

Original article

CC BY 4.0

<https://doi.org/10.15828/2075-8545-2026-18-3-363-378>

Influence of delayed ettringite formation on the durability of mortars: the importance of thermal control

Comlan V. Zomahoun^{1*} , Kocouvi A. Houanou¹ , Marc Sodomon^{2*} , Svetlana V. Samchenko² 

¹ University of Abomey-Calavi, Abomey-Calavi Polytechnic School, Laboratory of Energetics and Applied Mechanics, Abomey-Calavi, Republic of Benin

² National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoe shosse, 26, Russian Federation

* Corresponding authors: e-mail: vianneyzomahoun@gmail.com, sodomonmarc@yahoo.fr

ABSTRACT

Introduction. This study is part of a broader investigation into the phenomenon of delayed ettringite formation (DEF) in concrete and its consequences on the durability of concrete–mortar systems. The objective of the research is to analyze the influence of the initial thermal conditions of fresh concrete on the development of internal sulfate reaction (ISR), the mechanical properties of concrete, and the behavior of mortar applied to the surface after hardening. **Materials and Methods.** Three concrete mixtures, designated BP1, BP2, and BP3, were produced and subjected to DEF testing on cubic specimens, including continuous temperature monitoring. The temperature of fresh concrete was intentionally varied in order to evaluate its influence. The experimental program was carried out in Africa, specifically in Benin. Compressive and tensile strength tests were performed. After verifying that the concrete was suitable, mortar was applied to the concrete surface. The behavior of the mortar was then monitored over a period of 90 days through visual observation of the mortar surface. It was particularly interesting to observe the evolution of the mortar surface over time. **Results and Discussion.** The results has shown that for concretes BP1 and BP2, when the initial temperature was below 35 °C, the thermal behavior during the DEF test was stable, and the maximum temperature did not exceed 80 °C. Under such conditions, appropriate mechanical properties and a uniform coating of mortar were obtained without any visible cracking or surface damage. Nevertheless, for concrete BP3 with initial temperature higher than 35 °C, the thermal behavior became unstable, but the maximum temperature remained lower than the critical one. It was observed that this instability negatively affected the mechanical properties and reduced the durability performance of the material. **Conclusion.** The control of the initial thermal conditions of fresh concrete is a key parameter for limiting the development of DEF, preserving the mechanical properties of concrete, and ensuring the durability of applied mortars. In particular, the initial temperature of fresh concrete should not exceed 35 °C, since higher temperatures may promote the development of internal sulfate reaction (ISR) within the concrete itself.

KEYWORDS: internal sulfate reaction, delayed ettringite formation (DEF), concrete, mortar, thermal conditions, mechanical properties

ACKNOWLEDGEMENTS: The authors thank EIFFAGE GENIE CIVIL MARINE and EIFFAGE GENIE CIVIL for providing laboratory access and their valuable support.

FOR CITATION:

Zomahoun C.V., Houanou K. A., Sodomon M., Samchenko S.V. Influence of delayed ettringite formation on the durability of mortars: the importance of thermal control. *Nanotechnologies in Construction*. 2026;18(3):363–378. <https://doi.org/10.15828/2075-8545-2026-18-3-363-378>. – EDN: NYMFH.

Влияние позднего образования этtringита на долговечность растворов: важность термического контроля

Комлан Вианней Зомахун^{1*} , Кокуви Агапи Хоуану¹ , Марк Содомон^{2*} , Светлана Васильевна Самченко² 

¹ Университет Абомей-Калави, Политехническая школа Абомей-Калави, Лаборатория энергетики и прикладной механики, Абомей-Калави, Республика Бенин

² Национальный исследовательский Московский государственный строительный университет, 129337, Москва, Ярославское шоссе, д. 26, Российская Федерация

* Авторы, ответственные за переписку: e-mail: vianneyzomahoun@gmail.com, sodomonmarc@yahoo.fr

АННОТАЦИЯ

Введение. Данное исследование является частью более широкого изучения явления позднего образования этtringита (DEF) в бетоне и его последствий для долговечности бетонно-растворных систем. Цель исследования заключается в анализе влияния начальных температурных условий свежего бетона на развитие явления внутренней сульфатной реакции (BCP), механические характеристики бетона и поведение раствора, нанесенного на поверхность после затвердевания. **Методы и материалы.** Были изготовлены три бетонные смеси, обозначенные как BP1, BP2 и BP3, которые подверглись испытанию DEF на кубических образцах, включая непрерывный мониторинг изменения температуры. Температура свежего бетона намеренно варьировалась с целью оценки ее влияния. Экспериментальная программа проводилась в Африке, а именно в Бенине. Мы сделали тесты на прочность при сжатии и растяжении. Убедившись, что бетон подходит, мы нанесли раствор на бетон. Затем мы следили за поведением раствора 90 дней, просто глядя на поверхность раствора. Было интересно наблюдать, как меняется поверхность раствора. **Результаты и обсуждение.** Мы видим, что у бетонов BP1 и BP2, когда стартовая температура была ниже 35 °C, тепловое поведение в тесте DEF оставалось стабильным, а максимум температуры не поднимался выше 80 °C. При таких условиях получились хорошие механические свойства и ровное покрытие раствора – треск и повреждения на поверхности не заметили. А вот бетон BP3, у которого стартовая температура была выше 35 °C, вел себя иначе: тепловой режим стал нестабильным, хотя максимум все равно оставался ниже критического порога. Нестабильность ухудшила механические свойства и ухудшила эксплуатационные характеристики материала. **Заключение.** Контроль начальных тепловых условий свежего бетона является ключевым параметром для ограничения развития DEF, сохранения механических характеристик бетона и обеспечения долговечности нанесенных растворов. В частности, начальная температура свежего бетона не должна превышать 35 °C, так как более высокие значения температуры могут способствовать развитию внутренней сульфатной реакции (BCP) внутри самого бетона.

КЛЮЧЕВЫЕ СЛОВА: внутренняя сульфатная реакция, позднее образование этtringита (DEF), бетон, раствор, тепловые условия, механические характеристики

БЛАГОДАРНОСТИ: Авторы статьи выражают благодарность компании EIFFAGE GENIE CIVIL MARINE за предоставленную лабораторию.

ДЛЯ ЦИТИРОВАНИЯ:

Зомахун К.В., Хоуану К.А., Содомон М., Самченко С.В. Влияние позднего образования этtringита на долговечность растворов: важность термического контроля. *Нанотехнологии в строительстве*. 2026;18(3):363–378. <https://doi.org/10.15828/2075-8545-2026-18-3-363-378>. – EDN: NYVMFH.

