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The effect of real curing temperatures on early age concrete strength development in massive concrete structures

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ABSTRACT

At the early maturity stage, the curing temperature has a significant impact on the mechanical properties of concrete. Concrete cubes are cured in water baths at different temperatures—5 °C, 20 °C, 35 °C, and 50 °C—in order to measure their compressive strength. This method is predicated on the knowledge that the pace of cement hydration is strongly influenced by the curing temperature. Then, the realistic curing temperature regime was imposed where the temperature of the curing water was modified based on the temperature patterns obtained from semi-adiabatic testing of concrete mixes to simulate curing conditions in the core of massive concrete structures. Ordinary Concrete: Compared to specimens cured at an isothermal curing at 20 °C, those cured in water baths at realistic curing showed an increase in compressive strength of 48% at seven days and 18.5% at 28 days. Fly Ash 18% Replacement: Compared to specimens cured at at 20 °C, the compressive strength of those cured at realistic curing increased by 45% at seven days, with a modest rise of 0.2% by the 28th day. Slag 18% Replacement: Compared to specimens cured at 20 °C, the compressive strength of those cured at realistic curing increased significantly by 121% at seven days and by 21.7% at 28 days.

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KEYWORDS
Early age concrete strength; curing temperature; maturity development; equivalent age of concrete

1. Introduction

1.1. Scope and motivation of the research

Engineers are frequently worried about the influence of curing on strength, both in the literature and in practice (Bushlaibi, 2004; Taylor, 2013), as the research shows that poor curing quality leads to a significant loss in strength. This is not surprising, given that the key feature of concrete which affects system performance, especially in structural design, is its strength.

It has long been recognized that the temperature and moisture content of concrete play a critical influence in the hardening process and, as a result, in strength development. Early testing showed that high temperatures increased strength. However, later tests found that continued high curing

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temperatures lowered the strength. The words 'cross-over effect' and 'COE' are used to describe this phenomenon. Curing at high temperatures has been linked to a loss of strength (Nurse, 1949; Saul, 1951; Yousuf et al., 2019; Zeyad et al., 2022). According to Zeyad et al. (2022) and Kjellsen et al. (1990) greater curing temperature resulted in increased porosity and coarser pore structure, which could explain the reduction in strength with age.

The issue of strength evolution complicates further in mixed binders with significant additions of slowly reacting pozzolans such as fly ash and slag. The use of the addition of this supplementary cementitious materials is widespread as their incorporation in cement production and their use as partial replacements in concrete results in technical and environmental advantages and provides economic efficiencies, aligning with the wider objectives of sustainable development (De Belie et al., 2018; Cement, 2019). In addition to their environmental benefits, these materials play a crucial role in reducing the thermal effects of the hydration process, particularly in preventing delayed ettringite production and other unfavourable effects related to generation of huge amount of hydration heat, especially in massive concrete structures (Eduardo & Azenha, 2019). It is also important to mention that there is a significant delay in the cross-over effect when the amount of cement substituted by fly ash is increased (De Belie et al., 2018; Elsageer, 2011).

Typically, the characteristics of concrete are evaluated in controlled laboratory settings with constant temperature conditions of 20 °C (Fib Bulletin No. 70, 70, 2013; Neville, 2011). While In Sweden, Luleå university procedure, concrete cubes are cured in water baths at different temperatures—5 °C, 20 °C, 35 °C, and 50 °C—in order to measure their compressive strength. This method is predicated on the knowledge that the pace of cement hydration is strongly influenced by the curing temperature. Strength usually develops more quickly at higher temperatures because they speed up hydration responses. Curing at temperatures between 35 °C and 50 °C, for instance, can improve the production of hydration products and raise compressive strength. Lower temperatures, like 5 °C, on the other hand, have a tendency to slow down these reactions, which results in a delayed strength increase. These requirements serve as the fundamental framework for designing and assessing the risk of cracks under realistic temperature situations. Nevertheless, isothermal testing approaches fail to consider the significant impact of temperature on the rates at which pozzolanic materials such as fly ash and slag respond. While these materials may initially underestimate the heat output, they ultimately contribute to increased concrete strength in subsequent phases (Al-Gburi & Yusuf, 2022; Krauss & Paret, 2014). In addition, the standard curing temperature of 20 °C does not accurately reflect the actual thermal conditions experienced by concrete in the early stages of its formation. Concrete in massive structures can reach temperatures exceeding 50 °C (Eduardo & Azenha, 2019; Klausen et al., 2018; Möller et al., 1982). Using a maturity temperature of 20 °C frequently leads to an excessively cautious safety buffer, thereby increasing the related expenses. Because of the impact of high temperatures during the initial stages of hydration, the actual compressive strength of massive structures is substantially higher than that of concrete cubes cured at 20 °C. As a result, less reinforcement may be used. To avoid the additional cost of a high safety factor, it is desirable to realistically represent concrete curing temperatures (Waller et al., 2004).

As a consequence, this work aims to develop a 'realistic curing' technique which will more closely mimic concrete's temperature exposure in the real-world structural applications – especially for concrete structural elements with important massivity (Av Jean-Louis Tailhan, 2022). The goal is to create a curing method which can be adjusted to suit different types of concrete compositions, presenting a solution to the cross-over effect. Two main questions serve as the basis for the investigation:

1. What is the behaviour of concrete at a curing temperature which follows realistic temperature trajectories, wherein the exothermic hydration process causes an initial rise, which is then gradually decreased until the material reaches equilibrium with ambient atmospheric conditions?
2. When using fly ash or slag in place of some or all of the conventional cementitious ingredients, how does applying this realistic curing strategy affect the mechanical characteristics of concrete—specifically, its compressive and tensile strengths?

