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Development of Numerical Models to Predict the Compressive Strength of High Strength Concretes Based on Maturity Method

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Abstract: The aim of this study was to develop numerical models to predict the compressive strength of HSCs using Nurse-Saul and Arrhenius (NS-Arr) maturity functions. For this purpose, 9 concrete series with different concrete mix ratios of 400-450-500 kg/m3 binder dosage were produced. Silica fume was used instead of cement at the rate of 5-10-15% by volume and marble powder was used instead of fine aggregate at the rate of 8-10-12% by volume. While the specimens were kept in standard water curing, the temperature values were measured every 5 minutes at the end of the 1st, 3rd, 7th, 14th and 28th days to be used in the maturity test and the results were transferred to the computer. The compressive strength test was also performed in the same time periods. The data obtained from the test results were analyzed and a separate numerical model was developed for each maturity function applied. In addition, with the use of these models, it is thought that concrete compressive strength will be predicted with high accuracy in a short time, the project-work plan will be carried out without loss of time and environmental sustainability will be contributed.

Key words: High strength concrete, compressive strength, maturity, silica fume, marble powder.

Yüksek Dayanımlı Betonların Basınç Dayanımının Olgunluk Yöntemi Tabanlı Tahmin Eden Sayısal Modellerin Geliştirilmesi

Öz: Bu çalışmanın amacı, Nurse-Saul ve Arrhenius (NS-Arr) olgunluk fonksiyonlarını kullanarak yüksek dayanımlı beton (YDB)'lerin basınç dayanımını tahmin etmek için sayısal modeller geliştirmektir. Bu amaçla, 400-450-500 kg/m^3 dozajlı farklı beton karışım oranlarına sahip 9 beton serisi üretilmiştir. Çimento yerine hacimce %5-10-15 oranında silis dumanı ve ince agrega yerine hacimce %8-10-12 oranında mermer tozu kullanılmıştır. Numuneler standart kürde bekletilirken, olgunluk testinde kullanılmak üzere 1., 3., 7., 14. ve 28. günlerin sonunda her 5 dakikada bir sıcaklık değerleri ölçülmüş ve sonuçlar bilgisayara aktarılmıştır. Basınç dayanımı testi de aynı zaman dilimlerinde gerçekleştirilmiştir. Test sonuçlarından elde edilen veriler analiz edilmiş ve uygulanan her olgunluk fonksiyonu için ayrı bir sayısal model geliştirilmiştir. Ayrıca bu modellerin kullanımı ile beton basınç dayanımının kısa sürede yüksek doğrulukla tahmin edileceği, proje-iş planının zaman kaybı olmadan yürütüleceği ve çevresel sürdürülebilirliğe katkı sağlanacağı düşünülmektedir.

Anahtar kelimeler: Yüksek dayanımlı beton, basınç dayanımı, olgunluk, silis dumanı, mermer tozu.

1. Introduction

In the concrete industry, determining the compressive strength at the construction site with non-destructive tests is of great importance in terms of knowing the project durations. For example, in order to remove the moulding as soon as possible after pouring the concrete in place, it is of great benefit to take advantage of knowing the strength gain time of the concrete depending on the temperature increase in the concrete. The maturity method, which is one of the non-destructive testing methods, is also a method that helps the progress of constructions to be made safely. This method provides a simple approach to the determination of concrete compressive strength [1, 2]. The maturity method is related to the temperature sensitivity of early strength development and there is no single maturity function applicable to all concrete mixes. The applicable maturity function for a given concrete can be obtained by measuring the variation of the rate constant with the curing temperature [1].

Numerous studies and standards recommend the evaluation of the initial strength development of concrete according to the temperature history of the sample using the maturity method [3]. The maturity curves available in different concrete mixtures, developed based on the temperature increase, are used to estimate the early age strength of concrete [4,5]. In other words, this approach is based on the correlation between the compressive strength of cement, which is directly related to the internal temperature, and the rate of hydration [6]. Frequently

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used functions to calculate the maturity index of concrete from the measured temperature history are described in ASTM C1074 [5]. ASTM C1074 includes two different maturity functions: The first is the Nurse-Saul equation, which estimates the compressive strength of concrete depending on the temperature change [7]. The second one is the Arrhenius (Freiesleben Hansen and Pedersen) equation developed depending on the activation energy [8]. Apart from these equations, different maturity equations have also been proposed, but they are not explained in detail due to the lack of in-depth analysis of their reliability and limitations [9].