INTRODUCTION

In African countries, particularly in Benin, climatic conditions are characterized by high temperatures, which frequently exceed 30 °C and may rise even higher depending on the season. These thermal conditions constitute an important environmental factor influencing the behavior of construction materials, especially concrete and mortar.

High temperatures during the early stages of concrete hardening or during mortar application may alter the me-

chanical and physicochemical properties of these materials. Numerous studies have shown that elevated temperatures (above 25 °C) accelerate cement hydration reactions [1–3]. An increase in temperature during concrete curing disrupts the internal microstructure and promotes the development of defects in concrete, including internal sulfate reaction (ISR).

Delayed ettringite formation (DEF) is a concrete anomaly first identified in real structures at the end of the 1980s. Some researchers reported cases in which precast elements subjected to heat curing subsequently

experienced deterioration, leading to a reduction in their mechanical properties [4].

Delayed ettringite formation (DEF) was first identified in precast reinforced concrete elements in the late 1980s [4]. Subsequently, numerous case studies and expert reports were published in the literature, including [5] and [6], describing cases involving the simultaneous occurrence of alkali–silica reaction and delayed ettringite formation [7–9]. In France, internal sulfate reaction was identified in several dozen massive concrete structures [10–13], as well as in precast reinforced concrete elements [14].

Sulfate attacks represent a major durability problem for concrete structures. These attacks damage concrete by degrading its mechanical properties. In particular, internal sulfate reaction leads to delayed ettringite formation, which causes expansion within the concrete and the development of network cracking [15].

When a structure is affected, it is essential to accurately diagnose the development of defects, assess its serviceability, predict the mechanical evolution of the structure, and apply appropriate repair methods. Achieving these objectives requires a thorough understanding of the consequences of DEF at both the microstructural and macrostructural levels. Numerous experimental and theoretical studies have been carried out to identify the physicochemical mechanisms and parameters influencing delayed ettringite formation (DEF). However, the complexity of the underlying processes makes it difficult to directly extrapolate this knowledge in order to explain structural-scale effects. Therefore, macroscopic approaches may provide additional insights based on the knowledge already available in the literature [2].

The development of defects also affects mortar coatings applied to concrete substrates, thereby degrading the visible surface quality, whereas the actual cause of cracking and other observed damage lies in the DEF occurring within the concrete itself. Such deterioration generally appears after several years or even decades, making both the study of this anomaly and the selection of appropriate repair strategies aimed at extending the service life of damaged structures particularly difficult [3].

The objective of this work is to evaluate, under real environmental conditions, the risk of delayed ettringite formation (DEF) in concrete, and then to analyze the behavior of coatings applied to this substrate in order to assess the long-term evolution and surface condition of the mortar.

To achieve this objective, the adopted methodology was based on the following main aspects:

- Evaluation of temperature rise in accordance with the IFSTTAR guidelines (October 2017) [16];
- Conducting a test on a 1 m cubic specimen equipped with thermally insulated sensors (semi-adiabatic conditions), using the concrete mixture exhibiting the highest temperature rise;

- Conducting a test on a 1.6 m cubic specimen equipped with non-insulated sensors, using the concrete mixture exhibiting the highest temperature rise;
- Application of a plaster coating onto the corresponding concrete using mortars reinforced with jute fibers, in order to monitor the surface condition of the mortar over a period of 90 days.

MATERIALS AND METHODS

Research Equipment

During the experimental program, laboratory equipment complying with current standards for the analysis of the mechanical and physical properties, as well as the durability of materials, was used. All the equipment employed was certified and recognized within standardized protocols, thereby ensuring the reliability and reproducibility of the obtained results.

Materials

The materials used in this work are as follows:

- 0/4 sand from Cocotomey in southern Benin.
- Crushed stone (0/5, 5/15, and 15/25) from Setto in central Benin.
- Admixtures from SIKA Chemical Corporation (Sika ViscoFlow 800 POWER, Sika ViscoFlow 200 TIMER, and SikaTard 300 SLS).
- CEM III/B 42.5N cement from NOCIBE Benin (New Cement Plant of Benin).
- The mixing water comes from SONEB (Benin National Water Corporation).
- The jute fibers come from jute bags from the Dantopka market (Benin).

Methods

The tests performed on the concrete and mortar were carried out in accordance with the applicable regulations regarding the constituents and performance of concrete. They are primarily based on harmonized European standards (NF EN) adopted by AFNOR, as well as on French standards from the NF P series and national normative documents such as fascicule de documentation.

Tests related to delayed ettringite formation (DEF) were conducted following standardized and widely recognized protocols for evaluating this type of concrete pathology. In particular, the experimental procedures were carried out in accordance with the IFSTTAR (French Institute of Science and Technology for Transport, Development and Networks) recommendations aimed at preventing and identifying ISR-related disorders.

To ensure the reliability and statistical robustness of the results, each test was repeated six (6) times. The re-

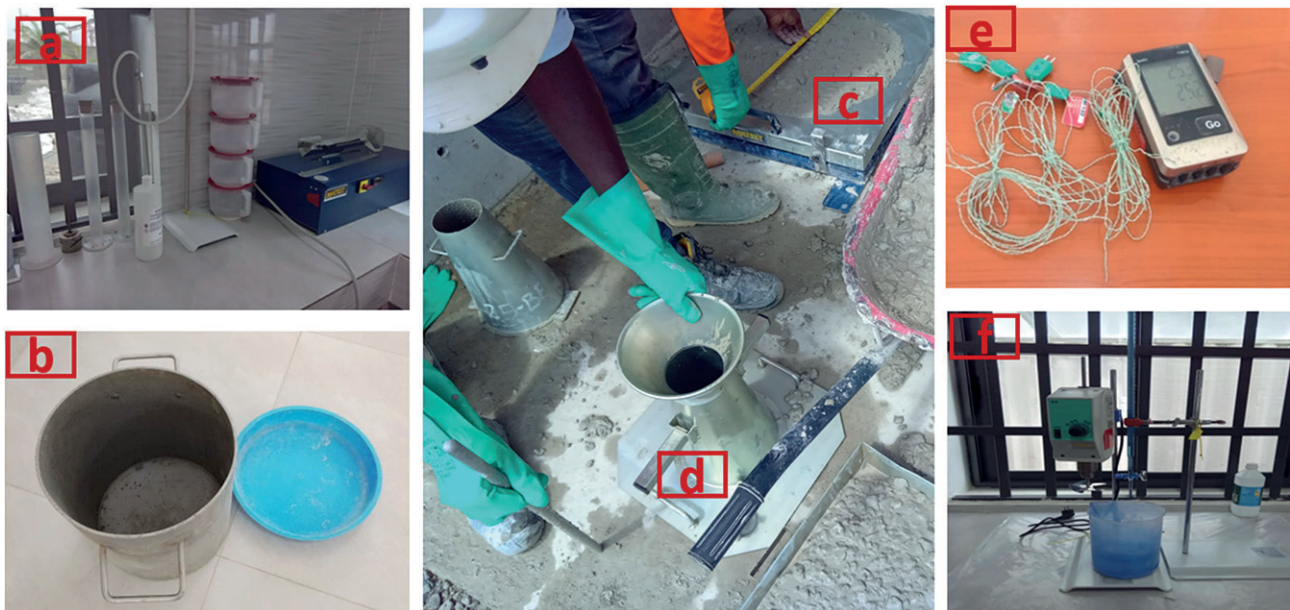


Fig. 1. a – Sand equivalent test apparatus; b – Free bleeding test apparatus; c – Flow table; d – Slump test (Abrams cone test); e – Thermocouple; f – Methylene blue value test apparatus



