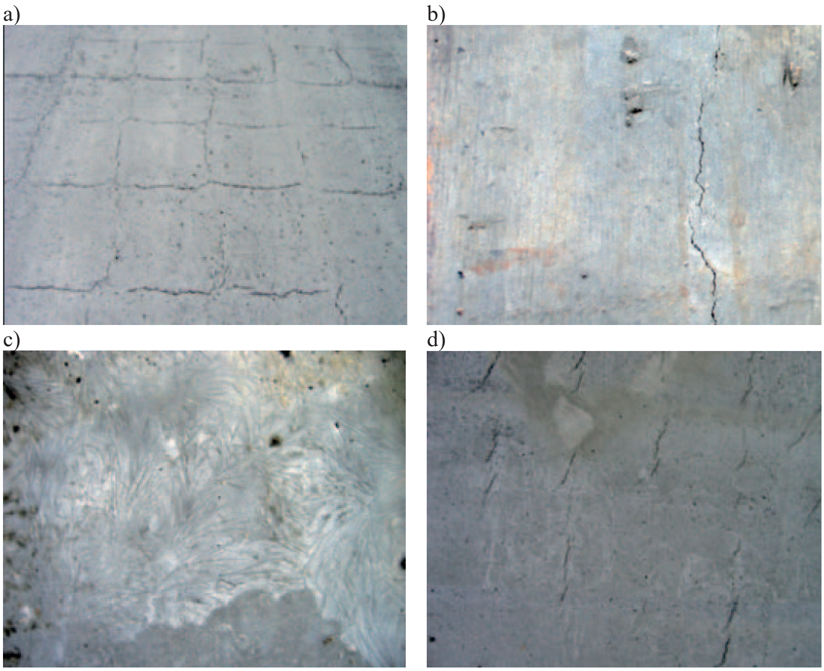

Fig. 1. Effects of poor concrete care: a) cracks in the bridge slab due to plastic shrinkage, b) cracking of the tank wall due to contraction of the hardening, c) damage to the concrete surface due to freezing of fresh concrete, d) scratches in the bridge slab due to vibrations from the adjacent bay during concreting. *Source:* [4]

The basic methods of concrete care during the summer are [5]:

- sprinkling the concrete surface with water (wet care),
- laying wet mats on the concrete surface and keeping them moist,
- covering the surface of wet concrete with construction foil,
- coating the concrete surface with care products with specific properties,
- concreting in tents ensuring proper temperature and humidity,

In the winter season, the care consists in [5] [6]:

- securing the concrete element with heat-protective materials, e.g. polystyrene foam, mineral wool, bubble wrap,
- concrete heating by air, steam, heating mats, electric current, infrared heaters or electromagnetic field,

- concrete in tents to ensure proper temperature and humidity,
- using special formworks.

proper care is also affected by admixtures of various kinds which have the task to modify properties of a concrete mix and/or a hardened concrete, so as to facilitate placing concrete in winter or in high temperatures. When the concrete is being made in winter, aerating admixtures are applied which enable introducing tiny air bubbles during mixing, hence improving the concrete frost resistance. Still, though less frequently due to the progress in the concrete manufacturing technologies, admixtures are applied in winter which accelerate the concrete bonding and hardening.

If the concrete is placed in high temperatures, when – for example – layers of the concrete being placed must bond to each other, retarding admixtures are applied which have to retard the cement bonding process, hence prolong the liquidity period of a concrete mix [7].

The above mentioned measures, especially in the case of "winter" care, can be applied individually or in combination depending on the prevailing conditions.

The improper cure negatively affects the concrete properties, especially its compressive strength. For example, lack of the frost protection retards the hydration process in the concrete and reduces assumed utility properties of the concrete, including compressive strength, and can also evoke exfoliation of the concrete surface as well as scratching and cracking. Increased temperature in the initial phase of concrete maturation, in turn, speeds up the cement hydration process which results in shorter concrete bonding time and faster strength development – what can result in lower compressive strength. Fast evaporation of water from the concrete mix can be also a reason for plastic shrinkage cracking [5].

The problem of improper concrete care and concrete samples taken at the construction site, were pointed out in the paper [8]. As the authors show, the problem of improper sample care, i.e. inconsistent with the standard, often occurs [9]. Improper care of concrete samples often results from the inability to guarantee the required storage conditions or is caused by negligence (Fig. 2). This results in underestimation of the measured compressive strength.

