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An assessment of the carbon footprint of concrete mixtures in relation to early strength development, evaluated using various maturity models

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ABSTRACT

This research aims to establish robust strength-maturity correlations for concrete produced using various cement binders, along with a comprehensive assessment of the carbon footprint of ready-mix concretes manufactured with each cement type. The study employs two maturity calculation methods: the time-temperature factor (TTF) approach and the weighted maturity method, to evaluate early strength development. Six cement binders were tested, including CEM I 42.5R, CEM V/A (S-V) 32.5R-LH, and various CEM II variants. The heat of hydration for each binder was measured, and the development of mechanical properties was monitored through temperature measurements and compressive strength tests. Additionally, a carbon footprint analysis was conducted to evaluate the environmental impact of the ready-mix concrete in relation to its early strength development. The results confirm significant variations in strength development, with rapid growth observed in concretes containing CEM 42.5 classes, whereas slower strength gain was noted in concretes manufactured with CEM II/B-M (V-LL) 32.5R and CEM V/A 32.5R-LH. At the same time, binders with slower early strength development are characterized by a significantly lower carbon footprint, contributing to the positive environmental impacts of the investigated mixtures produced with low-emission binders. These findings underscore the challenges of balancing the use of low-emission binders with the construction industry's demand for accelerated processes.

Keywords: early strength development, carbon footprint, time-temperature factor (TTF), weighted maturity index.

INTRODUCTION

The hardening process of cement paste and the early-stage strength development of concrete have been a subject of interest for many researchers since the 1950s. Scholars have extensively examined how time and curing temperature influence the development of compressive strength in concrete. Initial investigations, like McIntosh's work in 1949, examined techniques for electrically curing concrete, which subsequently paved the way for the establishment of maturity methods around 1950 to enhance the comprehension of steam curing's impact on strength development [1, 2]. Accurate assessment of early-age concrete strength is crucial in applications such as bridges and buildings [3]. In the production of precast concrete, understanding real-time strength-maturity provides benefits like optimizing demoulding time, lowering heating expenses, and facilitating the early identification of potential problems. Over the decades various advanced testing methods, such as electrical methods, nuclear magnetic resonance, wave propagation, acoustic emission, and computational modelling, have been and continue to be employed to study these phenomena [4, 5]. A comprehensive body of knowledge on this topic was released in 2005 by the RILEM association [6]. From an engineer's point of view, the weighted maturity approach, which is based on the temperature–strength correlation, appears to be the most useful and practical method [7–12]. However, further improvements and additional investigation are still required regarding the application of the novel binder materials [13]. Some researchers highlight the advantages of the ultrasound method over the maturity approach [14] or propose combining methods to achieve greater accuracy [5, 15, 16]. Interesting studies on heat generation and heat conduction properties of concrete have been presented by Fernandez and Less [17]. Nonetheless, only CEM I and the substitution of ground granulated blast-furnace slag (GGBS) were analysed. Moreover, neither mechanical tests nor the carbon footprint of the analysed mixtures were determined. Kanavaris, Soutsos et al. [18, 19] introduced different maturity models to predict the strength development of concrete mixtures with various substitutions of GGBS for Ordinary Portland Cement (OPC). However, they only mentioned that such treatment leads to a reduction in the carbon footprint of concrete. In Polish literature, concrete maturity has been studied by Kurdowski and Pichniarczyk [20], Wawrzeńczyk et al. [21, 22], and Bajorek et al. [23–25]. Still, the environmental impact is not within the scope of interest in these reports. An in-depth analysis of the possibilities for decarbonization in the civil engineering sector, particularly the concrete industry, often focuses solely on the replacement of traditional materials with low-emission alternatives [26–31] or on the novel approach to the design process [32]. The analysis of the environmental impact of the manufacturing process usually considers material transportation [33] or curing treatments in terms of compressive strength at 28 days [34], while omitting the significant influence of low-emission additives on early strength development.

