The effect of realistic curing temperature on the strength and E-modulus of concrete

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Abstract

The strength and E-modulus of concrete are decisive parameters when it comes to ultimate limit state design, serviceability limit state design, and early age crack assessment. The properties of concrete are generally determined in the laboratory under 20 °C isothermal conditions and then used as the basis for calculations under realistic temperature conditions. It is well-known, however, that the curing temperature affects both the rate of property development in concrete and the "final value" of a given property. The current study investigated the effect of a realistic temperature history on the compressive cube strength, the tensile strength, and the tensile E-modulus for two concretes, a reference concrete and a fly ash concrete. Concrete specimens were subjected to either 1) 20 °C isothermal curing conditions, or 2) realistic temperature curing conditions for 14 days and then 20 °C isothermal conditions, until they were tested after 28 and 91 days. Parallel tests performed in a Temperature-Stress Testing Machine were also used to evaluate the results. The reference concrete showed a general reduction in strength and E-modulus when subjected to a realistic curing temperature, whereas the fly ash concrete showed an 11% increase in the 28-day E-modulus when cured under realistic temperature conditions. Furthermore, in both isothermal and realistic curing temperature conditions, the fly ash concrete showed a pronounced property development beyond 28 days, which could not be described by the material model currently used.

Keywords *Concrete; Strength; Property development; Temperature; Fly ash;*

1. Introduction

Tensile strength and E-modulus are decisive parameters when it comes to ULS (ultimate limit state) design, SLS (serviceability limit state) design, and early age crack assessment of concrete. Another important parameter is compressive strength, whose 28-day value is usually considered the quality class parameter defining the concrete. Moreover, compressive strength is a fundamental and much studied concrete property, which is relatively easy to determine and is therefore often used in correlation with other properties, e.g. tensile strength and E-modulus. In most cases, concrete strength tests are performed at the age of 28 days. This is merely for comparison purposes, because most concretes continue developing strength after 28 days. These increases in strength after 28 days are often regarded as a contribution to the safety factor of a structure, but since the late 1950s, several codes of practice for reinforced and prestressed concrete allow the gain in strength over time to be taken into account in the design [1]. While the existing Eurocode 2 (EC2) defines the compressive strength value at 28 days as the quality class parameter, the upcoming revised EC2 is likely to allow other reference ages in the range of 28–91 days. This modification is important for environmental and sustainability issues as new binders come onto the market. The material model used in the present article is included in the most recent EC2 draft, but has not yet really been verified for ages beyond 28 days of maturity. It is also important to note that the ratio between "standard strength" and "strength in structures" can change considerably with the introduction of new binders, which ideally should not change the "safety level" of the structure. The addition of pozzolans, e.g. fly ash, is known to cause a slower strength and temperature development than that of ordinary Portland cement alone. Yet, the ultimate strength developed over longer times may reach and/or even exceed that of ordinary Portland cement [1–5].

The properties of concrete are generally determined by experiments in the laboratory under 20 °C isothermal conditions and then used as the basis for ULS design, SLS design, and crack risk assessment under realistic temperature conditions. It is well-known, however, that the curing temperature affects both the rate of property development in concrete and the "final value" of a given property. Ordinary Portland cement has been found to show reduced final strengths when subjected to elevated temperatures during curing, while the final strengths of concretes with fly ash have been found to be unaffected or even increased by high curing temperatures [1, 6, 7].

Hardening phase volume changes in concrete, caused by autogenous deformation (AD) and thermal dilation (TD), are known to be of considerable importance. If these movements are restrained, stresses will start to generate and may further lead to cracking. The stress development and the corresponding risk of cracking in a concrete structure can be simulated and predicted, and the tensile strength and E-modulus development are key properties in this context. A comprehensive experimental test programme on fly ash concretes has been carried out at NTNU in recent years [8–10]. The aim has been to determine decisive parameters for early age crack assessment. An important part of this test programme has been the Temperature-Stress Testing Machine (TSTM), which measures stress development in the hardening phase under a given degree of restraint [8]. Due to observations in connection with TSTM tests, additional mechanical tests were initiated to study the effect of a realistic temperature history on compressive strength, tensile strength, and E-modulus in tension. The present paper presents results from this additional test program, and thus provides a somewhat different approach than the majority of corresponding studies found in the literature. While most studies on the effect of temperature on the property development of concrete are based on an elevated but isothermal temperature over time, the present study deals with the effect of an in-situ temperature history, hence representing the actual temperature condition in a massive concrete structure.

2. Experimental set-up

The following test methods were used:

Heat development

Semi-adiabatic calorimeter tests (15-litre samples) were performed to determine the hydration heat evolution of the concretes. The temperature development in the concretes was measured and converted to isothermal heat development as a function of maturity. The heat loss to the environment was compensated for by assuming that the heat flow out of the box was proportional to the temperature difference between the concrete and the environment. The proportionality coefficient is called the "cooling factor" and can be measured or calculated. This method is described in NS 3657:1993 [11].

Compressive strength test

The 100 mm cube is the standard specimen for compressive strength testing in Norway. In the current study, compressive strength was measured on cubes in accordance with NS-EN 12390-3:2009 [12].

Uniaxial tensile test

In the uniaxial tensile test, tensile strength is measured directly by applying a uniaxial load until a 100x100x600 mm specimen develops failure in tension. The load was applied as clamping forces at each end of the vertically oriented specimen using a gripping device. Most of the clamping force, and therefore most of the tensile stress, was applied near the ends of the specimen to ensure a smooth transition to a uniform stress field. The deformation was measured over the 100 mm mid-section using two displacement transducers placed on opposite sides of the specimen. The strain rate was approximately 100×10^{-6} per min. The uniaxial tensile test method was developed by Hansen [13], and has been the standard method for uniaxial tensile strength determination at SINTEF/NTNU in Norway for several years.