Although the maturity method is generally used in conventional concretes, no study has been found in the literature regarding its use in high strength concrete (HSCs). In this study, the applicability of maturity functions in determining the compressive strength of HSCs was investigated and numerical models were developed to predict concrete compressive strength. HSCs are special types of concrete with low water/cement (W/C) ratio, extremely durable and advanced mechanical properties [9,10]. Many HSC applications in the United States, Germany, Canada, France and Turkey have demonstrated the advantages of this concrete type [11,12]. Determining the project duration is one of the most important conditions when constructing these high-strength structures. It is very important that the project is completed in the targeted time before the start of production. When the project period is exceeded, significant additional costs come and financial problems are experienced. One of the most important issues affecting this period is the duration of the concrete to gain strength. The speed of the project depends on the demoulding removal and moulding advancement speed. The parameter that directly affects this speed is the concrete compressive strength. Methods for determining the compressive strength of concrete are explained in the standards of many countries such as European Standard, ACI and TSE [13, 14]. These methods are destructive test (DT) and non-destructive test methods (NDT) [15]. Evaluation with the coring method in the DT method is quite expensive and time consuming. It is also difficult and impractical in some cases [16]. The application of the NDT method provides many conveniences in terms of time, cost and labor. The NDT method provides the opportunity to evaluate the durability, homogeneity and internal structure of the concrete as well as the strength property of the concrete [17,18,19].

Real-time evaluation of concrete compressive strength by maturity method, which is one of the non-destructive test methods, is of great importance for the construction industry. The maturity method provides a simple and applicable approach to evaluate the compressive strength of concrete. Although this method is currently used in conventional concretes, no study has been found in the literature regarding its application in HSCs. The aim of this study is to develop numerical models that predict the compressive strength of concrete using Nurse-Saul and Arrhenius (NS-Arr) maturity functions for HSCs. Accordingly, 9 concrete series with different concrete mixing ratios with cement dosage of 400-450-500 kg/m^3 were prepared. In the prepared concrete mixtures, silica fume was used by replacing the cement at 5-10-15% by volume, and marble powder by replacing 8-10-12% by volume with fine aggregate. The produced samples were kept in the standard cure. According to the C1074 standard, the temperature values were measured every 5 minutes at the end of the 1st, 3rd, 7th, 14th and 28th days for the maturity test and the results were transferred to the computer [20]. A multi-channel temperature measuring device was used for temperature measurement. Compressive strength test was also applied in the same time periods. The data obtained from the test results were analyzed and a separate numerical model was developed for each maturity function applied. As a result, by estimating the compressive strength of concrete with high accuracy with the obtained numerical models, it was ensured that the production times were determined during the design phase and accurate determinations were made during the manufacturing phase in special projects using HSC. In Figure 1, the experimental procedure is presented schematically.

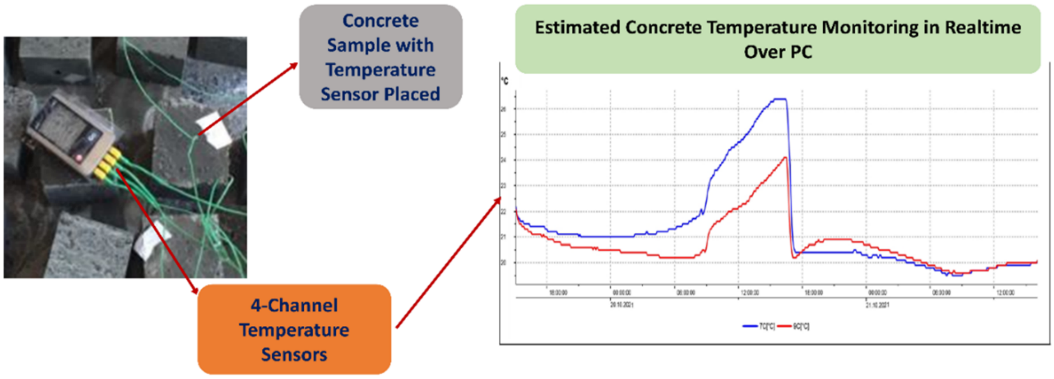


Figure 1. Experiment Procedure.

2. Materials and Methods

Within the scope of the study, CEM I 42.5 R portland cement produced in accordance with TS EN 197-1 standards and supplied from the Elazig Seza cement factory was used as the binder in the production of HSC [21]. Andesite aggregate, silica fume from Antalya Eti metallurgy and marble powder from Elazig organized industrial zone were used. The physical and chemical properties of the HSC components are presented in Table 1.

Table 1. Physical and chemical properties of using materials (%).

