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A unified approach for temperature and strength control of concrete

Abstract. The development of theoretical and experimental research in the field of quality control has led to the development of many methods for assessing the strength of concrete. The temperature-strength control (TSCC) method, which is based on the relationship between concrete temperature and curing time, is the most adapted method for quickly determining the strength of the concrete in the formwork during the early phase of curing. The concrete strength tests must be carried out in accordance with the requirements of the standards. The most adapted standards are ASTM C1074 (USA); NEN 5970 (Netherlands); ST-NP SRO SSK-04-2013 (Russia). However, there are no existing approaches to TSCC that consider all the advantages of each method. Using the method of paired comparison, the authors determined the weights of the significance of each criterion of methods and tasks for TSCC. Based on of the obtained results a unified approach to temperature-strength control of concrete has been formed considering the assessment of its applicability. This approach will solve the problem of limitation of the application of most methods, which in its basis have the best methods in solving tasks of control stages. The unified approach to temperature-strength control of concrete will allow to achieving high quality and durability of concrete and reinforced concrete structures.

Keywords: standard; concrete curing temperature; non-destructive testing of concrete; embedded sensor.

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Introduction

The fixing of the concrete hardening temperature enables timely monitoring of the concrete hardening process, its regulation and forecasting during documentation. In addition, as numerous studies have shown [1-4], the temperature factor is fundamental in determining the required concrete properties. When concrete strength is controlled using various measuring systems, the current temperature values are sent to the measuring instrument. The temperatures and measuring times are used to calculate the current strength of the concrete. The standards specify methods of determination of concrete hardness. Each of the existing methods has a specific scope of application and has advantages and disadvantages. However, the possibility of using alternative methods of temperature-strength control of concrete (TSCC) in practice is limited due to the lack of relevant normative and technical documents, regulations, and standards. In this regard, the development of a unified approach to TSCC will serve as an important tool for controlling temperature and strength gain during all stages of concrete curing. The approach should incorporate best practice techniques from around the world, as global experience is an important factor in the choice of techniques and objectives for TSCC.

Analysis of best practices from around the world to TSCC

The software "Snow Leopard" was applied in the study [5], which allows to predict the final strength of concrete and the time of cooling, and in case of negative predictions to choose the heat treatment mode or the required thermal insulation. Another advantage of the program is the possibility to automate the data entry process, obtained from multi-channel recorders, which increases quality, accuracy, and productivity. Registration of temperature at the enterprise was carried out using device Terem-4.1.When observing the temperature of the concrete at reference points, a temperature-strength control list is drawn up. With the help of "Snow Leopard" program schedules of temperature changes and concrete strength gain were built for each of the control points.

In a study [6] to control the temperature of concrete curing, cube specimens were made of fine-grained concrete of class B25, size 100*100*100 mm using Portland cement of grade M400. The samples were placed in the body of the heated volume of the floor slab structure model. Temperature measurement data were entered in the on-site computer and processed using a program that performs a complete analysis of temperature parameters of concrete with the determination of concrete strength at control points [6].

In April 2019, a construction company specializing in complex projects began experimenting with Giatec SmartRockTM sensors during the construction of a major arch bridge project [7]. To investigate the benefits of using SmartRock technology, the team conducted extensive testing by embedding the sensors at key points on the bridge. By placing the sensors in the center and at the edge of the arch, the strength gain was measured at different locations in the reinforced concrete element. The sensor placed at the edge recorded a lower temperature profile and therefore the lowest strength gain. Whereas sensors placed in the center of the arches measured the point of greatest temperature and strength gain. By monitoring these locations, the actual strength of the concrete element at the critical point was measured. This is only possible with the sensors, as the laboratory samples cannot reproduce the actual curing conditions of the concrete element.

CIBC Square (Ontario, Canada) is a highly visible pair of innovative 3 million square foot office towers in the city center. Exact Technology sensors were used in the construction of the facility. These precision devices provide concrete maturity monitoring at CIBC Square to determine when concrete strength is approaching the 16 MPa threshold [8] that allows self-compacting formwork to be moved, and formwork pressure readings for self-compacting mix loads. Relays, recorders, and probes are in the center of the Exact sensor for maturity and temperature control. The use of the sensors has had a positive effect on construction.