Fig. 2. a – Hydrometer ; b – Balances ; c – Tensile testing machine

sults presented correspond to the average of the measurements obtained, which helps minimize the influence of experimental uncertainties and improves the scientific significance of the conclusions.

RESULTS

Material Characterization

Sand

The measured characteristics are summarized in the table above and are compared with the standard speci-

fications. According to the results, the sand gradation complies with the requirements.

The measured values show that the 0/4 sand from Cocotomey (Benin) can be classified under Code A, according to Article 10 of standard NF P 18-545 (2021). It therefore meets the requirements and is considered suitable for use in concrete.

Crushed aggregate

Crushed aggregate 15/25

The measured values show that the 15/25 fraction can be classified under code A according to Article 10



Fig. 3. a – Series of sieves; b – Oven; c – Compression testing machine

Table 1. Results of the particle size analysis of the sand

Sieve (mm)	5.6	4 (2*D)	2.8 (1.4*D)	2	1	0.50	0.250	0.125	0.063	
Unit – Method	Cumulative passer (%) – NF EN 933-1 (2012)									
Values found	100	100	100	99	96	72	30	6	1.0	
Limit values	Max	–	100	100	100	100	–	50	–	10
	Min	–	100	95	90	60	–	0	–	0

Table 2. Summary of the test results on sand

Parameter	Method	Unit	Average Value	Specification
Real density	NF EN 1097-6 (2022)	Mg/m ³	2,62	Declared value
Water absorption coefficient		%	0,5	≤ 2,5 Ab _A ≤ 5,0 Ab _B
Fineness modulus (FM)	NF EN 12620 + A1 (2008)	–	1,97	1,5 ≤ FM ≤ 4
Fines content	NF EN 933-1 (2012)	%	1,0	≤ 10 f _A ≤ 16 f _B
Sand equivalent (SE)	NF EN 933-8 (2015)	%	77	≥ 65 P _A ≥ 60 P _B
Friability coefficient (FS)	NF P 18-576 (2013)	%	18	–
Methylene blue value (MB)	NF EN 933-9+A1 (2022)	g/kg	1,0	≤ 1,5 (P _A et P _B)
Prohibited impurities	XP P 18-546 (2020)		<0,01	≤ 0,1
Water-soluble chlorides	NF EN 1744-1+A1 (2014)	%	0,004	To declare
Total sulfur	NF EN 1744-1+A1 (2014)	%	0,12	≤ 1 (S _A et S _B)
Acid-soluble sulfates	NF EN 1744-1+A1 (2014)	%	0,04	≤ 0,2 (S _A et S _B)
Humic substances	NF EN 1744-1+A1 (2014)	–	Absent	Absent
Soluble active alkalis	XP P 18-544 (2015)	%Na ₂ O _{eq}	0,0300	Declared value
Alkali-reaction	FD P 18-542 (2023)	–	NR	To declare

Table 3. Results of the particle size distribution analysis of the 15/25 crushed aggregate

Sieve (mm)	31.5 (1.4*D)	25	22.4 (D)	20	16	14 (d)	12.5	6.3 (d/2)	0.063	
Unit – Method	Cumulative passer (%) – NF EN 933-1 (2012)									
Values found	100	99	94	84	39	11	4	2	0.8	
Limit values	Max	100	–	99	–	–	20	–	5	1.5
	Min	98	–	90	–	–	0	–	0	0

Table 4. Summary of test results on the 15/25 crushed aggregate

Parameter	Method	Unit	Average Value	Specification
Real density	NF EN 1097-6 (2022) et 9 (2014)	Mg/m ³	2.76	Declared value
Water absorption coefficient		%	0.4	≤ 2,5 Ab _A ≤ 5,0 Ab _B
Flakiness Index (FI)	NF EN 933-3 (2012)	%	11	≤ 20 FI _A ≤ 35 FI _B
Alkali-reaction	FD P 18-542 (2023)	%	NR	To declare

of standard NF P 18-545 (2021). Therefore, this material is considered suitable for use in concrete mixes with a 14/22.4 grading, corresponding to particle size classes: series 1 and series 2 (the 15/25 fraction is not recognized in standard NF EN 12620 (2008)).

Crushed aggregate 5/15

The measured values show that the 0/5 aggregate can be classified under Code A in accordance with Article 10 of standard NF P 18-545 (2021). Consequently, this material is considered suitable for use in concrete mix designs with a 0/5.6 grading, corresponding to a granular

class: base series + series 1 (the 0/5 size fraction is not recognized in NF EN 12620 (2008)).

Crushed aggregate 0/5

The measured values show that the 0/5 aggregate can be classified under Code A in accordance with Article 10 of standard NF P 18-545 (2021). Consequently, this material is considered suitable for use in concrete mix designs with a 0/5.6 grading corresponding to a particle size class: basic series + series 1 (the 0/5 size fraction is not recognized in standard NF EN 12620 (2008)).