1.2. The study's objective

This article aims to investigate the impact of high temperatures generated within massive concrete elements during early hydration on the mechanical characteristics of various concrete mixes. Concrete exposed to high temperatures at early ages has a substantially different compressive strength than concrete cured at typical curing temperatures of 20 °C. Furthermore, through this research, it is possible to ascertain the true mechanical properties of concrete, which can be leveraged in the design of concrete elements based on their actual compressive strength. This strength is typically greater than that of concrete samples cured under isothermal conditions at 20 °C, which does not reflect the real strength of massive concrete structures. The novelty of the study is that it is now possible to build massive concrete structures with a true compressive strength, which allows for a reduction in the amounts of reinforcement steel utilised, as well as a drop in the quantities of cement required to reach the appropriate compressive strength.

1.3. Influence of curing temperature on strength development

One useful method for showing how concrete strength has increased is the maturity function. Saul (1951) developed the idea of maturity to describe how temperature affects the way concrete qualities change over time. His maturity approach states that regardless of their temperature histories, samples of a given concrete gain the same strength when equal maturities are reached. The time-accumulated excess of the current temperature, (*t*), above a threshold temperature, T_0, below which hardening would not occur, is the maturity of concrete:

$$M = \int_0^t (T(t) - T_0)\mathrm{d}t \tag{1}$$

Rastrup first proposed the idea of the equivalent age as a more computationally practical substitute for maturity (Rastrup, 1954). According to Hansen and Pedersen's proposal (Hansen & Pedersen, 1977), the equivalent age was determined by applying the Arrhenius law to determine how long the concrete would need to cure at a constant reference temperature, or *T*-ref., in order to reach the same maturity as the concrete going through the actual curing history.:

$$t_{\mathrm{eq}}(t, T) = \int_0^t \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}}\right)\right]\mathrm{d}t \tag{2}$$

The concept of the equivalent age has been widely accepted for modelling of the temperature dependence on the strength development of concrete, and implemented also in design standards, including Eurocode 2 (EN 1992-1-1, 2004, 2023). It must be emphasised, however, what most design methods fail to acknowledge, that the rate of maturity gain depends strongly on the activation energy, which depends on the binder composition. The activation energy differs for ordinary Portland cement (OPC) and binders with pozzolanic additions, which explains slower strength development of mixed binders. The design standards, such as Eurocode 2, provide a simplified form of Equation (2) by assuming the $T_{\mathrm{ref}} = 20°C$ and $E_a/R = 4000$ [1/K]: where: K: represents temperature in Kelvin Ea: the activation energy of the hydration process in cement, R: the universal gas constant.

$$t_{\mathrm{eq}}(t, T) = \sum_{i=1}^{n} \Delta t_i \cdot \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)}\right] \tag{3}$$

while experimental evidence shows that the value of E_a/R can reach as much as 7000 [1/K] for slag (Fernández-Jiménez & Puertas, 1997) and 8000 [1/K] for fly ash (Biernacki et al., 2001). With an increasing use of mixed binders it is, therefore, important to explicitly use the actual value of the activation energy in calculations.

2. Experimental set-up

2.1. Materials and experimental program

The experimental program was performed the Luleå University of Technology (LTU), Sweden.

Construction cement, also known as anläggningscement (ANL), is a particular variety of Portland cement that is mostly utilised in medium-to-coarse construction projects. It is appropriate for situations where temperature variations could cause cracking because of its modest heat generation during curing. 5% fly ash is added at the factory while cement is being made. The study included three concrete mixes: ANL Ref, ANL FA18, and ANL Slag18, with total fly ash and slag content expressed as a replacement percentage of cement weight. Table 1 shows the detailed concrete compositions.

The reference concrete, ANL Ref, was created using 430 kg/m3 of OPC. The ANL FA18 concrete was made by substituting additional FA 1:1 by weight for cement, with cement weighing 353 kg/m^3 and fly ash weighing 77 kg/m^3. The fly ash concentration indicated the percentage of fly ash replaced by cement in the ANL FA18 mix, which followed a specified weight ratio. The cement was substituted with an equivalent amount of fly ash to reach the necessary 18% fly ash content, and the water-to-binder ratio was meticulously maintained at 0.379. Portland–fly ash cement manufactured at the Slite plant, denoted as Anläggningscement FA, was used (Cementa, n.d.). Analogically, the ANL Slag18 concrete was produced by replacing cement with slag 1:1 by weight, cement 353 kg/m^3, and Slag was 77 kg/m^3, while keeping the water-to-binder ratio constant. The water-to-binder ratio in the concrete was 0.379. The temperature variation during realistic curing was determined using a semi-adiabatic test for each mix, as shown in Figure 1.

2.2. Samples preparation and testing

The testing process followed a predetermined order of steps. Phased casting was the result of the mixer's 68-liter capacity constraint. All concrete combinations, including the reference mix and those with 18% slag and 18% fly ash replacements, were subject to the same methods.

The first step was to cast a 10-liter concrete batch for semi-adiabatic calorimetry and another 15-liter batch for the TSTM tests. The next step involved casting concrete cubes meant to be used to evaluate splitting tensile and compressive strengths, and assigning them to the water tanks with varying temperatures in line with the set temperature histories.

2.3. Testing procedures

2.3.1. Early-age strength development under various curing temperatures

The aim of this testing program was to determine the influence of various curing temperatures on early-age strength development of the analysed concrete mixes. The test was performed for 7 days after casting of the samples.

The tests were performed on cubic samples cured in water tanks. Each tank had a different temperature, with one tank at 20 °C for reference, and other tanks at, respectively, 5 °C, 35 °C, 50 °C, see Figure 1 and a 'realistic tank' which followed the adiabatic curve temperature, See Figure 2. The 5 °C container was used for maturity tests simulating casting in cold weather. The second and third container were for the assessments of the elevated temperature impacts on concrete strength development. Finally, the temperature-regulated curing tank was used for 'realistic temperature' profile to recreate the thermal profile retrieved from the semi-adiabatic calorimetry measurements (shown in Figure 2).