Modulus of elasticity in tension

The modulus of elasticity in tension was calculated from the load-deformation curve in the previously described uniaxial tensile test using Equation 1.

$$E = \frac{\sigma_{40\%} - \sigma_{10\%}}{\varepsilon_{40\%} - \varepsilon_{10\%}} \qquad \text{Equation 1}$$

The stress and strain values in Equation 1 are values at load levels corresponding to 10% and 40% of the failure load.

Prior to the above described tests, half of the specimens were cast in temperature-controlled moulds and subjected to a realistic temperature history, Fig. 1. The moulds were tightly covered and stored in a well-insulated container, and the temperature was measured in both the specimens and the surrounding air inside the container during curing. The other half of the test specimens were cast in regular moulds and cured under 20 °C isothermal conditions. All the specimens were demoulded and wrapped in aluminium foil after 14 days and further cured under 20 °C isothermal conditions.

In addition to the test methods described above, parallel tests performed in the Temperature-Stress Testing Machine (TSTM) were also used to evaluate the concrete property development results obtained. The TSTM System at NTNU consists of a dilation rig and a TSTM. Both rigs are connected to a temperature-control system (Julabo FP45), which can provide an accurate control of the concrete temperature during testing. The dilation rig measures the free deformation, i.e. TD and AD, of a sealed concrete specimen. The TSTM is constructed to measure the stress generation of a sealed concrete specimen during the hardening phase under a chosen degree of restraint. The degree of restraint (R) is entered as a parameter in the software and determines how much the concrete specimen is allowed to move. A degree of restraint of 0% means that the specimen is free to move, while R = 100% provides a fully restrained specimen. A threshold value for the length change measured in the TSTM is entered as a parameter in the software. When this threshold value is reached, the software induces a feed-back adjustment which moves the concrete specimen a given distance based on the chosen degree of restraint. During the feed-back adjustment in the TSTM, deformation and load data are recorded 10 times a second. This feature provides a stress-strain ratio for each feed-back adjustment during a test in the TSTM. The concrete E-modulus can then be determined based on the recorded data, providing an incremental E-modulus development over time during the testing in the TSTM. The E-modulus obtained from the TSTM equipment has been shown to give good agreement with the corresponding E-modulus determined from independent mechanical testing [8]. Similar correspondence between E-moduli obtained from TSTM tests and parallel methods has also been seen in other studies [14]. A thorough description of the TSTM System is given in Klausen [8].

3. Materials and experimental programme

Two concretes were included in the current test programme: ANL Ref. and ANL FA33 (33% fly ash), where the total fly ash content is given as percentage by weight of cement and fly ash content. Detailed concrete compositions are given in Table 1.

ANL Ref. is the reference concrete. It contains no fly ash and was made with Portland cement CEM I "Norcem Anlegg" (ANL). The fly ash concrete was made with Portland-fly ash cement CEM II / A-V "Norcem Anlegg FA" (ANL FA) which has a fly ash content of 17%. The composition of these cements is described in Klausen [8]. For ANL FA33, a fly ash content of 33% was achieved by replacing cement with extra fly ash 1:1 by weight, while keeping the water-to-binder ratio and the cement paste volume constant. Both concretes were made with a water-to-binder ratio of 0.4 and a cement paste volume of 292 l/m3 and both concretes contain 5% silica fume (by weight of cement and fly ash).

While half of the test results presented were from specimens cured under 20 °C isothermal conditions, the other half were subjected to various semi-adiabatic curing conditions: each concrete was given its own semi-adiabatic temperature history representing a selected section of an 800-mm-thick wall exposed to Norwegian summer conditions [8]. These temperature histories were determined using the program CrackTeSt COIN [15] and were based on calorimetric heat development test results for each concrete and the geometry of the wall, see Fig. 2. The maximum temperature during realistic temperature curing was calculated to be 61.8 °C and 45.0 °C for ANL Ref. and ANL FA33, respectively.

Compressive tests, uniaxial tensile tests and TSTM tests were performed for the two concretes. The test programme is given in Table 2. It should be noted that the number of test specimens in the strength tests was limited by the number of temperature-controlled moulds available.

4. Material models

Prior to the current test programme, the concretes were thoroughly tested at 20 °C isothermal conditions as part of the project COIN [16]. That test programme and the corresponding results are presented in Kjellmark and Klausen [17] and Klausen [8]. Material models were fitted to the obtained results to describe the property development of the given concretes. The material models and the corresponding model parameters obtained from that test series are summarized below. All modelled property developments presented here are based on these values, i.e. the previously performed test programme. It should be noted that the previous test programme was performed with different cement batches than the current test programme, which could cause some deviation in the results. However, the results from the current test programme and the TSTM results reported were based on the same cement batches and the same temperature histories.

In the current study, the maturity principle was used to describe the effect of curing temperature on the heat and property development of concrete. The reference temperature was set to 20 °C, and the Arrhenius equation was used as temperature function [18].

The heat developments of the two concretes were modelled by fitting the Freiesleben Hansen model, Equation 2 [18, 19], to the calorimetric heat development results obtained.

$$Q(t_{eq}) = Q_\infty \cdot exp\left(-\left(\frac{\tau}{t_{eq}}\right)^\alpha\right) \qquad \text{Equation 2}$$

In Equation 2, $Q(t_{eq})$ is the heat generation as a function of equivalent age t_{eq}, Q_∞ is the final heat after "infinite" time as well as a curve-fitting parameter, while τ and α are curve-fitting parameters.