The study [9] recommends the use of three or more marks per gauge to obtain the most accurate maturity and strength. This leads to the conclusion that the maturity of the poured concrete will depend on the lowest slab temperature and not necessarily on the temperature in the middle of the slab.

In the study [10] three concrete mixtures were considered: the first mixture of pure Portland cement, the others included a partial replacement of cement with fly ash and ground granulated blast furnace slag at 30 % respectively. In this work the reference temperature was chosen to be 11°C, which is an average value among those recommended [11]. The concrete specimens in the single cube moulds were covered with polyethylene foil immediately after pouring and cured at room temperature (approx. 20 °C) [12] for one day. They were then removed from the moulds and placed in a water bath set at 20 °C. A computer-controlled programmable water bath was used to simulate the temperature conditions in situ. The test ages of the standard curing concrete specimens were 1, 2, 3, 5, 7, 14, 28, 42, 84, 156, and 365 days, while the temperature cured concrete specimens were tested at 1, 2, 3, 3, 7, 14, and 28 days. According to [13], "equivalent" mortar mixtures can be used to determine the activation energy of concrete mixtures. The Dutch method for determination of maturity and the method for determining the equivalent age depends on the mix and require the determination of a weighted Cn factor and activation energy. A close convergence between the strength data at 20°C and 50°C was not obtained. Thus, the authors note the difficulties encountered in additional investigations with the Dutch method and the Arrhenius equation method for determining maturity.

The authors [14] monitored the hydration temperature continuously after the concrete was poured and temperature sensors provided data to assess the degree of maturity of the concrete as it hardened. The hydration temperature history data was applied to the Nurse-Saul function to predict the maturity index.

Research methods

By analyzing the best practices reviewed, it is possible to identify certain techniques and tasks of the methods used in them (i.e. methods of temperature and strength control of concrete), which have led to the effectiveness of the results obtained in the particular best practices. The list of these techniques and tasks is interpreted and presented in Table 1.

Table 1

List of techniques and tasks of best practice TSCC methods

Methods	Techniques and objectives
Best practice 1 [5]	
ST-NP SRO SSK-04-2013 [15]	The use of the "Snow Leopard" software made it possible to predict the concrete strength, cooling time and achievable final strength of the concrete; statistical processing of the results was carried out.
Best practice 2 [6]	
ST-NP SRO SSK-04-2013 [15]	The use of the program made it possible to determine probabilistic estimates of concrete strength and to advise on continuing heating and curing times for the entire sample of homogeneous structures under the prevailing curing conditions.
Best practice 3[7]	
ASTM C 1074 [13]	Sensor placement was carried out at key locations. By creating a maturity calibration, using and interpreting the SmartRock sensor data, the strength of the concrete was determined. A simple interpretation of the temperature graphs and monitoring of the concrete's strength development saved time.
Best practice 4 [8]	
ASTM C 1074 [13]	Wireless sensors were installed in the concrete formwork, fixed to the reinforcement, before pouring. Temperature data was collected by the sensor and there was no difficulty in using it. The concrete strength was calculated using the Nurse-Saul temperature-time factor.
Best practice 5 [9]	
ASTM C 1074 [13]	Particular attention was paid to the location of the concrete temperature measuring points, which allowed the most accurate determination of maturity, and showed that the maturity of the poured concrete would depend on the lowest slab temperature, and not necessarily on the temperature in the middle of the slab.

Best practice 6[10]	
ASTM C 1074 [13]	It is noted that the mixture calibration method is very simple, having made a minimum of 17 cylinders; 2 were used for temperature monitoring and the remaining samples for determining the compressive strength. By selecting minimum 5 time intervals, 1, 3, 7, 14 and 28 days, for each day the compressive strength of two cylinders was determined, during the intervals data was also obtained from two cylinders which were used for temperature monitoring and the average value of these values was determined. Entering these values into the Nurse-Saul function or the Arrhenius method gave a maturity value. To calculate the Arrhenius method, additional investigations were carried out to determine the activation energy, which was a time consuming process. The Nurse-Saul function does not differentiate the temperature sensitivity of different cement systems, especially for mixtures with different bases (with additives, accelerators).
NEN 5970 [16]	The "weighted maturity" method requires additional research, the determination of a weighted Cn coefficient, but in the study the strength data at 20 and 65 °C did not match.
Best practice 7[14]	
ASTM C 1074 [13]	The resulting Nurse-Saul concrete strength data provided accurate and reliable results. The application of the sensors did not cause any difficulty in use.