Chemical Properties	Cement (C)	Silica Fume (SF)	Marble Powder (MP)
CaO	63.19	0.40	40.45
SiO_2	19.07	94.10	28.35
Fe_2O_3	3.72	1.50	9.70
Al_2O_3	4.82	0.90	0.17
SiO_3	2.94	94.10	0.02
Na_2O	0.39	0.40	0.05
K_2O	0.62	0.90	0.01
MgO	1.83	0.10	16.25
Cl	0.0101	-	-
Insoluble residue	0.56	-	-
Loss of ignition	3.43	-	4.84
Physical Properties			
Specific surface cm^2/g	3838		3920
Specific gravity g/cm^3	3.13	2.20	2.71
Initial setting time (min)	135	-	-
Final setting time(min)	215	-	-
Total volume exp. (mm)	1	-	-

The suitability of andesite aggregate for use in HSC was determined by performing aggregate tests at the first stage (Table 2) [22]. Andesite aggregate is a material containing 52-63% quartz [23]. It is suitable for use in high-strength concretes due to its dark-colored, non-water-absorbing, water-dispersible and dense texture [24]. The maximum aggregate particle diameter used in the experimental study was 16 mm, and the aggregates were divided into 4 different groups as 0-2 mm, 2-4 mm, 4-8 mm, 8-16 mm (Table 3). Sieve analysis graph of the aggregate is presented in Figure 2.

Table 2. Los Angeles experiment results.

Number of marbles	Interval class	Load of marbles	Initial Weight	Weight after 500 cycles	Weight loss after 500 cycles
12	8-16 mm	5030 gr	5000 gr	4569.5	430.5
Aggregate Abrasion Resistance = L_A = 8.61					

Table 3. Mixing ratios of aggregate used (Saturated dry surface, gr/cm^3.

Aggregate size	Andesite	Mixing ratio (%)
0-2 mm	2.74	30
2-4 mm	2.71	20
4-8 mm	2.69	20
8-16 mm	2.69	30

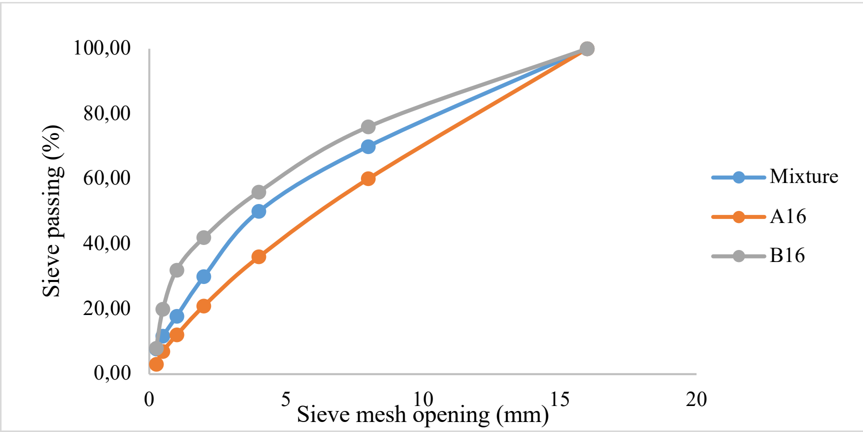


Figure 2. Aggregate granulometry curve.

After the aggregate tests, a pozzolanic activity test was performed for the mineral additive silica fume (Table 4). Pozzolan is a material that does not have a binding property on its own, but gains binding properties when it is finely ground and combined with calcium hydroxide in an aqueous medium. Silica fume is one of the most commonly used mineral additives with fine grain properties in materials science [25, 26]. In order to determine the adequate pozzolanic activity of silica fume, which is a pozzolanic material, pozzolanic activity tests are carried out in accordance with TS EN 196-2 standards [27]. In the same way, pozzolanic activity test was performed for silica fume and the pozzolanic activity index was determined with the help of the equation given in Equation 1 [28]. The P.A.I values obtained as a result of the experiment provided the relevant standard.

$$\text{Pozzolanic Activity Index (P.A.I)} = \left((A)/B \right)*100 \tag{1}$$

A : Average compressive strength of mortar samples with pozzolan
B : Average compressive strength of control mortar samples

The marble powder used in the concrete mixture was used to create a filling effect. In order to determine the usage rate of marble powder in concrete, many trial mixtures were poured and the optimum usage rate was determined [29, 30].

Table 4. Pozzolanic activity test results.

Control Sample (CS)			Pozzolan Sample (PS)		
	$f_c(7)$	$f_c(28)$		$f_c(7)$	$f_c(28)$
CS-1	27.6	40.6	PS-1	29.3	39.2
CS-2	28.1	37.1	PS-2	27.2	45.5
CS-3	25.8	39.4	PS-3	25.9	46.4
CS-ORT	27.2	39.0	PS-ORT	27.5	43.7

2.1. Preparation of Test Samples

Within the scope of the study, a wide range of trial mixes were poured in the first stage. As a result of these castings, 9 reference concrete mixes with dimensions of 100x100x100 mm were prepared with a W/C ratio of 0.20-0.25-0.30 and a binding material (cement + silica fume) dosage of 400-450-500 kg/m^3. (Table 5). In the series names in the table, the M value represents maturity and in the HSC400-25 expression, the value 400 represents the dosage and the value 25 represents the W/C ratio. Silica fume cement and marble powder were used as mineral additives in the prepared concrete mixtures by volume substituting with fine aggregate. The total amount of binder was kept constant. In all mixtures, CHRYSO Fluid 518 hyperplasticizer was used as a chemical additive at the rate of 3% of the cement amount.