Compressive strength, tensile strength, and E-modulus were modelled using Equation 3, which is a modified version of CEB-FIP MC 1990 [20], see [21, 22]:

$$X(t_{eq}) = X(28) \cdot \left\{exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0^*}{t_{eq} - t_0}}\right)\right]\right\}^n \qquad \text{Equation 3}$$

In Equation 3, $X(t_{eq})$ represents the concrete property as a function of equivalent age t_{eq}, X_{28} is the property value at 28 days, s and n are curve-fitting parameters, and $t_0 = t_0*$ is the start time for stress development [equivalent time]. The parameter t_0 was included in Equation 3 by Kanstad et al. [21], while t_0* was introduced later in the program CrackTeSt COIN [15, 23].

Consequently, the equations describing the compressive strength, tensile strength and E-modulus are as presented in Equations 4, 5 and 6, respectively. The s-parameter is the same for all properties, while the n-parameter varies. The 28-day properties and the curve-fitting parameters were determined by fitting the models to the test results obtained previously by using the method of least squares [17, 8]. The model parameters obtained are presented in Table 3.

$$f_c(t_{eq}) = f_{c2} \cdot \left\{exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_{eq} - t_0}}\right)\right]\right\}^{n_c} \quad (n_c = 1) \qquad \text{Equation 4}$$

$$f_t(t_{eq}) = f_{t2} \cdot \left\{exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_{eq} - t_0}}\right)\right]\right\}^{n_t} \qquad \text{Equation 5}$$

$$E_c(t_{eq}) = E_{c2} \cdot \left\{exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_0}{t_{eq} - t_0}}\right)\right]\right\}^{n_E} \qquad \text{Equation 6}$$

The property development determined by the above models and parameters is presented in Fig. 3. The curves are based on 20 °C isothermal curing conditions.

The developments in compressive strength, tensile strength and E-modulus are not linearly correlated; see the relative development presented in Fig. 3 d). Several studies have reported that tensile strength tends to grow faster than compressive strength, [8, 24–27]. Similarly, the E-modulus has also been found to increase at a higher rate than compressive and tensile strength [8, 24, 26, 28]. This is unfortunate with respect to early age cracking, because stress development in early age concrete depends on the E-modulus, while the risk of cracking depends directly on the tensile strength.

5. Test results and discussion

The test results obtained are presented in Table 4, and further discussed in the following. To be able to compare the test results at isothermal and realistic temperature conditions, all results are presented in terms of the maturity (equivalent age) of the concrete specimen tested.

During testing, the temperature control system was slightly more efficient for higher temperatures than originally assumed. This resulted in an unintended slightly higher maximum temperature being applied to the ANL Ref. specimens during testing (63.5 °C) than in the temperature history initially calculated (61.8 °C). For ANL FA33, the temperature development measured in the specimens during curing was as planned, with a maximum temperature of 45.0 °C. Typical temperature measurements during curing are shown in Fig. 2.

Compressive strength

The results from the compressive cube strength tests are presented in Table 4 and illustrated in Fig. 4. Each compressive strength result in the table is the average of 3 parallel cubes, whereas the figure shows the value for each cube to give an illustration of the scatter in the results. A statistical evaluation of each set of parallel cubes shows that the internal variation is small: the coefficient of variation (CV) among the various sets lies between 0.3% and 1.2%.

When exposed to a realistic temperature history, ANL Ref. showed a 12% and 9% reduction in compressive strength after 28 and 91 maturity days, respectively. This reduced compressive strength at mature age is believed to be caused by the coarser and more continuous pore structure induced by a high maximum temperature exposure [29]. Similar results have been found by other researchers, e.g. Jonasson et al. [30] (realistic temperature histories) and Munch-Petersen and Munch-Petersen [31] (isothermal temperature histories at different levels).

The fly ash concrete ANL FA33 did not show an analogous compressive strength reduction when cured under realistic temperature conditions. This result is common and supported for instance by De Weerdt et al. [4], who studied the effect of increased curing temperature on the hydration (and compressive strength development) of cement paste with: 1) ordinary Portland cement, and 2) composite cements containing limestone powder and fly ash. They found that when the (isothermal) curing temperature was raised to 40 °C, the ordinary Portland cement showed an increased coarse porosity, resulting in a reduction in long-term compressive strength. In the case of the composite cement, this increase in coarse porosity with increasing curing temperature was not observed. Instead, the increased curing temperature enhanced the pozzolanic reaction of the fly ash and caused an increase in long-term compressive strength. They concluded that high curing temperatures may be detrimental for the long-term compressive strength of ordinary Portland cement, but beneficial for the composite cement containing fly ash. However, as previously described, in order to represent the same structural part, the currently tested concretes were subjected to different realistic temperature histories. ANL Ref. produces more hydration heat and therefore received a higher maximum temperature (63.5 °C) during testing than ANL FA33 (45.0 °C). It is likely that this has influenced the negative temperature effect on the compressive strength for ANL Ref. specimens. Despite the temperature-induced compressive strength loss effect found for ANL Ref., it still showed higher compressive strength at all test ages than ANL FA33.

For 20 °C isothermal curing conditions, the compressive strength results fit well with the model and model parameters determined from the previously performed test series, i.e. the current test results agree well with the previously performed test. It can also be seen that the models, which were based on model parameters determined from tests prior to 28 days, give a very accurate prediction of the currently found 91-day compressive strength values.