The main normative documents governing the requirements for TSCC are ASTM C1074 (USA); NEN 5970 (Netherlands); ST-NP SRO SSK-04-2013 (Russia), which are predominantly reflected in use, therefore, these standards were adopted for the analysis (Figure 1).

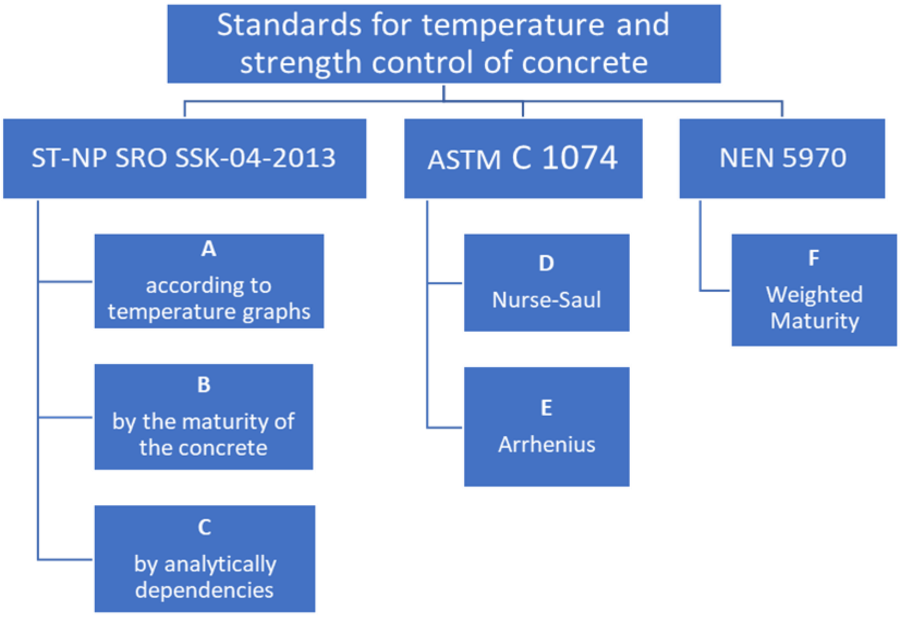

Figure 1. Standards for temperature and strength control of concrete

Three essential types of processes have also been defined: laboratory, field and resultant. Laboratory tests result in the acquisition of strength isotherms for a given type of mixture. Field tests are used to obtain data on concrete temperature, and the resulting calculation of concrete maturity. The sorted and classified science-based techniques and tasks of the TSCC methods are presented in Figure 2.