Fig. 2. Incorrect storage of concrete samples. *Source:* [8]

The pace of the compressive strength increase depends on many factors – apart from the content of the concrete mix, curing conditions are important.

The aim of the research was to check the influence of the care method on the compressive strength of ordinary concrete samples based on Portland cement and pozzolanic ash.

2. Materials and methods

So as not to restrict the investigations to one particular case, the batches were made for two concrete mix formulas using different types of cements, in aim to highlight the fact that modification of the concrete mix content through the change of the cement type can positively or negatively affect properties of the hardened concrete depending on the way of curing. For one recipe CEM I 32.5R cement was selected. This formula obtained the symbol R1. For the second one, CEM IV/B (V) 32.5R – LH/NA cement was used and this formula was named R2. CEM I 32.5R is produced by the Ożarów S.A. cement plant, while CEM IV/B (V) 32.5R – LH/NA is a pozzolanic cement from Lafarge. The compression strength classes of cement after 28 days are defined by the 32.5R symbol. The letter R indicates early high strength, the LH symbol indicates low hydration heat and the NA symbol indicates low alkali oxide content.

CEM I 32.5R according to [10] is characterized by moderate hydration heat, moderate dynamics of early strength build-up, wide compatibility and moderate dynamics of cooperation with chemical admixtures for concrete and mortar. Whereas CEM IV/B (V) 32.5R – LH/NA according to the manufacturer [11] is characterized by stable strength increase and increased strength during long periods of maturation. Due to low hydration heat this cement reduces the risk of shrinkage cracks. It is also characterized by good plasticity, workability and pumpability of the concrete mix. Average values of physical and chemical properties of the cements according to the manufacturers' data are presented in Tab. 1.

Table 1. Physical and chemical properties of the cements. *Source:* [10], [11]

Physical/chemical property	CEM I 32.5R	CEM IV/B (V) 32.5R – LH/NA
Specific surface	3300 cm^2/g	4303 cm^2/g
Start of bonding time	210 min	266 min
End of bonding time	300 min	363 min
Compressive strength after 2 days acc. to PN-EN 196-1	21 MPa	14.1 MPa
Compressive strength after 28 days acc. to PN-EN 196-1	45 MPa	38.5 MPa
Specific density	3.05 g/cm^3	2.71 g/cm^3
Water demand	26 %	32.3 %
Sulfate content (as SO_3)	3.17 %	2.71 %
Chloride content (as Cl_-)	0.080 %	0.061 %
Alkali content (as Na_2O_{eq})	0.78 %	1.53 %

The strength class was assumed as C20/25 and the exposure class – XC1. The composition of formulas (Tab. 2) was selected so that the consistency was malleable, i.e. that according to the slump test [1] [12] the fresh concrete had the consistency class S2 and the so-called bleeding phenomenon, i.e. occurrence of water on the sample surfaces caused by separation of concrete components, did not occur.

Table 2. Components of concrete mixes. *Source:* [14]

Ingredient	Amount [kg/m³]	
	Formula 1 (R1)	Formula 2 (R2)
CEM I 32.5R	280	-
CEM IV/B(V) 32.5R – LH/NA	-	280
Fractional aggregate 0-0.125 mm	40.8	40.8
Fractional aggregate 0.125-0.25 mm	40.8	40.8
Fractional aggregate 0.25-0.5 mm	97.15	97.15
Fractional aggregate 0.5-1 mm	198.75	198.75
Fractional aggregate 1-2 mm	377.5	377.5
Fractional aggregate 2-4 mm	163	163
Fractional aggregate 4-8 mm	510	510
Fractional aggregate 8-16 mm	612	612
Water	140	140
CHRYSO®Optima185 superplasticizer	0.0616	0.039