Tensile strength

The results from the direct tensile strength tests are presented in Table 4 and illustrated in Fig. 5. There is a rather pronounced variation within the sets of 2 parallel specimens, especially for ANL Ref. at 28 days of isothermal curing. The Coefficient of Variation (CV) varied between 1.0% and 9.0%, but the validity of a statistical evaluation could be discussed due to the limited set of specimens, i.e. the CV must be expected to have some variation. For comparison, similar tests reported by Kanstad et al. [7] had a CV of 3.9 – 9.2% in sets consisting of 4 parallel specimens.

ANL Ref. showed a reduction in tensile strength for both test ages when exposed to a realistic temperature history during curing, and the tensile strength of ANL Ref. also decreased from 28 to 91 days of maturity when subjected to a realistic curing temperature. If we allow for internal variation, it is questionable whether this temperature effect is significant or caused by variations in the test results. For ANL FA33, on the other hand, a realistic curing temperature had no negative effect on tensile strength. As discussed in connection with the compressive strength results, an increase in temperature during curing will affect the hydration and the resulting pore system in the cement paste [4]. It is likely that the temperature-induced enhancement of the pozzolanic reaction of the fly ash also will be beneficial for the tensile strength of the given fly ash concrete, whereas high temperatures will be detrimental for the reference concrete without fly ash. This statement corresponds well with the obtained test results.

The tensile strength of ANL FA33 continued to develop beyond 28 days of maturity. Between 28 and 91 maturity days, the increase in tensile strength was as much as 1.0 MPa (25%) in both temperature curing conditions. The corresponding tensile strength development for ANL Ref. was much lower, and at 91 days, ANL FA33 actually had a higher tensile strength than ANL Ref. when specimens subjected to a realistic temperature curing regime were compared.

The ANL FA33 tensile strength results and the corresponding results from TSTM tests are shown in Fig. 6. For all the “realistic” tests (both TSTM and the current test series), the specimens were subjected to the same temperature history during curing. However, it should be noted that there were some differences in test conditions between the current test series and the TSTM tests: the specimens in the TSTM were subjected to self-generated loading from setting time up until the final testing due to restrained conditions, while the specimens used for mechanical testing were not subjected to any loading prior to testing. For the currently reported TSTM tensile strength results, all test specimens were first unloaded and then reloaded until failure. Shkoukani and Walraven [32] found that tensile strength obtained under sustained loading was lower than under short-time loading. The same study also showed that when a specimen that had been subjected to long-term sustained loading was unloaded and reloaded until failure in a short-term test, significantly higher tensile strengths were achieved than in similar short-term tests on virgin specimens [32]. This hardening mechanism was seen for both concentric and eccentric tensile tests, and is also well-known for compression [1]. The presence of several different test factors complicated the comparison of the various ANL FA33 tensile strength test results: 1) Differences in testing conditions between the mechanical test series and TSTM tests, 2) Sustained loading prior to tensile strength tests in the TSTM, 3) Differences in cement batch, and 4) Differences in temperature conditions during curing. Despite these differences, all the test results showed that the given material model was unable to describe the considerable increase in tensile strength observed after 28 maturity days for the fly ash concrete; see Fig. 6.

ANL Ref. achieved a tensile strength of 4.4 MPa after 32 maturity days when tested in the TSTM System at realistic temperature curing conditions. This agrees quite well with the tensile strength of 4.2 MPa obtained after 28 maturity days in the current tensile strength tests at realistic curing conditions. The tensile strength model, i.e. the previously performed tensile strength tests, was somewhat lower. This was found to be related to the change in cement batch between the previously and currently performed test programme.

Tensile E-modulus

The tensile E-modulus results are presented in Table 4 and illustrated in Fig. 7. Each test set consisted of only two specimens, which is rather limited. Nevertheless, the Coefficient of Variation (CV) was within 2.6% for all tests, which must be regarded as quite satisfactory.

The CV for the tensile E-modulus is lower than the CV for the direct tensile strength even though the results originate from the same set of tests. The direct tensile strength is determined as the stress at which the specimens develop failure in tension. This parameter has been known to show some variation, because it depends on the weakest point in the concrete specimen. In contrast, the tensile E-modulus is determined from the slope angle of the stress-strain relationship between 10% and 40% of the failure load (i.e. tensile strength). This slope angle showed less variation between tests than the actual failure load. The CV for the E-modulus was therefore low, while the CV for the tensile strength was somewhat higher.

The reference concrete ANL Ref. showed a small reduction in E-modulus for both test ages when exposed to realistic curing temperatures. In contrast, ANL FA33 achieved an 11% increase in the E-modulus at 28 days of maturity after exposure to realistic curing conditions. By way of comparison, Bjøntegaard and Sellevold [33] report that a mechanical test series on specimens cured under 20 °C isothermal conditions showed that the 28-day E-modulus decreased with increasing amounts of fly ash, while a mechanical test series carried out on specimens cured under realistic temperature conditions one year later showed that the 28-day E-modulus did not decrease with increasing amounts of fly ash [34]. This is in line with the current results, and so is a mechanical test series reported by Kim et al. [35], where it was found that while the 28-day E-modulus increased after higher curing temperatures for fly ash concretes, the 28-day E-modulus for concrete without fly ash decreased. The difference in the effect of temperature on the E-modulus for ANL Ref. and ANL FA33 is most likely connected with the previously discussed difference in how a realistic temperature history affect the hydration and the resulting cement paste pore system for concretes with and without fly ash. It was shown that the E-modulus was less affected by temperature than the compressive and tensile strength, which can be explained by the fact that the E-modulus is an average material property value and not dependent on the weakest point in the concrete specimen.