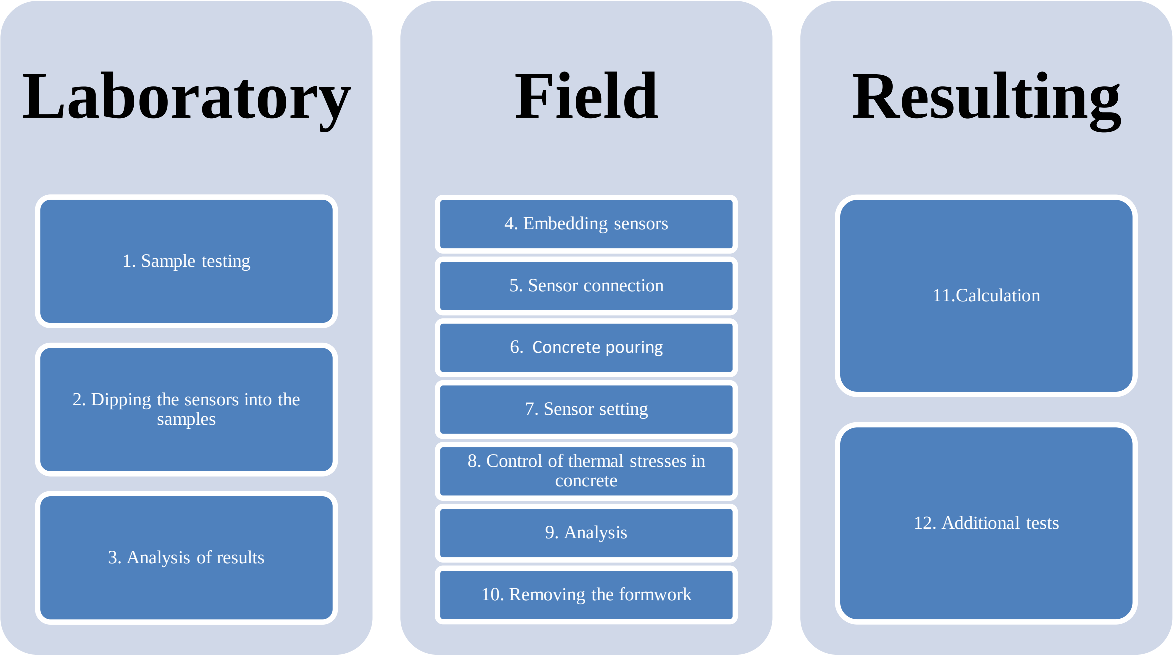

Figure 2. List of sorted and categorized evidence-based techniques and objectives of TSCC method

Based on the classified science-based techniques and tasks of TSCC methods (Figure 2), Table 2 presents a multi-criteria analysis based on the results of best practices, where the evaluation criteria for TSCC processes are: K1 - reliability of the method and availability of normative literature; K2 - possibility of application to various structures (by form, reinforcement, responsibility); K3 - labor input; K4 –the safety of testing; K5 - accuracy of calculations. The indexes are expressed in points from 1 to 10 with a scale of 1. A score of 10 indicates compliance with the quality criteria.

Table 2

Multi-criteria analysis

Process numbering as per Figure 2	Indicator	ST-NP SRO SSK-04-2013			ASTM C 1074		NEN 5970
		A	B	C	D	E	F
1	K1	10	10	10	9	9	9
	K3	10	10	10	8	8	8
	K4	9	9	9	9	9	9
	K5	10	10	10	8	8	8
2	K3	8	9	9	10	10	10
3	K1	6	9	10	8	8	8
	K3	5	10	8	9	6	8
	K5	8	10	9	10	9	10

4	K1	9	10	10	8	8	8
	K2	10	10	10	10	10	10
	K3	9	10	9	9	9	9
5	K3	9.5	9.5	9.5	10	10	10
6	K3	10	10	10	10	10	10
7	K3	9	9	9	10	10	10
8	K1	9	10	9	8	8	7
	K5	8	10	8	6	7	7
9	K1	9	9	10	9	9.5	9
10	K3	8	8	9	9	9	9
11	K1	5	7	6	10	8	8
12	K3	4	7	5	10	7	7

*A,B,C,D,E,F – Methods regarding figure 1

Using the paired comparison method, a criterion analysis was carried out for the TSCC methods, assigning a degree of preference to each pair of criteria, and constructing a matrix of paired comparisons (Table 3). Iterations were defined to determine the weights for each criterion. And the final weights were then found for each criterion: for K1- 0.312179; K2 - 0.129903; K3-0.188206; K4-0.071029; K5-0.298683. Based on the weights obtained for each process, a ranking of the data presented in Table 4 was carried out.

Table 3

Pairwise comparison of criteria

	K1	K2	K3	K4	K5
K1	1	4	0.33	2	4
K2	0.25	1	2	4	0.2
K3	3.03030303	0.5	1	1	0.25
K4	0.5	0.25	1	1	0.2
K5	0.25	5	4	5	1

Table 4

Calculation of the weighted sum

Name of processes	Indicator	A	B	C	D	E	F
1	K1	3.1218	3.1218	3.1218	2.8096	2.8096	2.8096
	K3	1.8821	1.8821	1.8821	1.5056	1.5056	1.5056
	K4	0.6393	0.6393	0.6393	0.6393	0.6393	0.6393
	K5	2.9868	2.9868	2.9868	2.6881	2.3895	2.6881
	Σ	8.6299	8.6299	8.6299	7.6427	7.3440	7.6427
2	K3	1.5056	1.6939	1.6939	1.8821	1.8821	1.8821
	Σ	1.5056	1.6939	1.6939	1.8821	1.8821	1.8821
3	K1	1.8731	2.8096	3.1218	2.4974	2.4974	2.4974
	K3	0.9410	1.8821	1.5056	1.6939	1.1292	1.5056
	K5	2.3895	2.9868	2.6881	2.9868	2.6881	2.9868
	Σ	5.2036	7.6785	7.3156	7.1781	6.3148	6.9899