Table 5. Mixture amounts of M-HSC (kg/m^3).

Serial Name	Cement	Water	Silica Fume	Marble Powder	Fine Aggregate (0-2) mm	Fine Aggregate (2-4) mm	Medium Aggregate (4-8) mm	Coarse Aggregate (8-16) mm
M-HSC400-1	400	80	28.1	103	559	368	406	609
M-HSC400-2	400	100	14.1	101	550	362	400	599
M-HSC400-3	400	120	14.1	79	547	360	389	583
M-HSC450-1	450	90	47.4	78	544	358	387	580
M-HSC450-2	450	113	47.4	114	504	332	374	562
M-HSC450-3	450	135	31.6	74	516	340	367	550
M-HSC500-1	500	100	17.6	116	513	338	381	572
M-HSC500-2	500	125	35.1	95	517	341	376	564
M-HSC500-3	500	150	52.7	87	473	312	344	516

2.2. Application of Maturity Tests

This study was carried out to develop numerical models that predict concrete compressive strength with high accuracy by using Nurse-Saul and Arrhenius maturity functions separately. With these maturity functions, the compressive strength of early age concretes can be estimated and the demoulding time can be determined. Thus, advantages are provided in terms of project duration, time and cost [31]. In the study, firstly, the Nurse-Saul method given in Equation 2, in which the compressive strength of the concrete is estimated by looking at the temperature history, was used.

$$M = \sum_0^t (T - T_0) * \Delta t \tag{2}$$

Here;
M = Maturity index (°C-hours or °C-days)
T = Average concrete temperature (°C)
T_0 = Reference temperature
t = Elapsed time (day or hour)
Δt = Time range (day or hour)

Copeland et al. in 1960 suggested that the effects of cement hydration on the strength gain rate of concrete can be described by the Arrhenius equation. In 1977, Freisleben Hansen and Pedersen proposed the following equation for equivalent age based on the Arrhenius equation (Equation 3) [7]. The application and numerical values related to the experiment are explained in ASTM C1074 [20].

$$t_e = \sum_0^t e^{-\frac{E}{R}\left(\frac{1}{273+T} - \frac{1}{273+T_r}\right)} \Delta t \qquad (3)$$

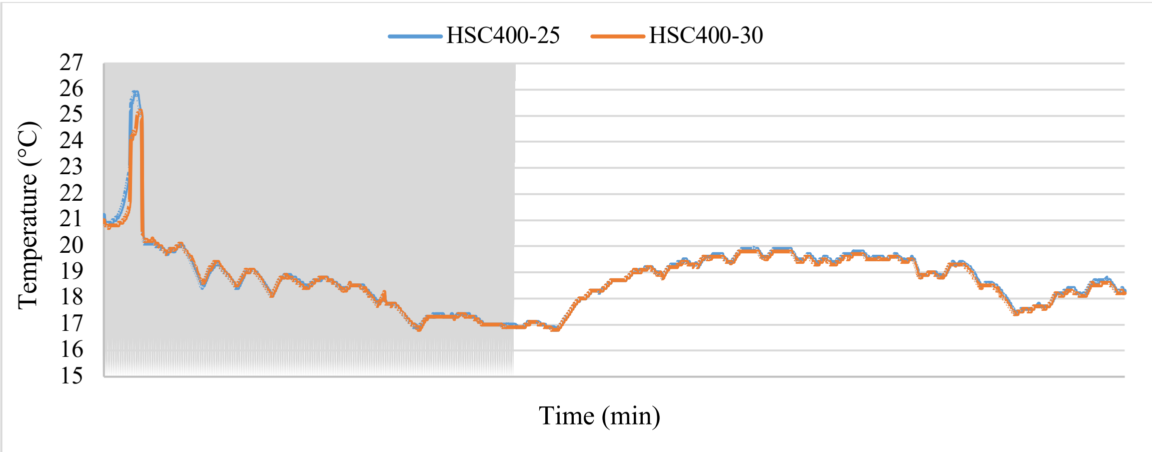
Here;
t_e = Equivalent age at reference temperature
E = Apparent activation energy
R = Universal gas constant
T = Average absolute temperature of concrete
T_r = Reference temperature

A multi-channel temperature measuring device was used to determine the concrete temperatures in the maturity calculations. The device was set up to take measurements every 5 minutes after the concrete was poured and placed in the mold and placed in the samples (Figure 3).