The current test programme was initiated when restrained stress experiments in the TSTM System involving incremental E-modulus determination showed an increase in the E-modulus for fly ash concretes that had been subjected to realistic temperature curing conditions. The main objective of the current test series was to investigate this observation. The results from the current test programme support the 28-day E-moduli increase observed for fly ash concretes cured under realistic temperature conditions in the TSTM. In view of the observed increase in E-modulus in the TSTM, the model was adjusted by replacing the original 28-day E-modulus with the 28-day value obtained from the realistic TSTM tests. This adjusted model agrees well with the current tensile E-modulus results after 28-days; see Fig. 7.

While ANL Ref. shows the same E-modulus development between 28 and 91 maturity days for both temperature curing conditions, ANL FA33 displays a pronounced difference in E-modulus development over the same time span between isothermal and realistic temperature curing conditions. ANL FA33 shows a faster initial E-modulus development for the concrete specimens cured under realistic temperature conditions than for the specimens cured under isothermal conditions. The specimens cured under realistic temperature conditions seem to have reached their final level after 28 days of maturity, whereas the specimens cured under 20 °C isothermal conditions continue to develop stiffness (E-modulus) after 28 days of maturity. At 91 maturity days, both curing conditions resulted in the same E-modulus level, but they seemed to have followed a different path in getting there. The E-modulus model and model parameters based on isothermal curing temperatures capture neither the more rapid E-modulus development before 28 maturity days for the concrete exposed to a realistic temperature history nor the continuous development of the E-modulus between 28 and 91 days of maturity for fly ash concrete cured under 20 °C isothermal conditions.

Property development

The various property developments between 28 and 91 days of maturity are summarized in Table 5. Under isothermal curing conditions, the long-term property development for ANL FA33 was generally considerably higher than for ANL Ref. Under realistic curing conditions, the long-term property development of ANL FA33 seemed to slow down, probably due to the increase in the 28-day values, whereas the long-term property development of ANL Ref. seemed rather unaffected by the realistic temperature curing regime.

The material models used to describe the material properties in the current work gave a good fit to the ANL Ref. results, but were not able to correctly describe the continuing development of the properties for ANL FA33 seen beyond 28 days. For instance, for ANL FA33, the model combined with the 28-day E-modulus would considerably underestimate the 91-day E-modulus. On the other hand, by including the 91-day E-modulus test results in the curve-fitting procedure, the model would overestimate the 28-day E-modulus and underestimate the 91-day E-modulus. However, it should be noted that the current test programme contains a rather limited set of data, so more research is needed to see whether the results have a general validity.

6. Summary and conclusion

- When exposed to realistic temperature curing conditions, the reference concrete, ANL Ref., displayed a reduction in compressive strength, tensile strength, and E-modulus at both 28 days and 91 days of maturity. The fly ash concrete, ANL FA33, showed a small increase in compressive and tensile strength, and a distinct increase in the 28-day E-modulus, when subjected to a realistic temperature curing regime. However, it should be noted that in order to represent the same structural part, the two concretes were subjected to different realistic temperature histories. ANL Ref. produces more hydration heat, and therefore received a higher maximum temperature (63.5 °C) during testing than ANL FA33 (45.0 °C).
- The fly ash concrete ANL FA33 showed an 11% increase in the 28-day E-modulus when cured under realistic temperature conditions. This increase could not be described by the maturity principle, and it could have a decisive impact on the cracking risk calculated in simulations at early ages. The increase in E-modulus was also observed at early ages for fly ash concretes subjected to realistic curing temperatures in several tests using the TSTM system.
- The absolute mechanical property values were higher for ANL Ref. than for ANL FA33, except for the 91-day tensile strength value for realistic curing conditions. The latter result was due to the reduction in tensile strength for

ANL Ref. under realistic curing conditions, combined with the pronounced long-term property development found for ANL FA33.

- ANL FA33 showed a much more pronounced property development beyond 28 days than ANL Ref., especially when exposed to isothermal curing conditions. The material models currently used could not accurately describe this increased long-term property development found for ANL FA33. More tests need to be performed to investigate whether the current results have a general validity.

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Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Human and animal rights: This article does not contain any studies with human participants or animals.

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Tables

Table 1. Composition of concretes

Materials	***ANL Ref.***	***ANL FA33***
Concrete composition [kg/m³]		
Cement	372.3	284.3
FA_{cem} (FA included in the cement)	0.0	47.2
FA_{added} (additional added FA)	0.0	71.1
Silica fume	18.6	17.6
Free water	163.8	156.2
Sand 0-2	201.1	201.1
Sand 0-8	740.2	740.2
Sand 4-8	275.0	275.0
Gravel 8-16	614.1	614.1
Plasticizer	2.05	1.56
Measured values: fresh concrete		
Natural air content [%]	2.0	2.3
Density [kg/m³]	2400	2370
Slump [mm]	175	180
Binder composition (ratio)		
Total FA-content, FA/(cem+FA)	0%	33%
Silica fume-content, Silica/(cem+FA)	5%	5%
w/b, $k_{FA\_added} = 1.0^{*}$	0.40	0.40
(w/b, $k_{FA\_added} = 0.7)^{*}$	(0.40)	(0.42)

*) k_{FA} = *efficiency factor*

Table 2. Test programme

Concrete	*Test*	*Curing conditions*	*No. of specimens*	*Test age*
ANL Ref.	Direct tensile strength	Isothermal	2 + 2	28, 91
		Realistic temp	2 + 2	28, 91
	Compressive cube strength	Isothermal	3 + 3	28, 91
		Realistic temp	3 + 3	28, 91
	TSTM	Isothermal	-	
		Realistic temp	1	
ANL FA33	Direct tensile strength	Isothermal	2 + 2	28, 91
		Realistic temp	2 + 2	28, 91
	Compressive cube strength	Isothermal	3 + 3	28, 91
		Realistic temp	3 + 3	28, 91
	TSTM	Isothermal	4	
		Realistic temp	2	