In aim to make both mixes, a coarse-grained natural aggregate with maximum grain diameter D_{max} = 16 mm was used. It was composed of two aggregate sets: fine, of fraction 0 ÷ 2 mm, and coarse, of fraction 2 ÷ 16 mm. The percentage of individual fractions in the given mix was: 2% of the fraction 0 ÷ 0.125 mm, 2% of the fraction 0.125 ÷ 0.5 mm, 7% of the fraction 0.125 ÷ 0.5 mm, 9% of the fraction 0.5 ÷ 1 mm, 18% of the fraction 1 ÷ 2 mm, 8% of the fraction 2 ÷ 4 mm, 25% of the fraction 4 ÷ 8 mm and 30% of the fraction 8 ÷ 16 mm. The obtained fines curve of the aggregate falls between the limit curves (Fig. 3). The superplasticizer CHRYSO®Optima 185 was added to both mixes. It is an agent reducing water content and produced from modified polycarboxylates and phosphonates. It prolongs the period of maintenance of a given consistency and influences good workability of a concrete mix without bonding retardation effect [13]. The ingredients of the recipes were then mixed in a mechanical mixer (concrete mixer). At first, sand and gravel was poured, then a half of water, then the cement. The agent was added to the remaining half of water and the water was poured gradually till a homogeneous mass was obtained.

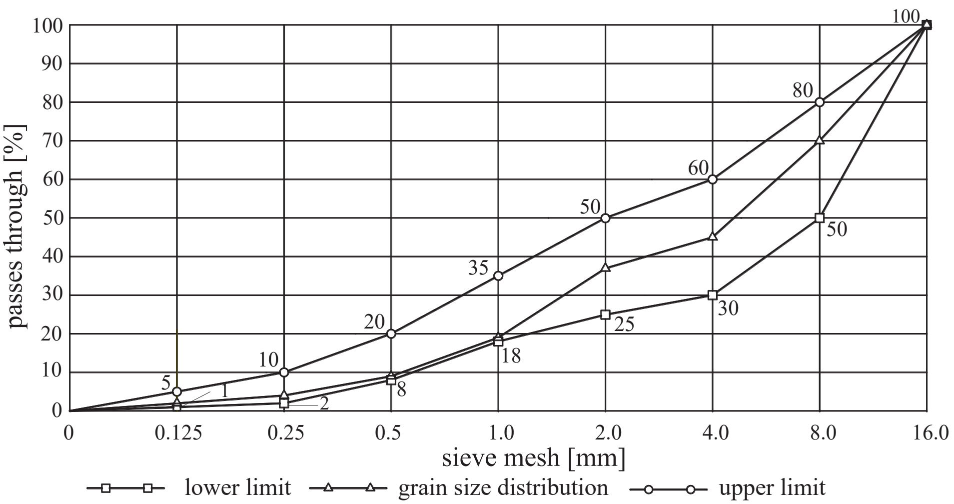

Fig. 3. Upper and lower limit curves of grain size and grain size distribution curve of aggregate. *Source:* Author's own study

The samples were formed in 100x100x100 mm moulds. After forming, the samples were stored for 24 ± 4 hours in a laboratory at 20 ± 2 °C and 40 % humidity. After this time the cubes were disassembled and placed in appropriate ripening environments. Concrete samples were stored: in water trays (A), soaked and wrapped in building film (B), in dry "room" conditions in the laboratory room (C) and in weather conditions outside the laboratory (D). The maturation conditions of the samples are shown in Tab. 3.

Maintenance in water sought to prevent drying shrinkage. It is used at high temperatures, strong sunshine and strong and warm winds to avoid drying out. As a consequence of this type of care, the hydration process may be disturbed.

The curing by soaking and wrapping in construction foil was designed to ensure that the heat released by the hardening concrete is maintained and to prevent water evaporation from the concrete. Unfortunately, this type of care can cause discoloration due to uneven condensation of water vapour on the surface of the membrane adjacent to the concrete.

Table 3. Maturation conditions of samples. *Source:* Author's own study

Description of ripening environment	Description of sample storage environment	Temperature [°C]	Humidity [%]
A	in water according to PN-EN 12390-2 [9]	20 ± 2	100
B	in the laboratory, soaked and wrapped in construction foil	20 ± 8	around 80
C	in a laboratory in a "room" environment	20 ± 5	around 40
D	outside the laboratory building in atmospheric conditions (September 2018) [15]	max. 29 min. 3 average 16	max. 91 min. 56 average 73
		number of rainy days 10	

Samples stored in room temperature in the laboratory were not exposed to changes in thermal and humidity conditions, while samples stored outside the laboratory were exposed to random thermal and humidity conditions depending on the prevailing weather (temperature, humidity, rain). Adequate control over them was lacking.