Table 5. Results of the particle size distribution analysis of the 15/25 crushed aggregate

Sieve (mm)	20 (1.4*D)	16	14 (D)	11.2	10 (D/1.4)	8	5.6 (d)	4	3.15 (d/2)	0.063	
Unit – Method	Cumulative passer (%) – NF EN 933-1 (2012)										
Values found	100	100	93	69	54	30	8	3	3	1.2	
Limit values	Max	100	–	99	–	70	–	20	–	5	1.5
	Min	98	–	80	–	25	–	0	–	0	0

Table 6. Summary of test results on the 5/15 crushed aggregate

Parameter	Method	Unit	Average Value	Specification
Real density	NF EN 1097-6 (2022) et 9 (2014)	Mg/m ³	2.77	Declared value
Water absorption coefficient		%	0.4	≤ 2,5 Ab _A ≤ 5,0 Ab _B
Flakiness Index (FI)	NF EN 933-3 (2012)	%	14	≤ 20 LI _A ≤ 35 FI _B
Fragmentation resistance	NF EN 1097-2 (2020) et 5 (2008)	%	27	≤ 20 LA _A ≤ 40 LA _B
Micro-Deval coefficient	NF EN 1097-1 (2023)	%	16	Declared value
Total sulfur content	NF EN 1744-1 + A1 – 11.1 (2014)	%	0.08	≤ 1
Water-soluble sulfates	NF EN 1744-1 + A1 – 12 (2014)	%	0.03	≤ 0.2

Table 7. Results of the particle size distribution analysis of the 0/5 crushed aggregate

Sieve (mm)	12.5	11.2 (2D)	7.1 (1.4D)	5.6 (D)	4	2	1	0.5	0.25	0.125	0.063	
Unit - Method	Cumulative passer (%) – NF EN 933-1 (2012)											
Values found	100	100	100	100	85	57	40	30	24	16	9.4	
Limit values	Max	100	100	100	100	90	–	60	–	–	–	11
	Min	100	100	95	90	50	–	20	–	–	–	1

Table 8. Summary of test results on the 0/5 crushed aggregate

Parameter	Method	Unit	Average Value	Specification
Real density	NF EN 1097-6 (2022) et 9 (2014)	Mg/m ³	2.76	Declared value
Water absorption coefficient		%	0.4	≤ 2,5 Ab _A ≤ 5,0 Ab _B
Fine content	NF EN 933-1 (2012)	%	9.4	≤ 11
Methylene blue value	NF EN 933-9 + A1 (2022)	g/kg	0.2	≤ 1.5 (P _A et P _B)
Water-soluble chloride	NF EN 1744-1+A1 (2014)	%	< 0.002	To declare
Humic substances	NF EN 1744-1+A1 – 15.1 (2014)	–	Absent	Absent
Water-soluble active alkalis	XP P 18-544 (2015)	%Na ₂ O _{eq}	0.0174	Declared value
Alkali-reaction	FD P 18-542 (2023)	–	NR	To declare

*Le cement***Table 9.** Chemical and Physical Characteristics of CEM III 42.5 Cement

Analyses	Unit	Result
Chemical Properties of Hydraulic Binders		
Siliceous constituents (P)	%	0.00
Calcareous constituents (C)	%	0.00
Setting regulator (R)	%	3.70
Clinker content (K)	%	30.80
Slag content (L)	%	65.51
Al ₂ O ₃ (XRF)	% m/m	10.38
CaO (XRF)	% m/m	48.04
Fe ₂ O ₃ (XRF)	% m/m	1.31
K ₂ O (XRF)	% m/m	0.35
MgO (XRF)	% m/m	5.17
Mn ₂ O ₃ (XRF)	% m/m	0.18
Na ₂ O (XRF)	% m/m	0.29
SiO ₂ (XRF)	% m/m	28.26
TiO ₂ (XRF)	% m/m	0.54
Na ₂ O equivalent (XRF)	% m/m	0.52
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (XRF)	% m/m	39.95

Continuation of the Table 9

Analyses	Unit	Result
MnO (XRF)	% m/m	0.16
Loss on ignition at 950 °C	% m/m	2.45
Mechanical Properties of Hydraulic Binders		
Analyses	Unit	Result
Average compressive strength (2 days)	MPa	14.2
Average compressive strength (7 days)	MPa	35.1
Average compressive strength (28 days)	MPa	49.8
Propriétés physiques des liants hydrauliques		
Analyses	Unit	Result
Soundness	mm	0
Water content for standard consistency	%	35.0
Specific surface (Blaine)	cm ² /g	5350
Specific surface (Blaine)	m ² /kg	535
Initial setting time	min	250
Average density	g/cm ³	2.80

Jute fibers

The jute fibers used in the cement mortar are short jute fibers with a maximum length of 5 mm. They were obtained through the preparation and treatment process described in [17]. This procedure, which has already been experimentally validated, ensured good fiber dispersion within the cementitious matrix, thereby providing a homogeneous mixture, as demonstrated in the referenced study.

– Prevention level

For our study, the structural category is Category II. The exposure class is XH3, as the concrete structure is regularly exposed to water splashing.

According to the matrix above, the corresponding exposure class is Cs.

– Precautions related to the prevention level

For this level of prevention, the risk of distress with regard to delayed ettringite formation (DEF) shall be taken into account through one of the following two precautionary measures, designated 1 and 2:

1. The maximum temperature reached within the concrete shall remain below 70 °C.

2. If the maximum temperature reached within the concrete cannot be maintained below 70 °C, it shall re-

main below 80 °C, and at least one of the following six conditions shall be satisfied:

- Thermal curing shall be properly controlled (Note 1); the duration during which the concrete temperature exceeds 70 °C shall not exceed 4 hours, and the active equivalent alkali content of the concrete shall be less than 3 kg/m³;
- Use of a cement complying with standard NF P 15-319 (ES), or a sulfate-resisting (SR) cement in accordance with standard NF EN 197-1 (except CEM I SR3 and SR5 cements), for concretes subjected to temperatures above 70 °C for periods exceeding 10 hours. CEM I SR3 and SR5 cements are permitted where the duration above 70 °C is less than 10 hours, provided that the active equivalent alkali content of the concrete is lower than 3 kg/m³;
- Use of a CEM I SR3 or SR5 cement bearing the NF Hydraulic Binders certification mark and qualified in accordance with the methodology specified in Annex 5, where the duration above 70 °C exceeds 10 hours;
- Use of cements not complying with NF P 15-319 (ES), of types CEM II/B-V, CEM II/B-Q, CEM II/B-M (S-V) with more than 20% fly ash, CEM III/A or CEM V, provided that all these cements have an SO₃

Table 10. Chemical characterization of jute fibers [16]

Designation	Alpha Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Density (g/cm ³)	pH
Average value	45.50	23.0	3.9	0.58	1.46	5.63

content not exceeding 3% and are manufactured from clinker with a C_3A content not exceeding 8%;

- Use, in combination with CEM I or CEM II/A cement, of fly ash complying with NF EN 450-1, ground granulated blast furnace slag complying with NF EN 15167-1, silica fume complying with NF EN 13263-1, or metakaolin complying with NF P 18-513. Their proportion in the binder (cement + additions) shall be at least 20% for fly ash, 35% for ground granulated blast furnace slag, 10% for silica fume (Note 2), and 20% for metakaolin. The binder used shall meet the following requirements: C_3A (relative to clinker) < 8% and SO_3 (relative to binder) < 3%;
- Verification of concrete durability with regard to DEF by means of a performance test and compliance with the decision criteria.

Due to the use of an SR cement in accordance with NF EN 197-1, the maximum permissible temperature during concrete setting is 80 °C.