Table 3. Material model parameters for ANL Ref. and ANL FA33

		ANL Ref.	*ANL FA33*
Q_∞	[kJ/kg cem]	350	307
τ	[h]	16.75	33.57
α	[-]	1.06	0.75
A	[$Jmol^{-1}$]	31482	37023
B	[$Jmol^{-1}K^{-1}$]	296	0
$f_{c28,\ cube}$	[MPa]	80.3	53.6
s	[-]	0.200	0.356
t_0	[mh^*]	8.8	12.0
f_{ct28}	[MPa]	3.86	3.05
n_t	[-]	0.484	0.486
E_{28}	[GPa]	32.45	27.8
n_E	[-]	0.348	0.252

$^{*)}$ *Maturity hours*

Table 4. Compressive cube strength, tensile strength, and tensile E-modulus for ANL Ref. and ANL FA33

				ANL Ref.	*ANL FA33*
Test	*Test age [md*]*	*Curing conditions*	*No of specimens*	*Mean [MPa]*	*Mean [MPa]*
Compressive cube strength	28	Isothermal	3	84.0	56.9
		Realistic temp	3	74.4	59.9
	91	Isothermal	3	86.8	65.3
		Realistic temp	3	79.0	63.9
Direct tensile strength	28	Isothermal	2	4.7	3.2
		Realistic temp	2	4.2	3.3
	91	Isothermal	2	4.6	4.1
		Realistic temp	2	3.8	4.0
E-modulus in tension	28	Isothermal	2	32200	27600
		Realistic temp	2	30500	30600
	91	Isothermal	2	32800	31000
		Realistic temp	2	31000	30300

*) *Maturity days*

Table 5. Property development between 28 and 91 days, 20 °C isothermal and realistic curing conditions

		Δfc [MPa]	*Δft* [MPa]*	*ΔEt [MPa]*
ANL Ref.	Isothermal	2.8 (3%)	0	600 (2%)
	Realistic temp.	4.6 (6%)	-0.4 (-9%)	500 (2%)
ANL FA33	Isothermal	8.4 (15%)	0.9 (27%)	3400 (12%)
	Realistic temp.	4.0 (7%)	0.7 (21%)	-300 (-1%)

*) *There was a rather pronounced variation within the sets of 2 parallel specimens*

Figures

Figure 1. Temperature-controlled moulds connected to a Julabo temperature-control unit: after sealing of the prisms, but prior to placing the insulation and top-cover on the container.

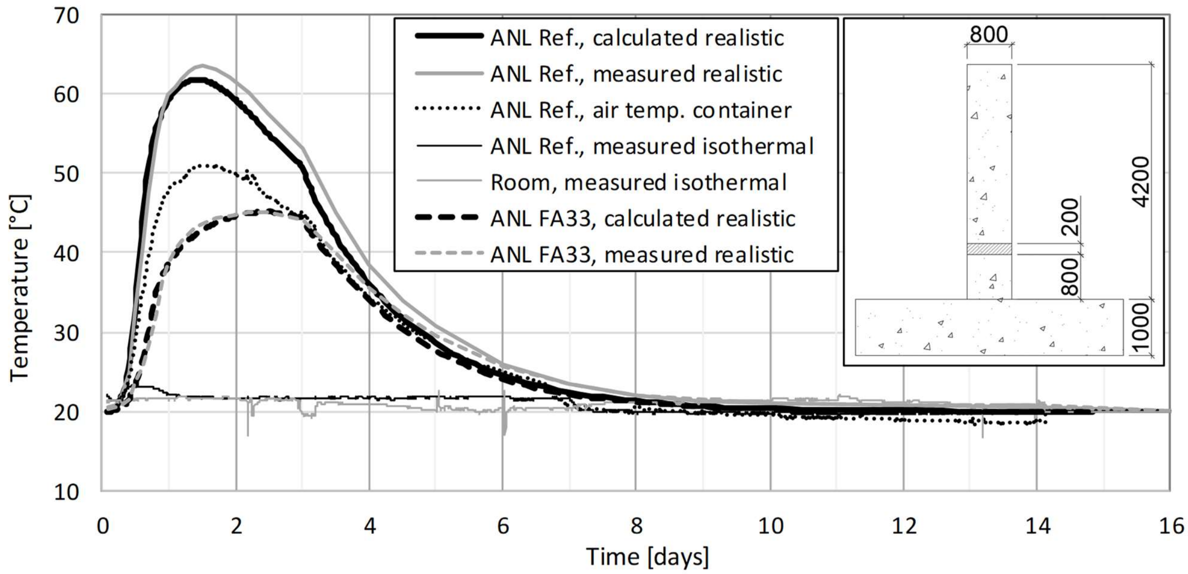
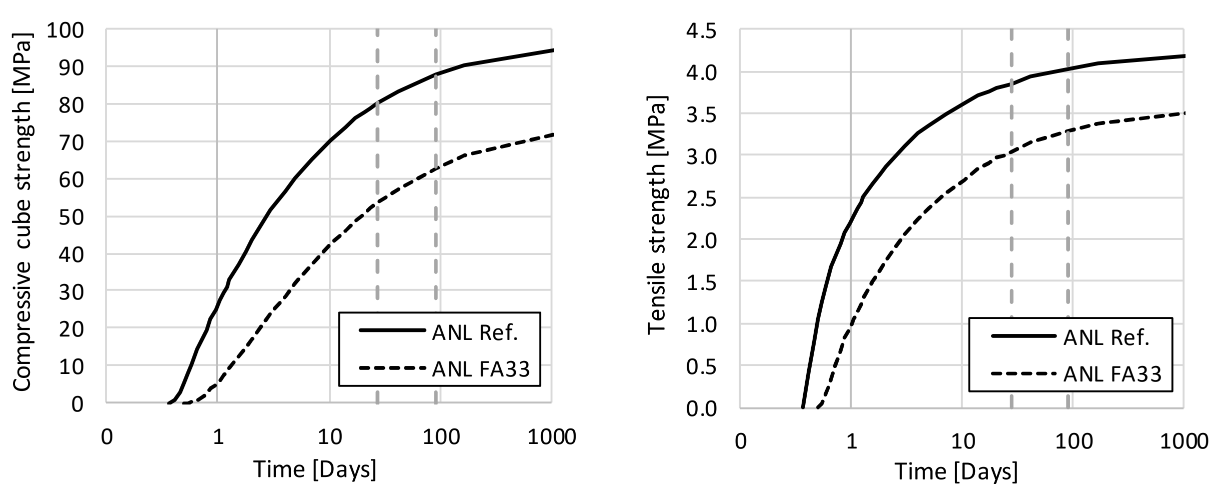