2.3.2. Long-term strength development under realistic curing temperature

The aim of this test was to investigate the influence of the curing temperature on the long-term development of concrete strength. The test was performed on all three analysed mixes for up to 90 days after casting of the samples. The system was calibrated based on the temperature reference curve obtained

Table 1. The ANL concrete compositions.

Materials	Density kg/m^3	ANL Ref	ANL FA18	ANL Slag18
Cement, kg	3050	430	353	353
Fly ash, [kg]	2300	0	77	0
Slag, [kg]	2890	0	0	77
Water, [kg]	1000	163.5	163.5	163.5
Sand 0–8 mm, [kg]	2690	989.7	976.6	986.8
Sand 8–16 mm, [kg]	2690	746.6	736.7	744.0
Master Glenium 592, [kg]	1050	4.09	4.09	4.59
Master Air 105, [kg]	1000	1.183	1.484	1.2

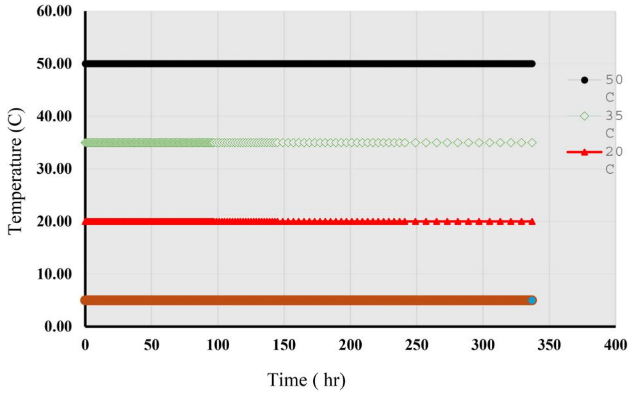


Figure 1. The curing of concrete cubes at different water temperatures.

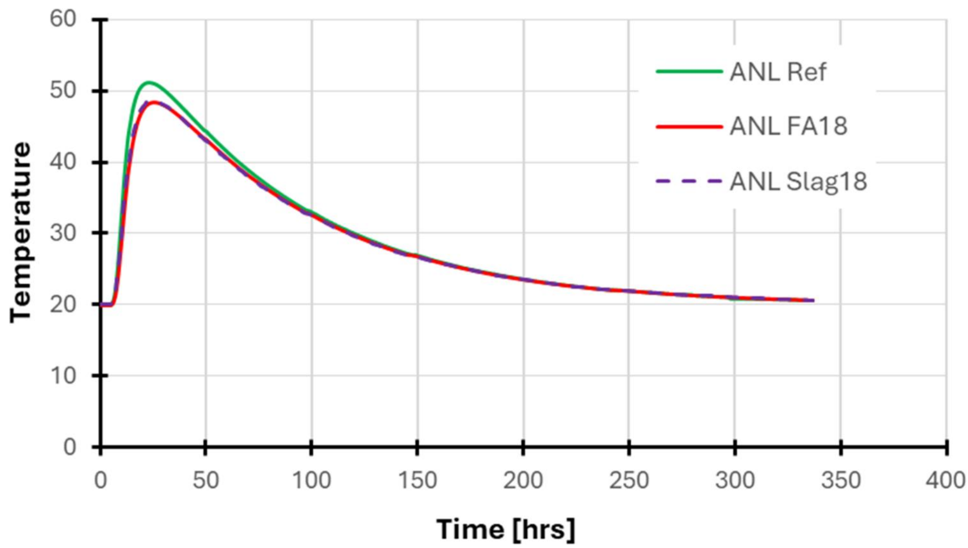


Figure 2. Temperature changes over time for different concrete mixes in adiabatic testing.

from semi-adiabatic calorimetry, as shown in Figure 2, to simulate the realistic core temperature in the massive concrete element.

2.4. Semi-adiabatic test

The semi-adiabatic test measures the temperature increase brought on by cement hydration and is mostly employed in the field of concrete technology. This test provides a more realistic knowledge of how concrete will perform in real-world situations by simulating conditions that are very similar to those seen in actual building locations. Although it is not a common practice to measure heat of hydration, it is critical when cement is given for a large concrete structure with significant massivity (Av Jean-Louis Tailhan, 2022). In such structures, a high rate of heat evolution during the early stages of cement hydration resulting in an extreme temperature differential between the surface and the structure's core must be avoided, or else forces sufficient to induce cracking may occur (Eduardo & Azenha, 2019).

Semi-adiabatic calorimeter tests were conducted on 10-liter samples to quantify the concrete's hydration heat evolution. To simulate the actual heat conditions that the concrete will be subjected to at the site, the temperature evolution of the three different concrete mixtures was measured by the semi-adiabatic test and applied as a maturity function to a realistic treatment where the temperature of the treated water was changed by the temperature change from semi-adiabatic test.

The experimental technique followed the methodologies specified in the Luleå University of Technology (LTU) scope, as described in reference (Fjellström, 2013). The results of the semi-adiabatic temperature measurements are collectively depicted in Figure 2. The analysis of the collected data revealed temperature variation curves, showing peak temperatures of 51 °C at 23 h for ANL Ref, 48.6 °C at 25 h for ANL FA18, and 49 °C at 25 h for ANL Slag18. The experimental design involved testing specimens under several semi-adiabatic curing settings, each mimicking the temperature changes experienced by a piece of a 700-mm-thick wall in a typical Swedish summer climate (Fjellström, 2013). Replacing 18% of the cement with fly ash or slag did not significantly decrease peak thermal values. This fact aligns with the conclusions made by De Belie et al. (2018), indicating that these modifications, although ecologically advantageous, do not effectively reduce the high temperatures generated during cement hydration.