3. Research results and analysis

Compressive strength tests were performed after 2, 7 and 28 days according to the standard [16]. The value of strength was determined according to the formula:

$$f_{c,cube(150mm)} = 0.95 \cdot f_{c,cube(100mm)} \tag{1}$$

In Tabs 4-5, apart from the ratio of average compression strength after 2 days to average compressive strength after 28 days, which is a measure of the development of concrete strength, the ratio of average compression strength after 7 days to average compression strength after 28 days is shown.

Table 4. Compressive strength ratio $f_{cm,2}/f_{cm,28}$ and $f_{cm,7}/f_{cm,28}$ and density of hardened concrete after 2, 7 and 28 days of curing in different conditions samples for R1 formula. *Source:* Author's own study

Formula R1		Care			
		A	B	C	D
Compressive strength (f_{cm}) in MPa after:	2 days	28.7	28.3	24.3	24.0
	7 days	33.0	32.5	29.8	31.9
	28 days	**43.5**	**36.6**	**36.2**	**39.2**
Relation	$f_{cm,2}/f_{cm,28}$	0.66	0.77	0.67	0.61
	$f_{cm,7}/f_{cm,28}$	0.76	0.89	0.82	0.81
Endurance development		fast	fast	fast	fast
Density ρ kg/m³ in	2 days	2360.9	2352.4	2314.4	2346.8
	7 days	2334.9	2337.5	2337.3	2348.4
	28 days	2354.7	2342.0	2284.3	2319.2

Although as per the standard classification according to the parameter $f_{cm,2}/f_{cm,28}$ the development of strength for samples made in accordance with both formulas and stored in all analysed ripening environments can be assessed as fast, because always $f_{cm,2}/f_{cm,28} > 0.5$, however this parameter assumed different values depending on the type of cement and care. After analysis of the value of the parameter $f_{cm,2}/f_{cm,28}$, it can be seen that the care method has a greater influence on the development of strength in the case of formula R2 – the value of this parameter ranges from 0.57 for wet care (in water) to 0.81 for dry care in an indoor environment.

Table 5. Compressive strength ratio $f_{cm,2}/f_{cm,28}$ and $f_{cm,7}/f_{cm,28}$ and density of hardened concrete after 2, 7 and 28 days of curing in different conditions samples for R2 formula. *Source:* Author's own study

Formula R2		Care			
		A	B	C	D
Compressive strength (f_{cm}) in MPa after:	2 days	25.5	25.9	26.9	26.3
	7 days	37.0	35.7	30.5	30.2
	28 days	**44.6**	**40.3**	**33.2**	**38.9**
Relation	$f_{cm,2}/f_{cm,28}$	0.57	0.64	0.81	0.68
	$f_{cm,7}/f_{cm,28}$	0.83	0.89	0.92	0.78
Endurance development		fast	fast	fast	fast
Density ρ kg/m³ in	2 days	2378.3	2317.4	2319.2	2329.1
	7 days	2335.9	2331.8	2303.8	2302.3
	28 days	2397.9	2328.5	2307.4	2357.0

The development of compressive strength is faster with R1 for wet care (A) and film care (B), while for dry room care (C) and weathering (D), R2 concrete has a faster strength development. However, after 28 days it was the samples according to the R1 formula that reached higher compressive strength values than those made according to the R2 formula under storage conditions C and D. This is due to the type of cement used. The effect of the used type of cement on the increase in compression strength is highlighted by comparison of the ratios $f_{cm,2}/f_{cm,28}$ and $f_{cm,7}/f_{cm,28}$. In the case of wet care (in water) the ratio $f_{cm,7}/f_{cm,28}$ informs that after 7 days the strength development for R2 samples is faster, although the ratio $f_{cm,2}/f_{cm,28}$ for R1 was higher than for R2. Eventually, the samples from R2 formula reached a higher compressive strength value. For foil care the ratio $f_{cm,7}/f_{cm,28}$ is the same for both formulas, although also the ratio $f_{cm,2}/f_{cm,28}$ for R1 was higher than for R2. Cement in R2 formula has lower hydration heat, therefore, in undisturbed care conditions, and as such can be considered conditions A and B, in the first 2 days the strength gain was at a lower level. For dry indoor care, the $f_{cm,7}/f_{cm,28}$ ratio is still higher for R2 formulation samples as was the case with the $f_{cm,2}/f_{cm,28}$, ratio, but the final value of compression strength, i.e. after 28 days, is 3 MPa lower for samples made according to this formula than for R1 formulation samples. For weathering treatment the ratio $f_{cm,7}/f_{cm,28}$ for R1 is higher than for R2, although for this treatment the ratio $f_{cm,2}/f_{cm,28}$ was higher for R2.