4	K1	2.8096	3.1218	3.1218	2.4974	2.4974	2.4974
	K2	1.2990	1.2990	1.2990	1.2990	1.2990	1.2990
	K3	1.6939	1.8821	1.6939	1.6939	1.6939	1.5056
	Σ	5.8025	6.3029	6.1147	5.4903	5.4903	5.3021
5	K3	1.8821	1.8821	1.8821	1.8821	1.8821	1.8821
	Σ	1.7880	1.7880	1.7880	1.8821	1.8821	1.8821
6	K3	1.8821	1.8821	1.8821	1.8821	1.8821	1.8821
	Σ	1.8821	1.8821	1.8821	1.8821	1.8821	1.8821
7	K3	1.6939	1.6939	1.6939	1.8821	1.8821	1.8821
	Σ	1.6939	1.6939	1.6939	1.8821	1.8821	1.8821
8	K1	2.8096	3.1218	2.8096	2.4974	2.4974	2.1853
	K5	2.3895	2.9868	2.3895	1.7921	2.0908	2.0908
	Σ	5.1991	6.1086	5.1991	4.2895	4.5882	4.2760
9	K1	2.8096	2.8096	3.1218	2.8096	2.8096	2.8096
	Σ	2.8096	2.8096	3.1218	2.8096	2.8096	2.8096
10	K3	1.5056	1.5056	1.5998	1.6939	1.6939	1.6939
	Σ	1.5056	1.5056	1.5998	1.6939	1.6939	1.6939
11	K1	1.5609	2.1853	1.8731	3.1218	2.4974	2.4974
	Σ	1.5609	2.1853	1.8731	3.1218	2.4974	2.4974
12	K3	0.7528	1.3174	0.9410	1.8821	1.3174	1.3174
	Σ	0.7528	1.3174	0.9410	1.8821	1.3174	1.3174

Results and discussion

The analysis shows that the significant processes that lead to the effectiveness of TSCC are those regulated by regulations:

- The process 1 – ST-NP SRO SSK-04-2013;
- The process 2 – ASTM C 1074;
- The process 3 – ST-NP SRO SSK-04-2013by the maturity of the concrete;
- The process 4 – ST-NP SRO SSK-04-2013by the maturity of the concrete;
- The process 5 – ASTM C 1074 Nurse-Saul;
- The process 6 – ST-NP SRO SSK-04-2013, ASTM C 1074;
- The process 7 – ASTM C 1074;
- The process 8 –ST-NP SRO SSK-04-2013by the maturity of the concrete;
- The process 9 – ST-NP SRO SSK-04-2013by analytically dependencies;
- The process 10 – ASTM C 1074 Nurse-Saul;
- The process 11 – ASTM C 1074 Nurse-Saul;
- The process 12 – ASTM C 1074 Nurse-Saul.

Concrete plays an important role in ensuring the safety, serviceability and durability of concrete and reinforced concrete structures, the quality of which is primarily determined by a combination of formulation and technological factors, and therefore the importance of concrete strength control systems cannot be overestimated.