2.5. Methodology for strength determination

2.5.1. Compressive strength and splitting tensile strength

Compressive strength and splitting tensile strength development were measured on water-cured cube samples of 100 mm × 100 mm × 100 mm dimensions. The 100 mm cube is the typical test specimen for compressive strength in Sweden. The compressive strength was evaluated in compliance with the SE-EN 12390-3:2019 standard (SE-EN 12390-3, 2019), and pertinent sample characteristics, including mass, volume, and compressive strength, were carefully recorded. The splitting tensile strength of concrete was measured by applying a vertical compressive force to the cubic concrete specimen placed with its axis horizontal between the testing machine's metal plates (ASTM International, 2017; SE-EN 12390-3, 2019).

Compressive strength development was also calculated using the formula from EN 1992-1-1:2004 for all three mixes (EN 1992-1-1, 2004):

$$f_c(t,T) = \beta_{cc}(t_{\mathrm{eq}}) \cdot f_{c,28} \tag{4}$$

where 28-day compressive strength was taken as the one measured for the analysed concrete in 20 °C isothermal conditions, equivalent age was calculated using Equation (3) with $E_a/R = 4000$ [1/K] and shape parameter s in time-development function β_{cc} was assumed based on the binder used in the mix:

$$\beta_{cc}(t_{\mathrm{eq}}) = \exp\left(s\cdot\left(1-\sqrt{\frac{28}{t_{\mathrm{eq}}}}\right)\right) \tag{5}$$

The assumed model parameters are collectively presented in Table 2.

Tensile strength development was first investigated on cubic samples; thus, the measured tensile strength was a splitting tensile strength. The relationship between the mean and splitting tensile strength has been experimentally established as (Thermal Cracking of Massive Concrete Structures, State of the Art Report of the RILEM Technical Committee 254-CMS, 2018; Testing Fresh Concrete Part 2: Slump-test, XXXX).

$$f_{ctm} = 0.9 f_{ctm,\mathrm{split}} \tag{6}$$

with splitting tensile strength calculated from Equation (7).

$$f_{ct,\mathrm{split}} = \frac{2F}{\pi A} = 0.637\frac{F}{A} \tag{7}$$

where F – the maximum applied load recorded by the device, kN. A – area of the specimen, mm^2.

The new version of Eurocode 2—EN 1992-1-1:2023 [24] proposes the following formula for time-development of tensile strength, analogical to that proposed for the compressive strength in Equation (5):

Table 2. Parameters used for calculation of compressive strength development according to EN 1992-1-1:2004 for the analysed mixes.

	ANL Ref	ANL FA18	ANL Slag18
$f_{c,28}$, MPa	54.5	50.4	53.0
s	0.2	0.25	0.25

$$f_{ct}(t,T) = \left[\beta_{cc}(t_{eq})\right]^{0.6} \cdot f_{ct,28} \tag{8}$$

The faster development of tensile strength is reflected by introduction of the 0.6 exponent in the time-development function β_{cc}. Modifications have also been introduced in the definition of the values of shape coefficient s in β_{cc} (see Equation (6)), which for normal strength concretes is advised to take values between 0.2 for high early-strength development binders to as much as 0.5 for low early-strength development binders.

It was not possible to test splitting tensile strength at curing temperatures of 5 °C, 20 °C, 35 °C, and 50 °C since the mixing machine's capability could not allow larger volumes. Samples were therefore only tested in realistic temperature conditions. Each result was an average of three cubic tests.

To satisfy the requirements of a particular concrete recipe, such as slump consistency and air content, in compliance with standard procedures (Staquet & Delsaute, 2020; Testing Fresh Concrete Part 7: Air Content-Pressure Methods, XXXX), At LTU, the cumulative mixing duration is set at seven minutes. In the mixer, the dry components were mixed for three minutes, followed by four minutes of adding water and additions. It takes about 30 min under typical conditions from the beginning of the sample casting to its placement in temperature-controlled water containers. After the components were cast, the cube moulds were opened 24 h later and kept in water until testing.

2.5.2. Tensile strength with TSTM

The evaluation of the characteristics of concrete was performed utilising the state-of-the-art Temperature–Stress Testing Machine (TSTM). To gain a thorough comprehension and delve into the finer aspects of the TSTM testing method, readers are advised to consult the reference (Wieslaw, 2014). The equipment available at LTU comprises rectangular hollow steel beams, precisely VKR 450 × 250 mm profile with a steel thickness of 16 mm, as seen in Figure 3. In the testing process, a concrete beam with a length of 1000 mm and a square 150 mm cross-section was used. The concrete was poured directly into the framework, and great care was taken to seal the formwork to prevent moisture loss after casting. The air fan system was used to regulate the concrete specimen's interior temperature accurately.

The experimental setup involved firmly attaching one end of the specimen to the frame and then securely attached to the ground. Meanwhile, the other end of the specimen was free to move longitudinally. During the thermal expansion of the concrete specimen, the servo-hydraulic cylinder, which has a force capacity of ±750 kN, counteracted this by pushing the movable end back to its initial position to keep the length of the specimen constant. In contrast, during the contraction phase of the specimen in the cooling stage, the cylinder operated to retract the moveable end to its original position. The specimen's length was carefully monitored and controlled using a displacement gauge, which recorded the relative movement of the mobile end between the stationary end and the ground. This gauge played a crucial role in regulating the length adjustment mechanism.