– Evaluated mix design

In order to assess the risk of delayed ettringite formation (DEF), a mix design leading to the highest temperature rise, with a high cement content, will be adopted.

The composition of the investigated mix, designated “BPS XA2-XA3 C35/45 Cl 0.65 210 ± 30 mm”, hereafter referred to as “Sprayed Concrete”, is presented in the Table 11.

– Estimation of temperature rise

The calculation carried out in accordance with the provisions of the DEF guidelines is presented in the Table 12.

Table 11. Constituent components of the sprayed concrete mix design

Sprayed Concrete Constituent	Dosage (kg/m ³)	Specification (kg/m ³)
CEM III/B 42.5 N – NOCIBE	420	≥380
Lagoon sand 0/4	633	–
Crushed aggregate 0/5	293	–
Crushed aggregate 5/15	480	–
Crushed aggregate 15/25	339	–
Sika ViscoFlow 800 Power	3.36 (0.80% of C)	–
Sika ViscoFlow 200 Timer	1.47 (0.35% of C)	–
Sika SikaTard 300 SLS	1.26 (0.30% of C)	–
Effective water	180.0	–
Theoretical density	2317	–

Table 12. Calculation performed in accordance with the IFSTTAR recommendations

Constituent	Sprayed concrete
Concrete thickness	1.02 m
Maximum temperature for Cs level	80 °C
Concrete density (kg/m ³)	2317
Cement content CEM III/42.5N – NOCIBE	420
Cement compressive strength at 2 days (MPa)	13
Cement compressive strength at 28 days (MPa)	47
Q41h cement (J/g)	178
Q120h cement (J/g)	194
Qm/Q41	1.39
Effective water (kg)	180
Effective water / Equivalent binder	0.43
Impact E/C-α	0.98
Adiabatic temperature rise ΔT (without heat dissipation)	39.5 °C
Thermal loss R	0.492
Temperature rise with heat dissipation ΔT	19.4 °C
Maximum initial temperature of the concrete	60.2 °C

Table 13. Mechanical and physical properties of fresh and hardened concrete

Parameter	Specification	Test Results on Fresh Concrete			
		BP 1	BP 2	BP 3	
Cube DEF		1 × 1 × 1 m	1.6 × 1.6 × 1.6 m	1.6 × 1.6 × 1.6 m	
Fresh concrete density (kg/m ³)		2418	2381		
Entrapped air (%)		1.0	1.3	1.1	
Bleeding (ml/min)		0	0	0	
Ambient temperature (°C)		32.0	32.5	32.0	
Concrete temperature (°C)	≤ 35	34.2	33.6	38	
Slump (mm)	210±30	220	223	230	
Inverted cone (s)	≤ 4	2.8	2.8	2.0	
Impact mark (mm)	600±50	600	600	620	
Test Results on Hardened Concrete					
Compression MPA	7 days		41.5	45.9	35.3
	28 days	≥ 49	51.9	55.2	42.6
Tensile strength MPA	28 days	≥ 2.7	2.9	3.4	2.34

The maximum concrete temperature at the time of placement must be lower than 60.2 °C in order to prevent the risk of internal sulfate reaction. Since the maximum permitted concrete temperature at the time of casting is 35 °C, this requirement will be met.

BP1: cubic specimen with dimensions of 1 × 1 × 1 m.

BP2: cubic specimen with dimensions of 1.6 × 1.6 × 1.6 m.

BP3: cubic specimen with dimensions of 1.6 × 1.6 × 1.6 m.

– Thermal test

A 1 m³ cube insulated with 10 cm of polystyrene on all six faces and two cubes measuring 1.6 m on each side were cast. The specimens were instrumented with three thermocouples (one at the top, one at the center, and one at the bottom). A fourth thermocouple was used to record the ambient temperature near the element. The cube was monitored over seven consecutive days.

– Thermal test on the 1 × 1 × 1 m cube (BP1)

The curves recorded by the three probes embedded in the concrete are similar, and the maximum temperature is maintained for several hours.

The maximum temperature rise recorded during the test was 31.2 °C (65.2 – 34.0). Given that the maximum concrete temperature at placement was 34.2 °C, the maximum temperature that could be reached during setting is therefore 66.2 °C. Since this temperature is below the 80 °C threshold associated with prevention level Cs, the concrete is considered compliant.

– Thermal test on the 1.6 × 1.6 × 1.6 m cube (BP2)

The curves recorded by the three probes embedded in the concrete are similar, and the maximum temperature is maintained for several hours.

The maximum temperature rise recorded during the test was 31.4 °C (63.4–32.0). Given that the maximum temperature of the concrete during placement was 35 °C, the maximum temperature that could have been reached during the setting process is 66.4 °C. Since this temperature is below the threshold value of 80 °C associated with the Cs prevention level, the concrete meets the requirements.

– Essai thermique au cube 1.6 x 1.6 x 1.6 m (BP3)

As shown in Figure 6, the temperature exhibits unstable behavior due to the high temperature of the fresh concrete. This instability is particularly evident in the temperature curve of the lower part of the concrete, where, after the concrete reaches its peak temperature—corresponding to the maximum recorded value—successive phases of temperature rise and fall can be clearly observed.

Applying Mortar to Concrete

The mortar was applied on the concrete to test the effect of the concrete on the mortar. To test whether the compliant concrete would have any effect on the mortar. No cracks or sudden changes were seen in the mortar after 90 days.

No cracks were observed on the mortar after its application on the compliant concrete up to 90 days.

DISCUSSION

As in the case of mixtures BP1 and BP2, the temperature of fresh concrete remained below 35 °C, which is considered a favorable condition for the proper progress