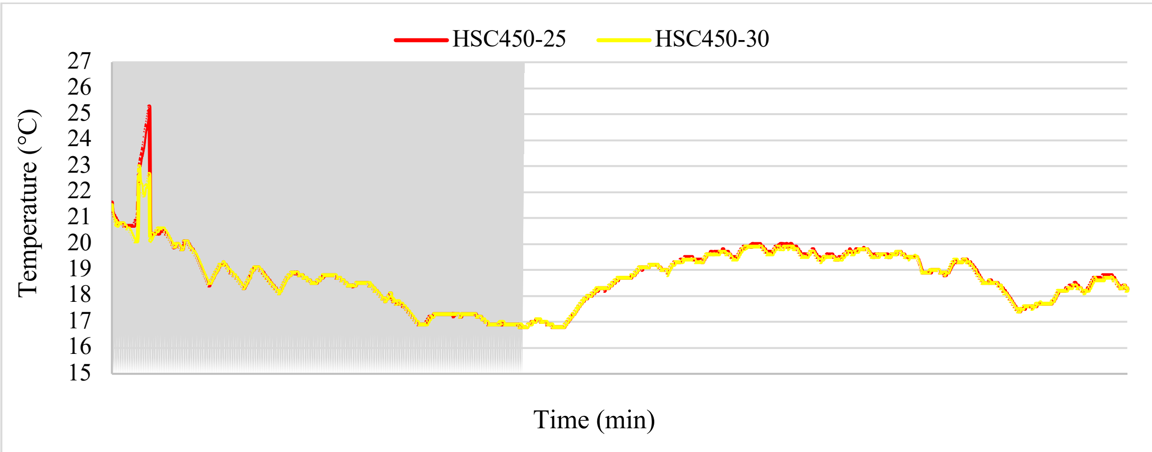
Figure 3. Placement of the temperature measuring device.

2.3. Measurements on Concrete Samples

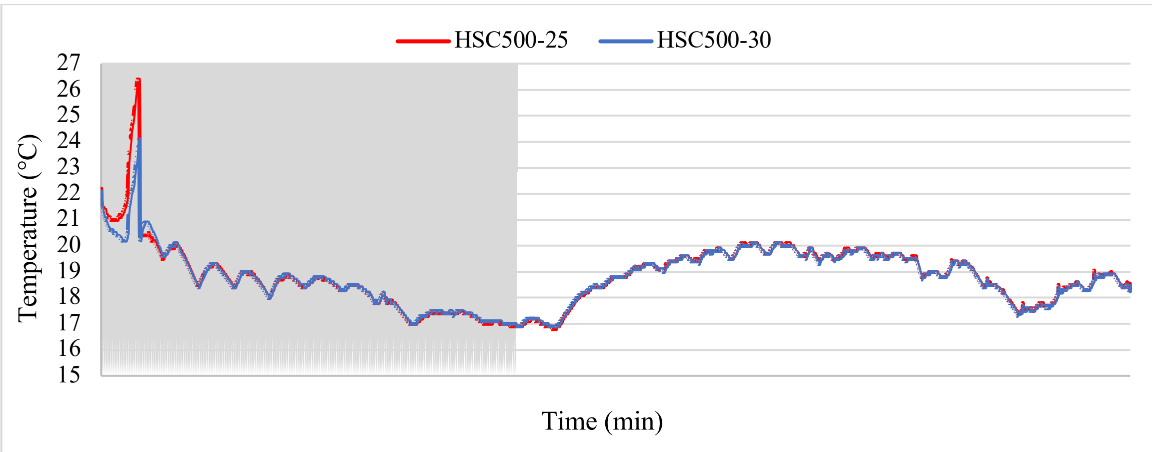
Temperatures were measured from the beginning of the concrete casting and the temperature results taken every 5 minutes at the end of the 1st, 3rd, 7th, 14th and 28th days within the scope of the C1074 standard were transferred to the computer. The time-dependent graph of these temperatures is given in Figure 4. Figure 4 shows the time-dependent variation of the temperatures forty-eight, ninety-six hours after the concrete is placed in the mold, and the average temperatures of one hundred and ninety-two, three hundred and sixty-six hours after it is placed in the mold.



(a)



(b)



(c)

Figure 4. (a) Temperature values of 400-dose series (b) Temperature values of 450-dose series (c) Temperature values of 500-dose series.