Conclusion

Based on the research, the processes regulated by the American standard are mostly included in the unified approach to TSCC. In process 1, however, the use of cubic specimens for laboratory tests is singled out for aggregation, and in order not to disturb the consistency of the ASTM C 1074 algorithm, it will be accepted that the use of at least 15 specimens is sufficient. The requirements for processes 3 and 4 are quite clearly described in the ST-NP SRO SSK-04-2013 standard and will be adopted in a uniform approach. The number of temperatures measuring points has been shown to play an important role as best practice. The concrete must gain sufficient strength at some critical points before the project proceeds to the next stage. Critical points may vary depending on the type of structural element being monitored. In single-sided or double-sided slab systems, structurally important zones are in negative and positive design moments. As a rule, the maximum positive moment is in the middle of the span and the maximum negative moment is located at the slab-column junction. The standard ST-NP SRO SSK-04-2013, which gives detailed recommendations and an algorithm of actions, also deals with the control of temperature stresses in concrete in a scrupulous manner. Changing temperature conditions have a great influence on deformations and stresses in concrete. During the construction period, temperature stresses arise during the development and dissipation of exothermic heat, often accompanied by cracking. Measurement of the concrete temperature is therefore mandatory when monitoring concrete stresses. This monitoring is especially important in winter when additional concrete heat treatment may be necessary.

The results of this study are important for builders as they will eliminate existing gaps in the current approaches used in temperature-strength control of the concrete.

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Бетонның температурасы мен беріктігін бақылаудағы бірыңғай тәсіл

Аңдатпа. Сапаны бақылау саласындағы теориялық және эксперименттік зерттеулердің дамуы бетонның беріктігін бағалаудың көптеген әдістерінің пайда болуына әкелді. Қалыптағы бетонның беріктігін жедел анықтау үшін ерте ұстау сатысында бетонның температурасы мен оны ұстау уақытының өзара байланысына негізделген температуралық–беріктік бақылау (БТББ) тәсілі неғұрлым бейімделген болып табылады. Бетонның беріктігін зерттеу стандарттардың талаптарына сәйкес жүргізілуі керек. Нормативтік құжаттама бойынша неғұрлым бейімделген стандарттар ASTM C1074 (АҚШ) болып табылады); NEN 5970 (Нидерланды); СТ–НП СРО ССК–04–2013 (Ресей). Алайда, БТББ әрбір әдістің барлық артықшылықтарын ескерген БТББ -ға қатысты қазіргі тәсілдері жоқ. Авторлар жұптық салыстыру әдісін қолдана отырып, БТББ әдістері мен міндеттерінің әр критерийі маңыздылығының салмағын анықтады. Алынған нәтижелер негізінде бетонның қолданылуын бағалауды ескере отырып, оның температуралық-беріктік бақылауына бірыңғай тәсіл құрылды. Бұл тәсіл бақылау кезеңдерінің есептерін шешуде ең жақсы әдістерге ие көптеген әдістерді қолдануды шектеу мәселесін шешеді. Бетонның температуралық-беріктік бақылауына біріздендірілген тәсіл бетон және темірбетон конструкцияларының Жоғары сапасы мен ұзақ мерзімділігіне қол жеткізуге мүмкіндік береді.

Түйін сөздер: стандарт, бетонның қатаю температурасы, бетонды бұзбай сынау, ендірілген сенсор.

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Унифицированный подход к температурно-прочностному контролю бетона

Аннотация. Развитие теоретических и экспериментальных исследований в области контроля качества привело к появлению значительного количества методов оценки прочности бетона. Для оперативного определения прочности бетона, находящегося в опалубке, на ранней стадии выдерживания наиболее адаптированным является способ температурно–прочностного контроля (ТПКБ), базирующегося на взаимосвязи температуры бетона и времени его выдерживания.

Исследования прочности бетона должны выполняться по требованиям стандартов. Наиболее адаптированными по нормативной документации являются стандарты ASTM C1074 (США); NEN 5970 (Нидерланды); СТ–НП СРО ССК–04–2013 (Россия). Однако существующие подходы к ТПКБ, которые учитывали бы все преимущества каждого из методов, отсутствуют. Авторы, используя метод парного сравнения, определили вес значимости каждого критерия методов и задач к ТПКБ. На основании полученных результатов был сформирован унифицированный подход к температурно-прочностному контролю бетона с учетом оценки его применимости. Данный подход позволит решить проблему ограничения применения большинства методов, которые в своей основе имеют лучшие приемы в решении задач этапов контроля. Унифицированный подход к температурно-прочностному контролю бетона позволит достигнуть высокого качества и долговечности бетонных и железобетонных конструкций.

Ключевые слова: стандарт, температура твердения бетона, неразрушающий контроль бетона, встраиваемый датчик.

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