Figure 2. Calculated temperature history in the hatched area of the wall, and typical temperature histories measured during testing

a) b)



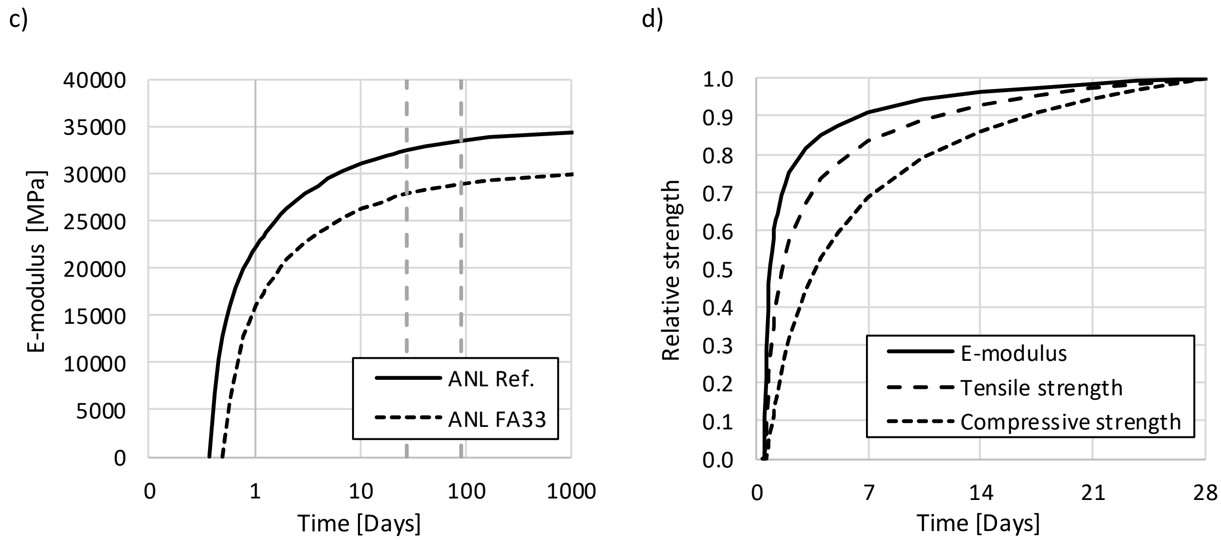


Figure 3. Material models: a) Compressive cube strength, b) Tensile strength, c) E-modulus, and d) Relative strength values for ANL FA33