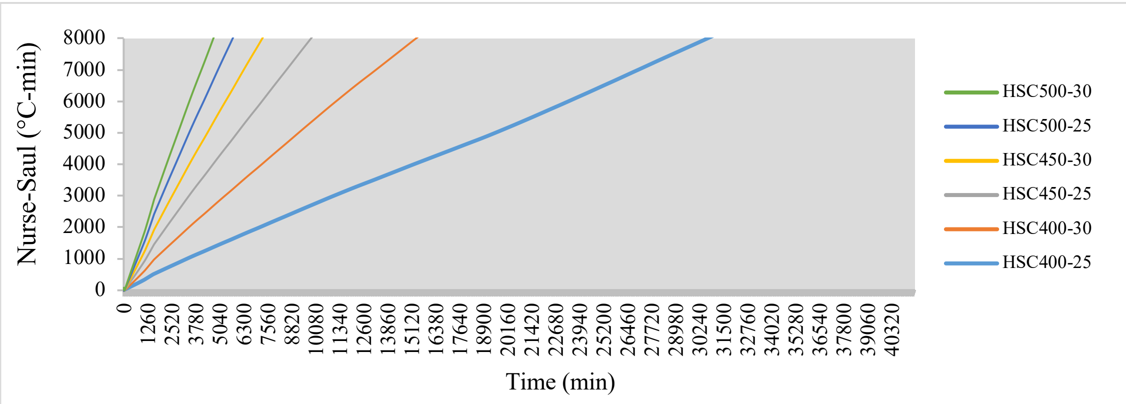
When Figure 4 is examined, the temperature values of the series in which the W/C ratio is 0.25 and 0.30 are given. Since there is not enough water in the environment as specified in the C1074 standard in the series with a W/C ratio of 0.20 and proper hydration has not occurred, the data of these series were not evaluated.

3. Evaluation of Experimental Results

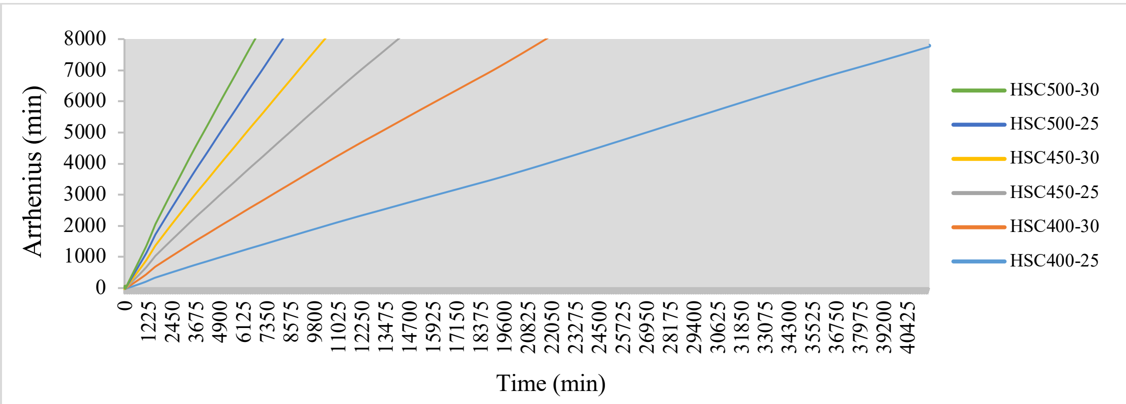
3.1. Concrete Temperature Values and Evaluation

Concrete temperatures were obtained using a multi-channel temperature measuring device. This temperature measurement started from the placement of the concrete in the mold (Figure 5.) When Figure 5 is examined, it is seen that the temperature change varies according to the usage rate of the materials in the concrete composition. For example, it is clearly seen that the temperature value of the series with a binder dosage of 500 and a W/C ratio of 25% is higher than the temperature value of a series with a binder dosage of 400 and a W/C ratio of 25%.

The temperature values in Figure 2 and the maturity functions in Equation 2 and Equation 3 were calculated separately and the Nurse-Saul-Zaman and Arrhenius-Zaman graphs given in Figure 4 were obtained.



(a)

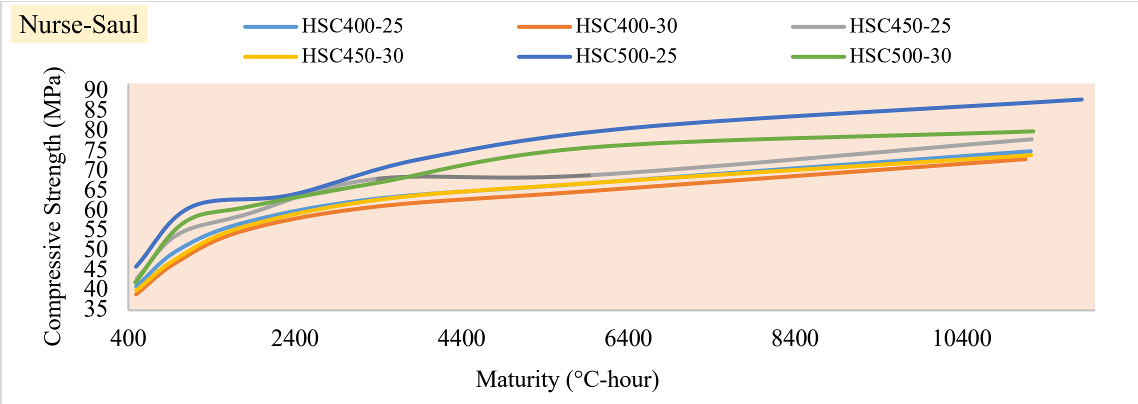


(b)