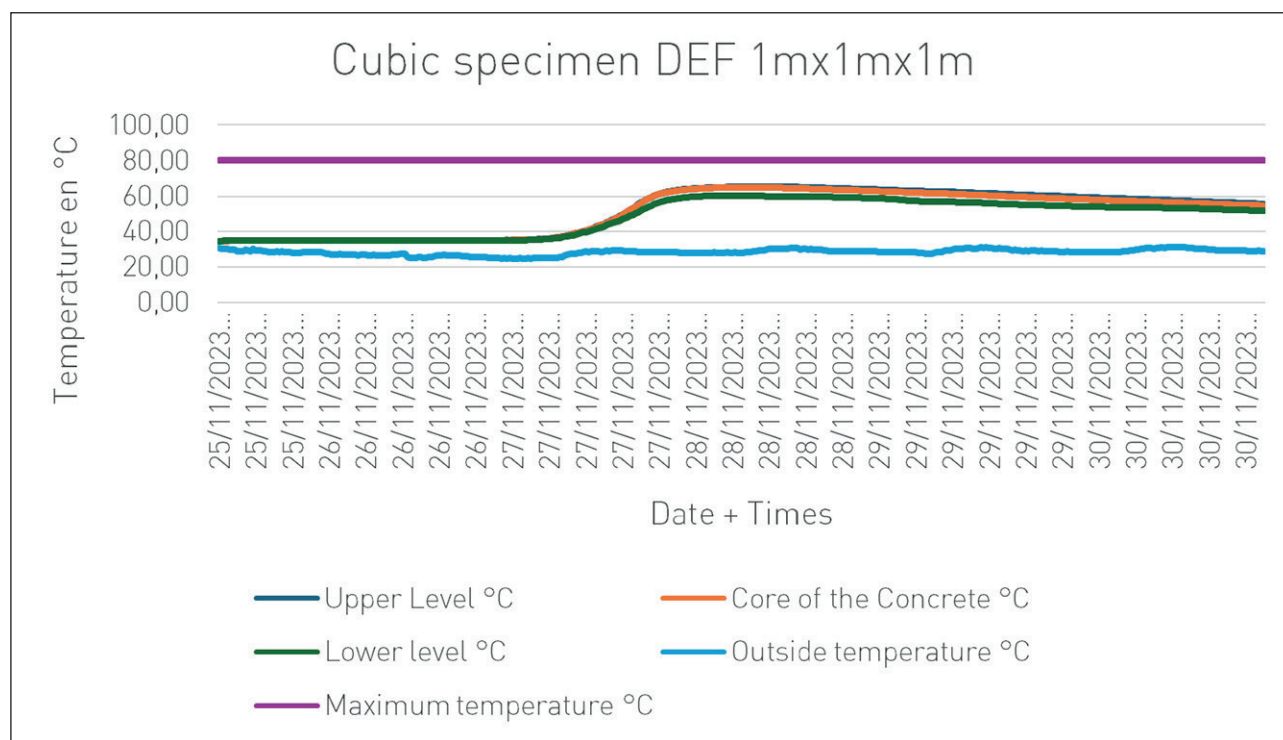


Fig. 4. Temperature evolution in the BP1 cubic specimen

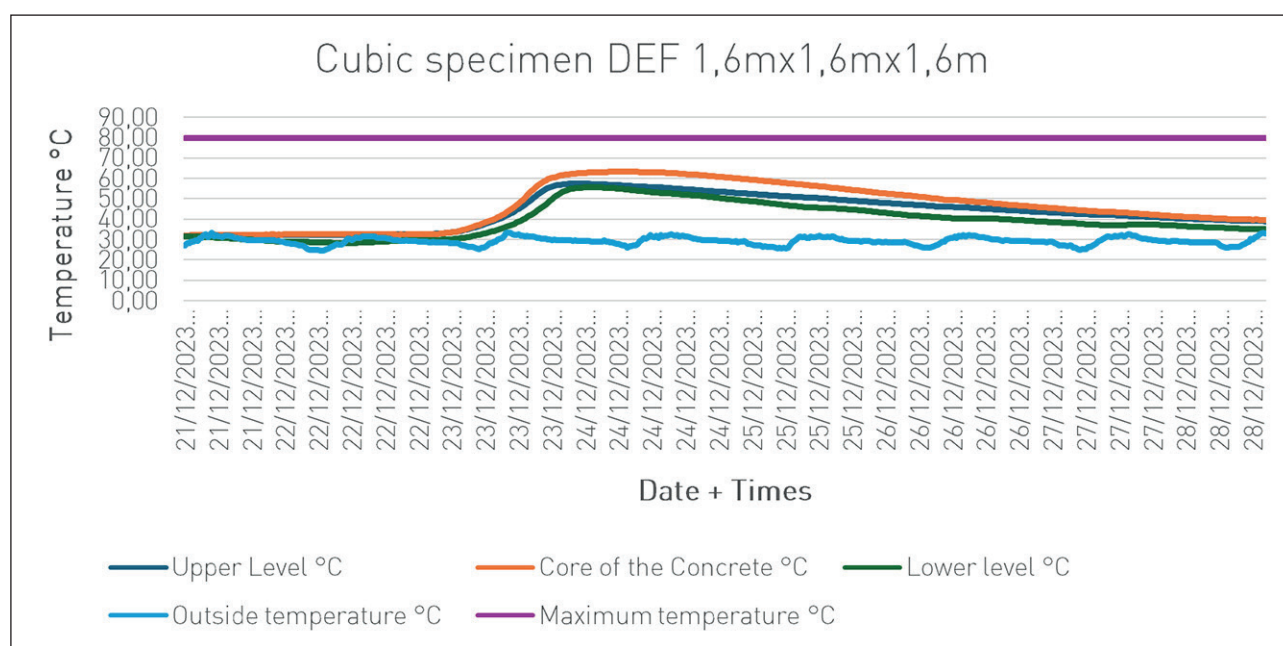


Fig. 5. Temperature evolution in the BP2 cubic specimen

of hydration reactions and the optimal development of mechanical properties. During the delayed ettringite formation (DEF) test on the cubic specimens, the thermal behavior remained normal, characterized by a gradual increase in temperature followed by a cooling phase, while the maximum temperature did not exceed 80 °C.

Such control of the thermal regime ensured mechanical properties that complied with standard requirements in both compression and tension. The results clearly show that controlling the temperature of fresh concrete is essential for obtaining good mechanical properties after hardening. Without temperature control, the mechani-