3. Results and discussion

3.1. Compressive strength of concrete under different curing temperatures

3.1.1. Early-age compressive strength

Figure 4 presents diagrams of early-age compressive strength development in time for three analysed mixes under various curing temperatures (5 °C, 20 °C, 35 °C and 50 °C) as well as under realistic

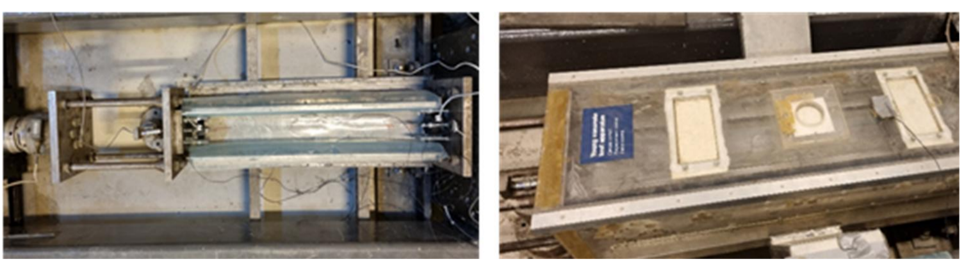
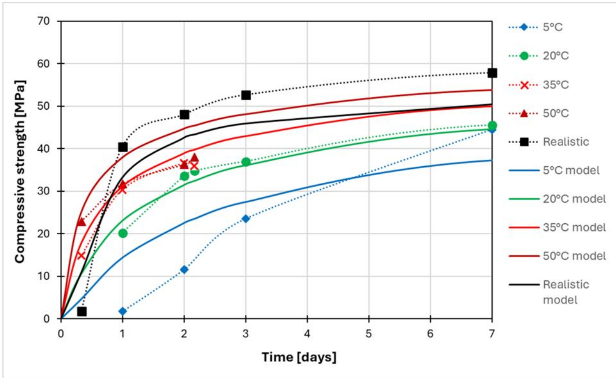
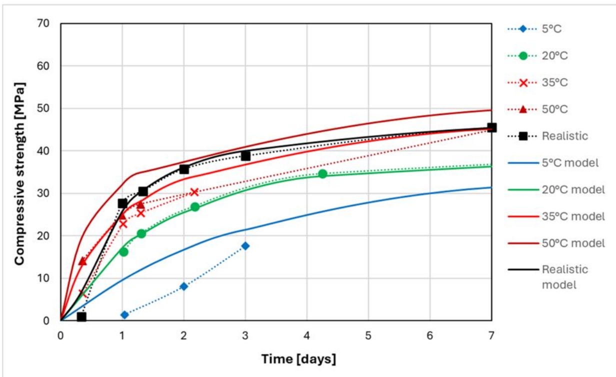


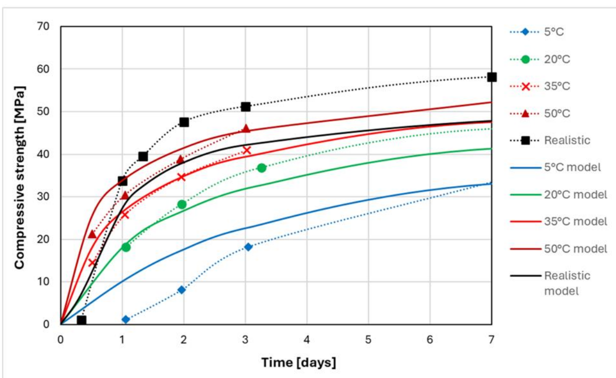
Figure 3. Evaluate the tensile strength of concrete using The TSTM a, before and b, after pouring.



a) Reference concrete ANL Ref



b) ANL FA18 concrete



c) ANL Slag18 concrete

Figure 4. Early-age concrete strength variations at various water curing temperatures in relation to the SE-EN model.

(semi-adiabatic) curing temperature. Figure 4 illustrate a comparison between the experimentally tested compressive strength and the strength predicted using the Eurocode 2—EN 1992-1-1:2023 EN 1992-1-1, EN 1992-1-1, (2023). The results indicate that the Eurocode 2 model aligns closely with the laboratory findings across various types of concrete at early ages.

Figure 4(a) shows that samples made of OPC matured in tanks at 50 °C and 35 °C had higher early compressive strength (31.7 and 30.8 MPa after one day) than samples cured at the reference temperature of 20 °C (24.0 MPa after one day). Later, however, samples cured at 20 °C gained greater strength than samples cured at 50 and 35 °C. Keeping the curing temperature at 50 °C for an extended period of time may reduce the strength gained at young age – (Burg, 1996; Federowicz et al., 2020; Gallucci et al., 2007; Muhammad et al., 2019; Wade, 2005) all mentioned the same phenomenon known as the cross-over effect. On the other hand, in samples cured in the temperature of 5 °C the early strength growth was the slowest among the compared samples, however, eventually after 7 days the strength comparable with that of the samples cured in the reference conditions was gained (44.6 MPa).

Samples maintained in the realistic curing conditions developed high early compressive strength (40.5 MPa after one day—the highest from the analysed cases). Thanks to subsequent cooling of the curing water (which simulates decrease in temperature of the element) after reaching the maximum hardening temperature of ~50 °C, the detrimental cross-over effect can be prevented—the sample was not subjected to the loss of strength growth earned in early age and the 7-day compressive strength was in this case the highest and equal to 57.9 MPa (with respect to 45.6 MPa for the sample cured in the reference conditions).

Figure 4(b) shows compressive strength development in the samples with partial fly ash replacement. When 18% of the cement was substituted with fly ash, the mix material became softer, even though the water-to-binder ratio remained same. see (De Belie et al., 2018; Eduardo & Azenha, 2019). As fly ash is substituted for cement, the compressive strength of all samples clearly decreases as compared to samples produced of OPC that were cured under the identical conditions.

The samples cured in realistic conditions had higher very early-age compressive strength (after 1–2 days) which was ~1.1 times compressive strength of samples cured in 50 °C and ~1.2 times the strength of the samples cured in 35 °C. This can be explained by the fact that with the realistic curing the temperature was increased gradually (6–8) hours, as it does in real life, and not as abruptly as in the 35 °C and 50 °C tanks, causing the samples to be shocked. Gradient heat in curing is preferable to sudden heat exposure for concrete (Aarre & Kaasgaard, 2016; Yousuf et al., 2019).