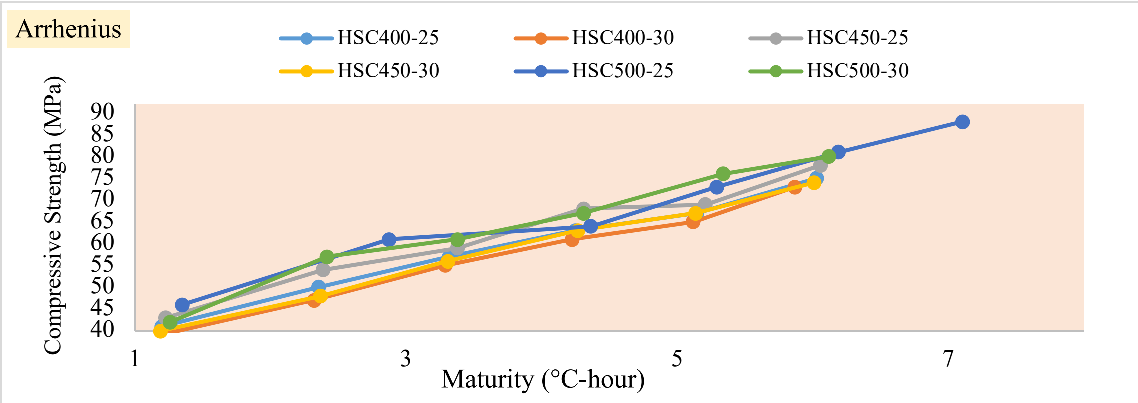
Figure 5. (a) Nurse-Saul values-Time (b) Arrhenius values-Time comparisons.

In the Figure 5 showing the time-dependent variation of the maturity function, it is seen that the binder dosage and maturity values are directly proportional. As the dosage value increases, the hydration increases, so the maturity value also increases. When evaluated in terms of W/C ratio, the maturity value was found to be higher in the 400 and 450-dose series in which the W/C ratio was 30%. This indicates that sufficient water for hydration is found in series with a 30% W/C ratio. In the 500-dose series, the maturity value of the series in which the W/C ratio was 25% was high.

The relationship between maturity values calculated by Nurse-Saul and Arrhenius equations and compressive strength is shown in Figure 6.



(a)



(b)

Figure 6. Comparison of (a) Compressive strength-Nurse-Saul values (b) Compressive strength-Arrhenius maturity values

In Figure 6, it is seen that there is a linear relationship between maturity and compressive strength depending on the change in concrete temperature. In accordance with the C1074 standard, the compressive strength value of the concrete increases with the increase of the maturity value [20].

3.2. Numerical Models

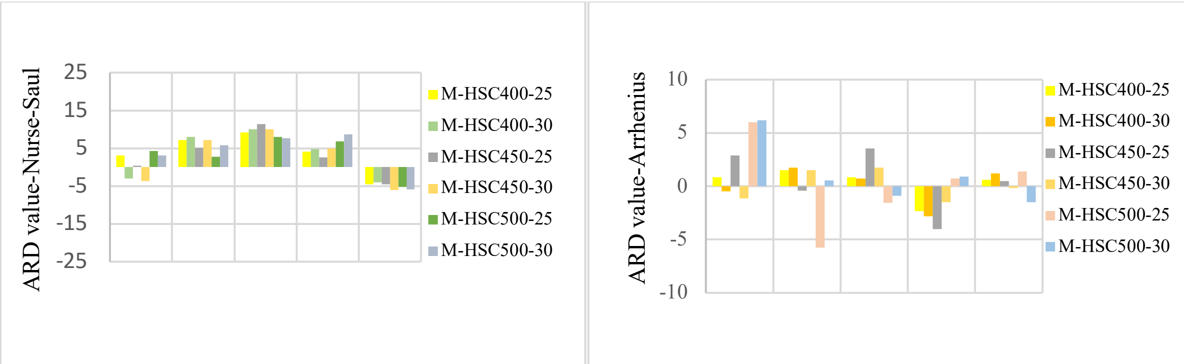
In this study, NS and Arr results were used in the design phase of the numerical models. The numerical models developed to predict the compressive strength values in the equations with high accuracy are given in the equation below. The parameters used in the equations refers to M is the maturity and fc is the compressive strength value (Table 6).