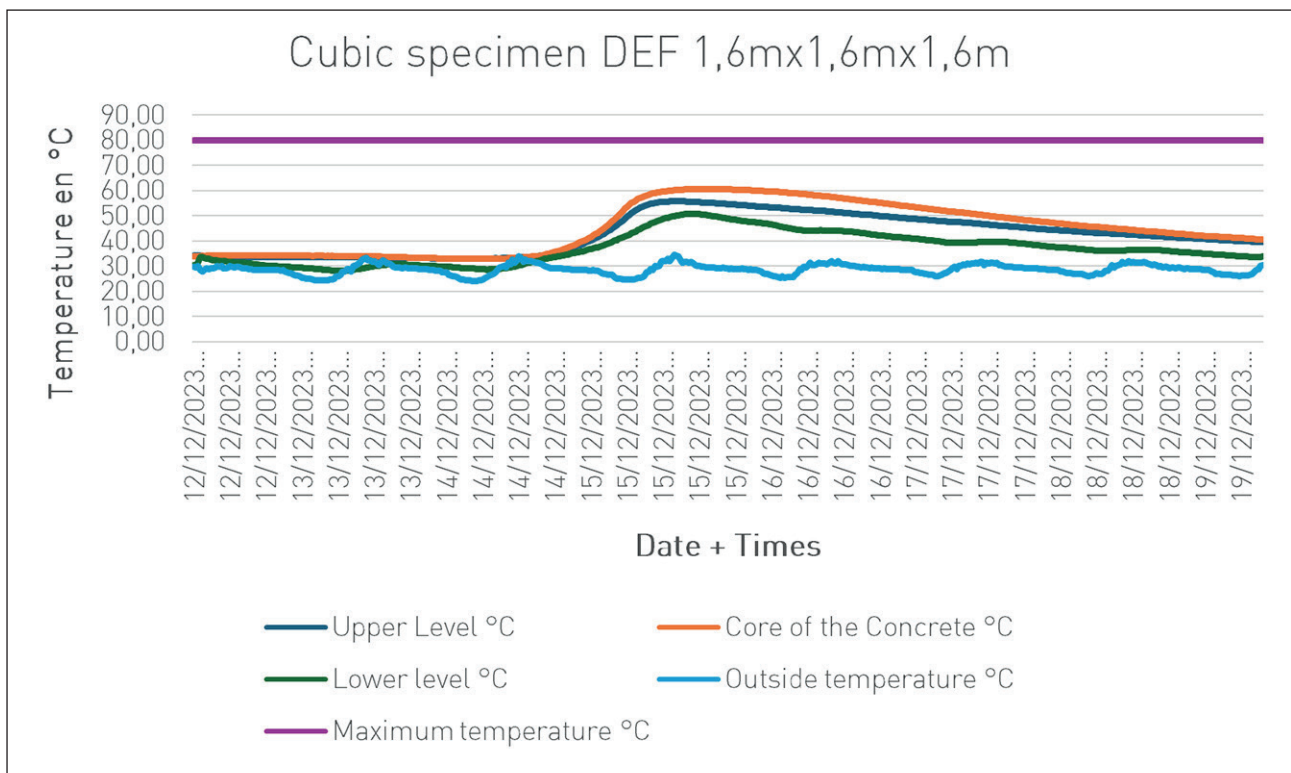


Fig. 6. Temperature evolution in the BP3 cubic specimen






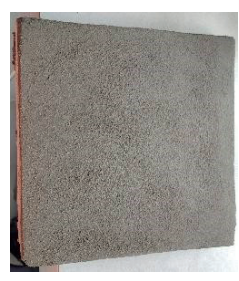










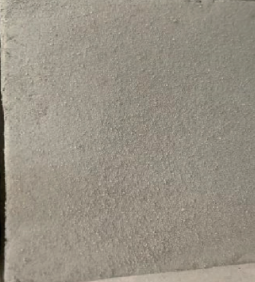

Fig. 7. On the left: DEF cube 1×1×1 m³, and on the right: DEF cube 1.6×1.6×1.6 m³

cal performance becomes poorer. Hydration reactions themselves generate heat, and massive structures tend to heat up more rapidly and cool down more slowly [18–22]. The observations made in this study are fully consistent with the conclusions reported by the authors in the literature.

For specimen BP3, the temperature of fresh concrete exceeded 35 °C, and this immediately affected the behav-

ior of the material. During the internal sulfate reaction (ISR) test, the thermal behavior became unstable, with repeated phases of temperature increase and decrease, although the maximum temperature still remained below 80 °C. This thermal instability led to poor mechanical properties. The material exhibited weaker performance in both compression and tension. In our opinion, this case clearly demonstrates that the higher the temperature

Table 14. Summary of mortar application on concrete

Days	Reference mortar	Mortar + 0.5% jute fibers	Mortar + 1.0% jute fibers	Mortar + 1.5% jute fibers
0 day				
7 days				
28 days				
90 days				

of fresh concrete, the poorer the mechanical properties become, even when the maximum temperature remains within the acceptable limits.

Mortar was then applied to the concrete, and no cracks were observed. This immediately shows that sound concrete is capable of maintaining the mortar coating in a stable and uniform condition. When the concrete is free from deformations caused by delayed ettringite formation (DEF), the mortar preserves its dimensions

and maintains a normal appearance without signs of deterioration. These results are consistent with findings reported in the literature, according to which the presence of ISR in concrete progressively reduces its mechanical properties. This problem is manifested by a decrease in compressive strength as well as a reduction in the ability to withstand tensile stresses. In our opinion, this issue is related to delayed ettringite formation promoted by poor thermal conditions. Such unfavorable thermal conditions

increase the risk of cracking and long-term deterioration of concrete [23].

CONCLUSION

In the course of this work, we found the following in this study: We believed that laboratory monitoring was necessary as early as the mix design stage and during the curing of the concrete. We also examined the occurrence of delayed ettringite formation (DEF). We observed that if the temperature of fresh concrete exceeds 35°C, instability can occur, even when the cube temperature remains below 80°C. This instability considerably reduces the strength of the concrete, especially in compression and tension. We think that without temperature control it is hard to achieve good results.

We put mortar on the surface to see what was underneath the concrete. If the concrete is sound, the mortar remains smooth and crack-free even after 90 days. If, however, the concrete has hidden defects, such as ISR, visible defects will appear in the mortar on the surface.

Controlling the temperature of fresh concrete is important from the very start of mixing. The temperature must be kept within the required limits. Otherwise, ettringite (DEF) may form. From our perspective, these parameters cannot be ignored either in the laboratory or on the construction site. This is because the concrete's service life depends on its temperature and the presence of ettringite. It also depends on how well the mortar layer will adhere. If the concrete deteriorates, the mortar will deteriorate as well. And then the entire structure will be at risk.