When the compressive strength of samples cured in the realistic conditions was compared to a 20 °C tank at one day, the compressive strength was ~70% higher. After two days, the gap appeared to narrow to ~40%, and after three days, the compressive strength ratio shifted to ~1.25 in favour of the realistic curing tank. The compressive strength of realistic curing was ~25% higher than that of 20 °C cured samples after 7 days. Relating this observation to previous research, a reference to the results of Klausen et al. (2018; Fjellström, 2013) should be made, who tested two concrete mixes (water/binder ratio was 0.47) and compared compressive strength with curing at 20 °C and with moulds subjected to variable heat according to the temperature curves. There was a significant decrease in compressive strength when compared to cube compressive strength at 20 °C. Aarre and Kaasgaard (2016), on the other hand, stated that the strengths of concrete with fly ash cured at a gradually increasing temperature to 60 °C are higher (8–11%) than the corresponding strengths of the samples cured at 20 °C.

Finally, Figure 4(c) presents compressive strength development in the samples with partial slag replacement. In case of the samples made with this mix, in contrary to previous mixes, no cross-over effect was truly observer—in general it can be stated that with an increasing curing temperature the rate of strength development increased. However, similarly to other cases, the realistic curing conditions allowed to obtain the greatest value of the compressive strength from all the cases (again, similarly, the strength gain was slower than for the samples cured constantly in 35 °C and 50 °C at very early ages, but then the strength started to develop faster).

When comparing the results obtained with slag-based concrete with other mixes, the compressive strengths of ANL Slag18 were in general higher than those obtained in the samples made of ANL FA18 mix for all ages and all curing regimes, but comparable to those obtained in the OPC samples. The comparison between the values of strengths obtained in samples made of different mixes and cured in different regimes is collectively presented in Table 3.

The diagrams of the calculated strength development (see Figure 4) do not reflect the behaviour observed in the tests—while the function fits quite well with the strength development in the reference curing temperature, the slower strength development in low temperature neither the cross-over effect in higher temperature is reflected by the formula. Especially the model does not mimic the beneficial effect of realistic curing conditions where varying curing temperature (according to the realistic temperature curves representing the core temperature in mass concrete) with the maximum value of ~50 °C ensures higher final value of the compressive strength than in case of curing the concrete in constant conditions of 50 °C. Finally, it is evident while analysing the strength development trends, that the model should account for the setting time of concrete—the fact that the strength starts to develop actually after setting, i.e. several hours after casting, not at the moment of casting. Taking this fact into account would allow to better fit the model curves to the results, effectively allowing to better represent very early age (up to 2 days) strength development, as proposed in Annex D to EN 1992-1-1:2023 (2023).

Table 3. Comparison of early age compressive strength development of mixes based on water curing temperature in different regimes with respect to the reference OPC mix.

	Temp curing	1	2	3	7
ANL Ref	5	1.75	11.60	23.55	44.55
	20	20.19	33.56	37.00	45.56
	35	30.38	36.58		
	50	31.71	36.32		
	Real	40.47	48.06	40.47	48.06
ANL FA18	5	1.44	8.07	17.60	
		82%	70%	75%	
	20	16.30	26.96		
		81%	80%		
	35	22.83	30.34		
		75%	83%		
	50	24.91			45.45
		79%			
	Real	27.66	35.79	38.88	45.51
		68%	74%	96%	95%
ANL Slag18	5	1.15	8.16	18.24	33.56
		66%	70%	77%	75%
	20	18.15	28.25	36.89	45.99
		90%	84%	100%	101%
	35	25.83	34.70	40.95	
		85%	95%		
	50	30.46	38.83	46.14	
		96%	107%		
	Real	33.78	47.64	51.24	58.20
		83%	99%	127%	121%

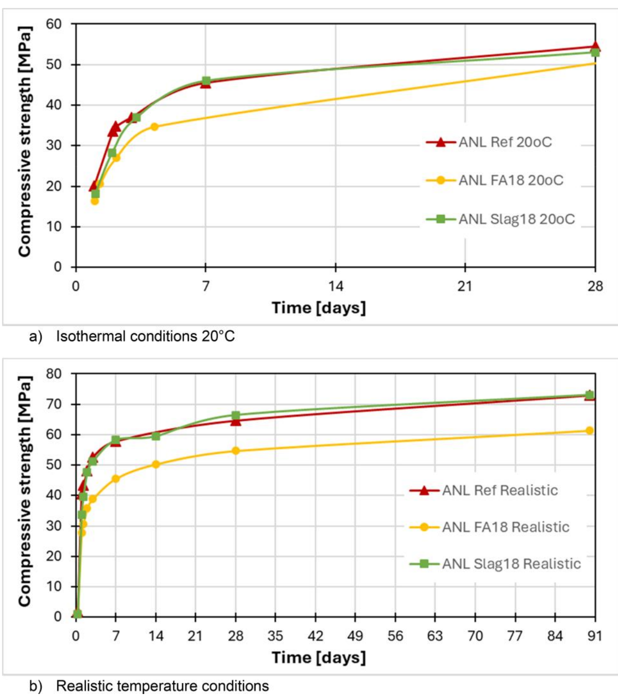


Figure 5. Variation of compressive strength with time for (a) isothermal and (b) realistic temperature conditions.

3.1.2. Long-term compressive strength

Figure 5 shows long-term compressive strength development of three analysed concretes under isothermal conditions (20 °C) see Figure 5(a), and under realistic temperature conditions see Figure 5(b).