In Figure 7, the estimation results and ARD values obtained by the numerical models developed with the experimentally calculated compressive strength values are given. When the experimental values and predicted values are compared, it is seen that the ARD values of the developed models are below 10%. It was noteworthy that all these values were below 5%, especially for early age strength. When the ARD values of the Arrhenius maturity function were examined, it was noted that it was the maturity function that predicted fc with the highest accuracy. Especially in fc-1 daily strength values, highly accurate predictions were made and ARD values were below 1% for almost all other days.

Although the ARD results estimated by the Nurse-Saul equation are higher than the ARD results obtained by the Arrhenius equation, the compressive strength values obtained with this function also have high accuracy.

Table 6. Numerical models developed with NS and Arr maturity methods.

Serial Name	NS	Arr
M-HSC400-25	$f_c = 0.0027M + 48.131$	$f_c = 6.7943M + 33.573$
M-HSC400-30	$f_c = 0.0027M + 45.805$	$f_c = 7.0137M + 30.937$
M-HSC450-25	$f_c = 0.0027M + 51.143$	$f_c = 6.8513M + 36.05$
M-HSC450-30	$f_c = 0.0028M + 46.995$	$f_c = 7.0219M + 31.914$
M-HSC500-25	$f_c = 0.0032M + 54.705$	$f_c = 6.9625M + 37.284$
M-HSC500-30	$f_c = 0.0029M + 52.118$	$f_c = 7.4902M + 35.333$



	M-HSC400-25			M-HSC400-30			M-HSC450-25			M-HSC450-30			M-HSC500-25			M-HSC500-30		
Days	fc	fc-NS	fc-Arr	fc	fc-NS	fc-Arr	fc	fc-NS	fc-Arr	fc	fc-NS	fc-Arr	fc	fc-NS	fc-Arr	fc	fc-NS	fc-Arr
1.	50	48.4	49.6	47	48.4	47.2	54	53.8	52.4	48	49.7	48.6	61	58.4	57.3	57	55.2	53.5
3.	57	52.9	56.1	55	50.6	54.0	59	56.0	59.2	56	52.0	55.2	64	62.2	67.7	61	57.4	60.6
7.	63	57.2	62.5	61	54.8	60.6	68	60.2	65.6	63	56.7	61.9	73	67.2	74.2	67	61.9	67.6
14.	67	64.2	68.6	65	61.9	66.8	69	67.3	71.8	67	63.7	68.0	81	75.5	80.4	76	69.5	75.3
28.	75	78.4	74.5	73	76.0	72.1	78	81.5	77.6	74	78.4	74.1	88	92.6	86.8	80	84.8	81.2

Figure 7. Experimental and predicted results.

4. Conclusions

In this study, numerical models were developed to predict the compressive strength of HSCs using NS and Arr maturity functions. In particular, to verify the validity of the maturity functions proposed so far, compressive strength-Nurse-Saul maturity function and compressive strength-Arrhenius maturity functions were compared and their suitability was determined. As a result of the study, the following conclusions were drawn:

1- The strength-maturity curve in each series of concrete mixtures followed the literature.
2- It has been determined that the maturity method can be used for HSCs, and it has been observed that the Arr method gives higher accuracy results in estimating the compressive strength of HSCs.
3- The average relative error percentage in estimating the compressive strengths of concrete varies between 0.1% and 10.1%. Mixtures producing the highest errors were generally found in the calculation made by the Nurse-Saul method. The compressive strength values obtained by the Arehnius method were closer to the experimental results.
4- In series with low W/C ratio, strength losses occurred due to insufficient hydration. Therefore, it is recommended to be more careful in the estimations to be made with the maturity method as the W/C ratio decreases in practice.
5- By using the maturity method and determining the strength gaining time of the concrete, the demoulding times can be determined. Thus, the problem of getting molds early is eliminated and an advantage is provided in determining the project durations.

6- In the current maturity functions, the concrete temperature is taken according to the standards. Concrete compressive strength can also be determined more accurately and with higher accuracy by obtaining the temperatures with high accuracy by using a temperature measuring device in concrete.
7- Verification of proposed modifications for in situ concrete strength estimation should also be done, especially for concretes made with different types of cement and additives.

As a result, the places where HSCs are used in practice are special productions. Therefore, the duration of the project is of great importance in such productions. The most important parameter for the construction to progress in accordance with the project period is the molding time. Since this period cannot be calculated correctly, the maturity method has emerged as a sensitive, fast and practical method. The use of this method will ensure that the concrete compressive strength is correctly estimated and the construction will continue in a healthy way in terms of strength and will proceed without loss of time in the project-work plan.

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