REFERENCES

1. Adrien Socié, Frédéric Dubois, Yann Monerie, Mejdj Neji, Frédéric Péralès. Simulation of internal and external-sulfate attacks of concrete with a generic reactive transport-poromechanical model. *European Journal of Environmental and Civil Engineering*. 2023;27(12):3679-3706. <https://doi.org/10.1080/19648189.2022.2146317>. – EDN SHMTKI.
2. Martin RP. *Analysis of the mechanical effects of internal sulfate reaction in concrete using model structures*. PhD Thesis Paris: École des Ponts ParisTech; 2011. Available from: <https://pastel.hal.science/tel-00558200v2> (access date 10.05.2026)
3. Kchakech B. *Study of the influence of thermal exposure on the risk of expansions associated with internal sulfate reaction in concrete*. PhD Thesis; 2016. Available from: <https://theses.hal.science/tel-01234288v2> (access date 10.05.2026).
4. Heinz D., Ludwig U. *Mechanism of secondary ettringite formation in mortars and concretes subjected to heat treatment*. In: Scanlon J.M., editor. *Concrete Durability (ACI SP-100)*. Detroit: American Concrete Institute. 1987;2059-2071. Available from: <https://trid.trb.org/View/281645> (access date 10.05.2026).
5. Tepponen P., Eriksson B.E. Damages in concrete railway sleepers in Finland. *Nordic Concrete Research*. 1987;6:199-209.
6. Shayan A, Quick GW. Microscopic features of cracked and uncracked concrete railway sleepers. *ACI Materials Journal*. 1992;89(4):348-361.
7. Mielenz R.C., Marusin S.L., Hime W.G., Jugovic Z.T. Investigation of prestressed concrete railway tie distress. *Concrete International*. 1995;17(12):62-68.
8. Thaulow N., Rostam S. Field cases of delayed ettringite formation. In: *International RILEM TC 186-ISA Workshop on Internal Sulfate Attack and Delayed Ettringite Formation*. Villars. Switzerland. 2002;85-97.
9. Santos Silva A., Pimentel A., Marques P. Diagnosis and prognosis of Portuguese concrete railway sleepers degradation – a combination of ASR and DEF. In: *13th International Conference on Alkali-Aggregate Reaction (ICAAR)*. Trondheim, Norway; 2008.
10. Divet L. Is there a risk of endogenous sulfate activity developing in large-mass concrete elements? The case of the Ondes Bridge (Haute-Garonne). *Bulletin des Laboratoires des Ponts et Chaussées*. 1998;213:59-72.
11. Divet L. *Internal sulfate reactions in concrete: contribution to the study of the mechanisms of delayed ettringite formation*. Paris: Central Laboratory of Roads and Bridges (LCPC); 2001.
12. Aubagnac C., Wendling J.C. *Presentation of the Gevry Bridge over the Doubs – RD 905*. In: *Internal Sulfate Reaction in Concrete: Risk Prevention and Management of Affected Structures*. Paris: LCPC Technical Day; 2007.

13. D. Kretz T.G.B. *Recommendations for the prevention of disorders caused by internal sulfate reaction*. Technical Guide of the Roads and Bridges Laboratories. Paris: Central Laboratory for Roads and Bridges (LCPC); 2007.
14. Pavoine A., Brunetaud X. *Development and validation of a test method for delayed ettringite formation: application to the study of the impact of different parameters on the kinetics and magnitude of expansion*. Paris: (LCPC); 2010. 224. Available from: http://www.ifsttar.fr/fileadmin/user_upload/editions/lcpc/ERLPC/ERLPC-OA-LCPC-OA65.pdf (access date 10.05.2026).
15. Bissonnette B., Pasquier M. Comparison of the durability of structural concretes made with different cements subjected to internal sulfate attack. In: *Proceedings of the AUGC Conference*; 2012.
16. IFSTTAR. *Recommendations for the prevention of disorders caused by internal sulfate reaction*. Paris: French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR); 2017.
17. Zomahoun C.V., Houanou K.A., Sodomon M., Samchenko S.V., Dossou S.K. Ecological Reinforcement of Cementitious Mortars with Jute Fibres: Effects on Mechanical Performance. *BioResources*. 2925;20(3):7514-7524. <https://doi.org/10.15376/biores.20.3.7514-7524>. – EDN: EICANL.
18. Bernard B. *Chemomechanical coupled modeling of concrete affected by internal sulfate reaction*. PhD Thesis. Paris: National School of Bridges and Roads; 2008.
19. Boenig A, Fúnez LM, Memberg L, Roche J, Tinkey B, et al. Structural assessment of bridges with premature concrete deterioration due to expansive reactions. *ACI Structural Journal*. 2009;106(2):196-204
20. Divet L., Pavoine A. Delayed ettringite formation in massive concrete structures: an account of some studies of degraded bridges. In: International RILEM TC 186-ISA Workshop on Internal Sulfate Attack and Delayed Ettringite Formation. *Villars (Switzerland)*. 2002;98-126.
21. Houndonougbo T. *Efficiency and durability of polymer coatings for the protection of concrete structures affected by internal sulfate reaction (ISR): from specimen to structure*. PhD Thesis; 2024. Available from: <https://theses.hal.science/tel-04621811> (access date 10.05.2026).
22. Pavoine N. *Combined effects of different factors on concrete expansion caused by delayed ettringite formation (DEF)*. PhD Thesis. Sherbrooke: University of Sherbrooke; 2003.
23. Shamaa M.A. *Study of the risk of development of an internal sulfate reaction and its consequences in structural concrete of nuclear facilities*. PhD Thesis; 2013. Available from: <https://theses.hal.science/tel-00787974> (access date 10.05.2026).

ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

INFORMATION ABOUT THE AUTHORS

Comlan V. Zomahoun – PhD Student, University of Abomey-Calavi, Abomey-Calavi Polytechnic School, Laboratory of Energy and Applied Mechanics, Abomey-Calavi, Republic of Benin, vianneyzomahoun@gmail.com, <https://orcid.org/0009-0009-3285-1807>

Kocouvi A. Houanou – PhD, Director of the Department of Civil Engineering, University of Abomey-Calavi, Abomey-Calavi Polytechnic School, Laboratory of Energy and Applied Mechanics, Abomey-Calavi, Republic of Benin, agapi.houanou@uac.bj, <https://orcid.org/0009-0008-4722-3291>

Mark Sodomon – Cand. Sci. (Eng.), Associate Professor, Department of Building Materials Science, Institute of Industrial and Civil Engineering, National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoe shosse, 26, Russian Federation, sodomonmarc@yahoo.fr, <https://orcid.org/0000-0003-4101-6538>

Svetlana V. Samchenko – Dr. Sci. (Eng.), Professor, Director of the Department of Building Materials Science, Institute of Industrial and Civil Engineering, National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoe shosse, 26, Russian Federation, samchenko@list.ru, <https://orcid.org/0000-0002-3523-593X>

AUTHORS CONTRIBUTION

Comlan V. Zomahoun – literature review, conducting experimental work, collection and systematization of experimental data, processing and analysis of experimental data using machine learning methods, graphical and tabular presentation of research results, drafting the initial text of the article, and formulation of final conclusions.

Kocouvi A. Houanou – scientific supervision; conceptualization and development of the research methodology; analysis of the research results; drafting of the article; formulation of conclusions.

Mark Sodomon – processing and analysis of experimental data using machine learning methods; graphical and tabular presentation of research results; drafting the initial text of the article; formulating the final conclusion; translation of the article into Russian.

Svetlana V. Samchenko – methodological support for the research, participation in the formulation of the research questions, peer review, editing and refinement of the manuscript, and verification of the validity of the research results and conclusions.

The authors declare no conflicts of interests.

The article was submitted 04.05.2026; approved after reviewing 09.06.2026; accepted for publication 13.06.2026.