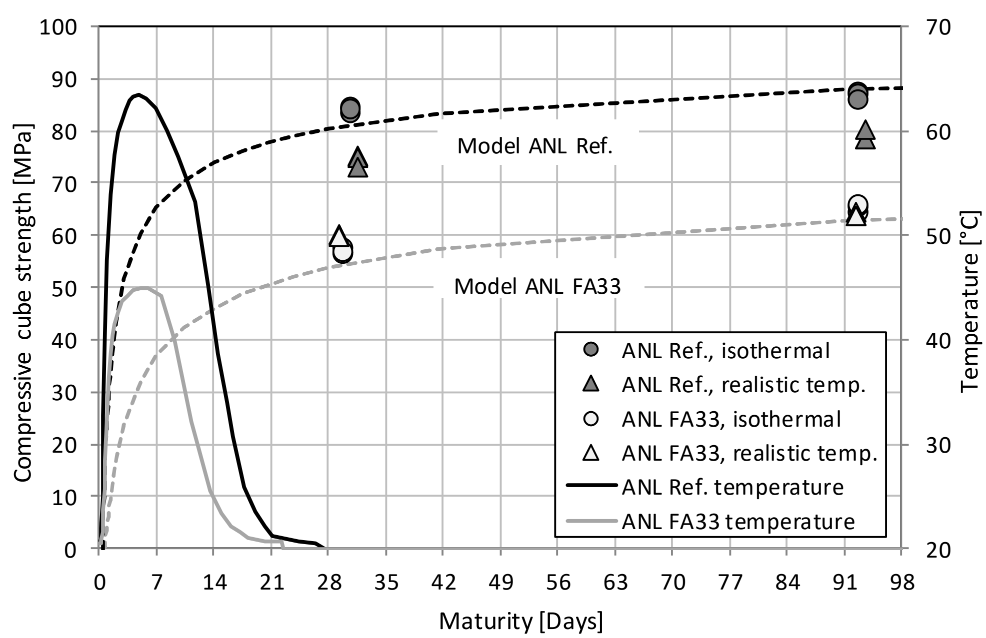


Figure 4. Compressive cube strength, ANL Ref. and ANL FA33

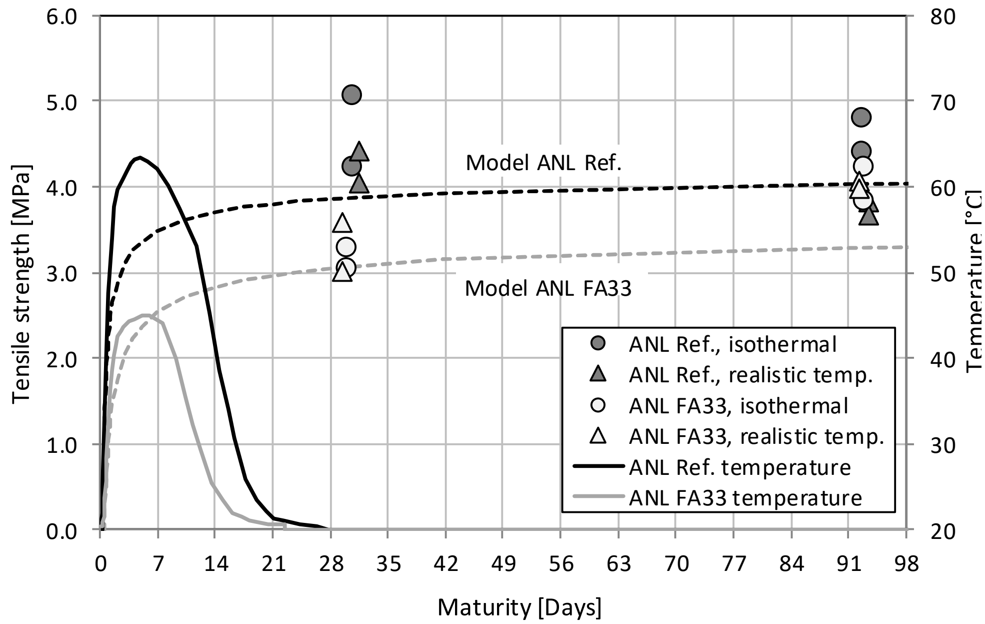


Figure 5. Tensile strength, ANL Ref. and ANL FA33

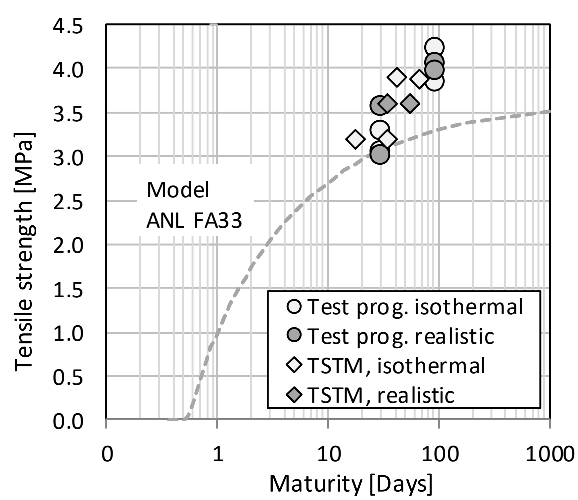


Figure 6. Tensile strength ANL FA33

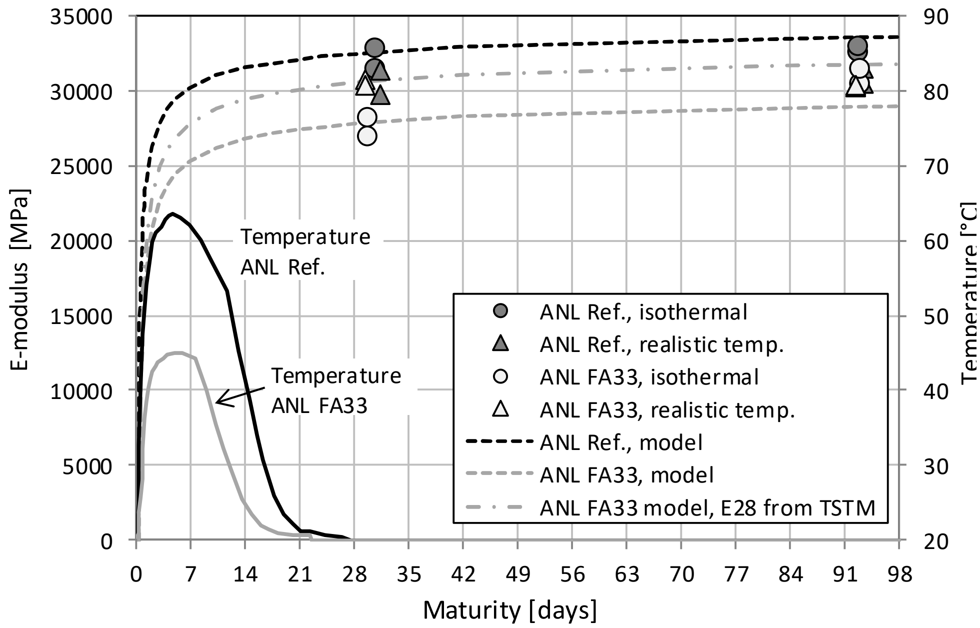


Figure 7. Tensile E-modulus, ANL Ref. and ANL FA33