To sum up, samples with ash cement with low hydration heat due to ash content are more exposed to temperature fluctuations. As the temperature increases, the hydration process accelerates and the strength of the young concrete increases, but this ultimately negatively affects the final compression strength. The cement hydration can progress properly only if the water amount in the mixture is greater than the amount of already bonded water.

The highest compressive strength after 28 days is achieved with samples stored in water. In the case of film care – for samples with CEM I 32.5R cement the difference in compressive strength after 28 days is 7.3 MPa compared to samples stored in water, and for samples with CEM IV/B (V) 32.5R – LH/NA the difference is 4.5 MPa.

It is worth noting that the values of compressive strength after 28 days for the samples based on the R1 formula stored in the foil and stored under room temperature conditions are practically the same, whereas in the case of the samples based on the R2 formula, there is a clear difference between the values of compressive strength after 28 days concerning the samples maintained in the foil and stored under room temperature conditions – by 7.5 MPa (see Fig. 4). This is, as indicated earlier, due to the type of cement used.

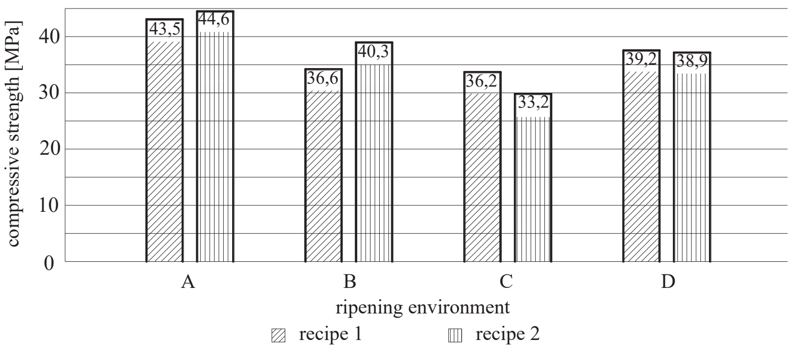

Fig. 4. Compressive strength value of samples after 28 days of care in given environments. *Source:* Author's own study

However, the compressive strength values of the samples from the two formulae, when stored outdoors in the weather after 2, 7 and 28 days, do not differ much from each other. The compressive strength after 28 days is higher for this treatment than for room temperature care and for R1 than for foil care. This was caused by the favorable conditions for accelerated hydration – the average daily outdoor temperature remained at the level of 18-22 °C for 12 days and was lower than 10 °C for only 4 days, similarly, the average daily humidity – for only 3 days was lower than 60 % [15]. It is worth emphasizing that in the case of these maturation conditions, the results obtained are closely related to the conditions occurring outside the laboratory in a given month.

4. Conclusion

The use of cement of even the best quality may become irrelevant if it is not properly cared for. In the case of water, foil and weathering treatments, concrete with CEM IV/B (V) 32.5R – LH/NA cement has a higher compressive strength. Only in the case of samples stored under dry conditions in a laboratory room, the samples with CEM I 32.5R had a higher compressive strength, this was due to the relatively low air humidity maintained at about 40 %, to which, as it turns out, pozzolanic ash cement with low hydration heat is sensitive.

The analysis of the obtained results indicates that for both types of concrete tested the best way of care from the point of view of the compressive strength value is wet care, which is quite an obvious conclusion. The lowest compression strength values were obtained for samples maintained in dry conditions (inside the laboratory). This is due to the evaporation of more water from the samples.

In summary, it can clearly be stated that both the composition of the concrete mixture and the way the concrete is cared for are crucial with regard to the compressive strength after 28 days.

On a construction site, after removal from moulds, the test specimens should be cured in water at a temperature 20 ± 2 °C. Loss of moisture and deviations from the required temperature should be avoided at all stages of transport of the specimens to laboratory. The most advantageous way is packing the specimens in plastic bags containing water or, if a transport distance is not large, wrapping the specimens in a foil to protect them against dehydration.

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