Utilizing 18% fly ash (FA) as a replacement for cement led to a reduction in compressive strength of 20% within 24 h and 8% over 28 days. However, substituting slag for 18% of the cement affected the development of very early age compressive strength; after one day, the strength was 10% lower than that of OPC concrete, but eventually after 28 days reached comparable strength to that of regular concrete (see Figure 5(a)). The strength of concrete which includes slag usually reaches the same levels as OPC concrete during 10 to 35 days, depending on the reactivity and fineness of the slag used in the combination (De Belie et al., 2018; Krauss & Paret, 2014). Similar observation can be made when comparing all mixes performance in long term under realistic curing conditions (see Figure 5(b)). The compressive strength development of OPC concrete and slag-enriched concrete are almost identical—very early-age strength development of slag concrete was slower (50% of ANL Ref concrete after 8 hrs and 85% after 1 day), but after 2 days the measured values were the same. The performance of the fly ash-based concrete was, however, visibly poorer—with respect to the ANL Ref concrete the strength was 50% after 8 hrs, 70% after 1 day, 75% after 2 days and ~85% since 7th day onwards. This advanced level of strength enhancement in slag-based concrete exemplifies the utilization of slag as an advantageous element in concrete mix designs, especially when delayed strength development is not harmful.

In a comparative analysis with the control mix (Ref 20 °C), the compressive strength of concrete without any supplementary replacements exhibited a remarkable increment under realistic curing conditions. Specifically, there was a 100% increase in compressive strength after the first day, which progressively diminished to 18.5% after 28 days, as illustrated in Figure 5(b). On the first day, a 36% increase in compressive strength was seen when fly ash was used to replace 18% of the cement content. This increment gradually tapered off, culminating in a marginal rise of 0.2% by the 28th day. In the case of concrete with 18% cement replaced by slag, a notable augmentation of 67.5% in compressive strength was observed on day one, eventually settling at an increase of 21.7% after 28 days. These observations underscore the enhanced performance of pozzolanic active additives like fly ash and slag under high curing temperatures. The hydration activity of these additives intensifies with heating, thereby augmenting the density of the cement paste and consequently enhancing the overall strength of the concrete (Fladr & Broukalova, 2019; Zeyad et al., 2022). The implementation of realistic curing conditions proved advantageous across all mix designs, encompassing standard, fly ash-, and slag-enriched concrete. This approach yielded superior compressive strength outcomes compared to the conventional isothermal curing at 20 °C. The most significant strength gains were predominantly observed within three days of curing. This pattern of strength development aligns with the findings reported by Elsageer (2011) and corroborated by other studies (De Belie et al., 2018; Han & Zhang, 2018), thereby reinforcing the efficacy of realistic curing in optimizing the mechanical properties of concrete.

A thorough examination of concrete under realistic curing conditions revealed that the first day of curing accounts for around 45% of the final compressive strength after 90 days. Three days later, the concrete had gained between 63 and 73% of its compressive strength. This proportion increases to almost 75% by the seventh day, reaching 88% of its compressive strength after 28 days. On the other hand, concrete exhibits an increase in compressive strength of 37% on the first day and reaches 83% on the seventh day at 20 °C, conventional curing conditions.

Replaced cement with an equivalent slag weight showed a negligible effect on compressive strength in the reference and realistic curing conditions. Slag has a specific gravity of 2,890 kg/m^3, similar to cement's particular gravity of 3,050 kg/m^3. Al-Gburi's research (Al-Gburi & Yusuf, 2022) has shown that a crucial factor in determining the compressive strength of concrete is the cement's specific gravity. However, under both curing conditions, the replacement of fly ash, which has a lower specific gravity of 2,300 kg/m^3, for an equivalent weight of cement results in a loss in the latter's compressive strength. Fly ash has a lower specific gravity than cement, which affects the final concrete mix's overall density and strength properties. This is the reason for this discovery.

3.2. Tensile strength of concrete under different curing temperatures

3.2.1. Long-term tensile strength development

The variations in concrete cubes' splitting tensile strength under actual curing circumstances are depicted in Figure 6. The OPC concrete had a notable tensile strength of 4.25 MPa after 32 h of casting, which remained consistent as it aged. The incorporation of fly ash as a substitute in concrete resulted in a significant rise in tensile strength over the first 32 h, reaching 2.98 MPa. This increase continued steadily,

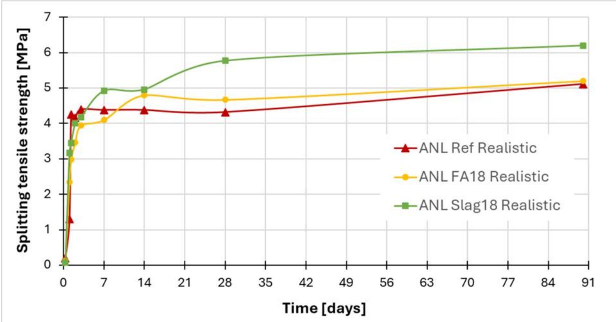


Figure 6. Variation of splitting tensile strength with time for different concrete mixes.

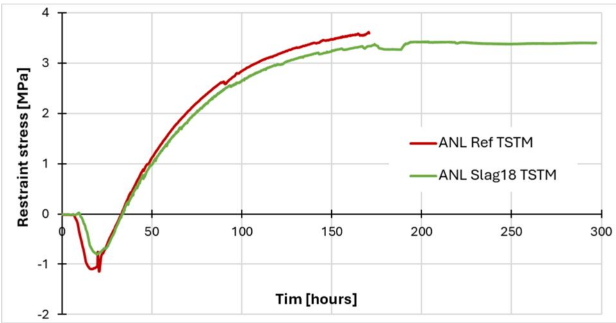


Figure 7. The restraint stress development with time by TSTM test for the two analysed concretes mixes.

with the strength reaching 4.1 MPa after 7 days and 4.67 MPa after 28 days. The slower strength growth rate can be attributed to the prolonged interactions with fly ash, which differ from the usual concrete hydration processes. Regarding concrete using slag as a substitute, the tensile strength was measured to be 3.34 MPa after 32 h after casting. It then increased gradually to 4.9 MPa after 7 days and reached its highest point at 5.77 MPa after 28 days, which was ∼20% higher than for the other two concretes. This further supports the use of slag as partial cement substitute in concrete. The slower kinetic interactions of slag, as compared to typical cement, are reflected in the more gradual strength growth seen.

This observation was validated in the TSTM test where OPC concrete and slag-enriched concrete were compared. Figure 7 illustrates restraint stress development in time for the two analysed concretes. This test allows to measure restraint stress induced by restrained strain caused by volume changes due to temperature variations. The stress is compressive in the phase of temperature increase and becomes tensile in the subsequent cooling phase. The value of stress at which cracking occurs signifies reaching tensile capacity of concrete. This can be understood as the current tensile strength of this concrete.

Comparing the behaviour of the two concretes it can be notices that the OPC sample reached its tensile capacity after 171 h at the stress level of 3.6 MPa, which corresponded to the temperature drop (from the maximum temperature of 51 °C reached after 23 hrs of curing) of 25.7 °C. In the slag-enriched sample after 297 h the stress level of 3.4 MPa was reached, which corresponded to the temperature drop of 27.5 °C (from the maximum temperature of 48.6 °C reached after 25 hrs of curing), but no cracking was observed.

This study gives valuable insight into the issue of tensile capacity of mass concrete structures which is a trade-off between the restrained strain and current tensile strength, as there is no direct relationship between stress and strain, rather between the rates of the two ($\dot{\sigma} \propto \dot{\varepsilon}$). In the compared cases the increase in strain was more rapid in the OPC concrete where higher maximum temperature was reached and the cooling process was faster. Therefore, tensile capacity was reached earlier. In case of the slag-based concrete the tensile strain was developing slower and capacity of concrete was not reached. This does not, however, allow to answer undoubtedly which concrete exhibited higher tensile strength.

Table 4. The ratio of the investigated concretes' splitting tensile strength to their compressive strength under realistic curing circumstances.

Curing time [days]	ANL Ref	ANL FA18	ANL Slag18
0.33	11%	13%	8%
1	3%	8%	9%
1.33	10%	10%	9%
2	9%	10%	8%
3	8%	9%	7%
7	8%	8%	8%
28	7%	9%	9%
90	7%	8%	8%

3.2.2. Relationship between compressive and tensile strength of concrete

Table 4 collectively presents the relationship between splitting tensile strength of concrete to its compressive strength at corresponding curing times for the analysed concretes cured in the realistic curing conditions.

In general, the splitting tensile strength of the analysed concretes was around 10% of the compressive strength, which follows the observation of Arioglu (n.d.). It must be, however, noticed that this percentage was the highest at very early ages and was generally decreasing in time, which signifies that the tensile strength develops more rapidly than the compressive strength. This behaviour is best visible in the OPC, and slightly less in the FA-based concrete and then slag-based concrete. This observation has been confirmed in other research, e.g. by Kanstad et al. (2011), as well as in the newest design standards.

4. Conclusions

This paper presets the results of experimental research performed on three concrete mixes (OPC concrete, fly ash- and slag-based concrete) cured in different regimes to investigate the influence of the curing conditions on the early-age and long-term strength development. The focus was put on massive concrete structures which undergo close-to-adiabatic curing conditions in the core. The following conclusions have been drawn from this study:

1. For OPC concrete the samples cured in 5 °C temperature exhibited slower strength development than in the samples cured in the reference temperature 20 °C, but in case of curing in higher temperatures (35 °C and 50 °C) the cross-over effect was observed – even though the very early-age strength (1–2 days of curing) was higher, the later strength development decelerated and the 28-day values of compressive strength were lower than in the samples cured in the reference temperature 20 °C. The same behaviour was observed in samples made with fly ash enriched concrete. The cross-over effect was not observed in the slag-based concrete samples.
2. The cross-over effect was effectively mitigated in samples made with all types of concrete when realistic curing regime was imposed. Gradual curing temperature increase allowed to build up high early strength which was later maintained as the curing temperature decreased.
3. When OPC concrete was cured under realistic curing conditions, its early-age compressive strength increased by 100% and 26.5%, respectively, in comparison to control concrete that was matured at 20 °C for one and seven days. For fly-ash-based concrete this increase was by 67% and 25.6%, respectively and for slag-based concrete by 86% and 26.5%, respectively.
4. Splitting tensile strength of OPC concrete and fly ash-based concrete cured in the realistic conditions was similar (4.32 and 4.67 MPa at 28 days, and 5.11 and 5.20 MPa at 90 days for OPC and FA concrete, respectively), while of the slag-based concrete was higher (5.77 and 6.20 MPa at 28 and 90 days).
5. The splitting tensile strength of all concretes was in general ∼10% of their compressive strength, although this percentage was the highest at very early ages and decreased in time, signifying more rapid development of tensile strength with respect to the compressive strength. Moreover, the speed of strength gain was the fastest in the OPC concrete, then in the FA-based concrete and the slowest in the slag-based concrete.

6. In TSTM testing slag-based concrete also exhibited prevailing behaviour to that of the OPC by providing higher tensile capacity (i.e. capacity to withstand the restrained thermal strain development with respect to the rate of tensile strength gain).
7. All the above observations support the use of slag as an efficient and environmentally-friendly replacement of cement, especially in mass concrete applications.

Finally, the study has shown that the results obtained under realistic curing conditions were more accurate than the results achieved under isothermal reference curing conditions (20 °C). This has been also proven from the modelling point of view when attempting to predict the strength development with the standardised functions based on the temperature-adjusted age of concrete. In case of massive concrete structures, where conditions close to adiabatic develop in the core, the models fail to predict (underestimate) the development of the strength with progressing maturity when strength is predicted based on the isothermal measurements. As a result, specifications for tests of mechanical properties of concrete, particularly in massive concrete elements with casting thicknesses greater than 70 cm, must be revised. Accurate estimation of is important to reduce the quantity of cement used in the production of concrete, lessen the amount of reinforcement or quicken the time to remove formwork.

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Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

The authors affirm that the data supporting the findings of this investigation are available in the paper [and/or] its supplementary material.

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