Different types of cement possess distinct characteristics that make them ideal for particular uses: CEM I is a high-strength Portland cement that achieves rapid strength gain, making it ideal for precast industry or cold-weather applications. CEM III and CEM V effectively reduces heat during hydration, which is beneficial for large structures such as dams. CEM II with the addition of the limestone or fly ash are an environmentally friendly Portland composite cement that provides good workability and a lower carbon footprint, suitable for general construction and mass concrete and precast elements. Nowadays, during the design process and construction site management, not only are the mechanical properties of materials crucial, but also their environmental impact, particularly their embedded carbon footprint. In the field of concrete technology, finding a balance between using ready-mix concrete with rapid early strength to maintain project schedules and reducing environmental impact by incorporating low-emission cement binders with slower strength development is one of the most important topics being discussed among scientists, technologists, and site management engineers. The lack of experimental and analytical studies on this topic prompted the authors to conduct the investigation presented below. This paper, therefore, presents the results of an assessment of the carbon footprint of concrete mixtures with various types of cement binders, evaluated in relation to their early strength using maturity models.

MATERIALS AND METHODS

In this study, six different types of ready-mix concrete were analysed to determine their early strength development. The ready-mixes varied based on the types of cement binders used. First, the heat of hydration for each cement binder was measured. The development of mechanical properties was monitored through temperature measurements of the concrete and compressive strength tests. Additionally, a carbon footprint analysis was conducted to evaluate the environmental impact of the ready-mix concrete in relation to its early strength development. The presented investigation is a preliminary study aimed at contributing to further research that considers various types of materials, mixture compositions, and curing conditions for concrete. For this purpose, a reference ready-mix concrete based on CEM I 42.5R and natural aggregates, with a compressive strength class of C35/45, was introduced. This type of ready-mix is commonly used in precast concrete technology due to its rapid early strength development. In the next step, the basic recipe was modified by incorporating various binder types with differing environmental impacts.

Ready-mix concrete

The early strength development of six types of ready-mix concrete was measured. For this procedure, concrete specimens were prepared following a recipe for 1 m^3, which included: 320 kg of cement binder, 144 litters of distilled water, 800 kg of sand (0–2 mm), 400 kg of fine gravel (4–8 mm), 800 kg of coarse gravel (8–16 mm), and 1% of the cement weight (c.w.) of superplasticizer.

The concrete mixtures were differentiated by the type of cement binder used:

- CEM I 42.5R,
- CEM II/A-V 42.5R,
- CEM II/A-LL 42.5R,
- CEM II/B-V 42.5 HSR/NA,
- CEM II/B-M (V-LL) 32.5R,
- CEM V/A (S-V) 32.5R-LH.

Heat of hydration

For this test the EN 196-9 procedure was followed for consistency [35]. Each batch included 450 g of cement binder, 1350 g of sand, and 225 ml of distilled water. The mortar was mixed in dedicated containers and casted into cylindrical moulds. For measuring heat of hydration, a research calorimeter and the LANGAVANT program were used. The procedure began by accurately measuring materials, and mixing for a set duration. The sealed container was then placed in the calorimeter, and data was recorded. After the test, the final weight was measured, providing insights into the exothermic reaction of each cement during hydration.

Maturity monitoring

Maturity serves as a non-destructive technique for assessing the strength of concrete by analysing its temperature history. It is presumed that concrete with an identical mix will attain equivalent strength upon reaching the same maturity index, irrespective of the curing conditions applied [9]. In this experiment, embedded sensors were placed in 100 × 100 × 100 mm concrete cubes to monitor temperature variations over time. The monitoring process began immediately after casting, with temperature readings recorded continuously until the 48-hour mark. Simultaneously, concrete cubes were prepared for compression tests conducted at intervals of 4 hours, starting from 12 hours (i.e., at 12 h, 16 h, 20 h, 24 h) and at 48 hours. These tests aimed to correlate the maturity values with actual strength development. At each time point, the compressive strength test was performed on three cubes. This side-by-side comparison provided a reliable means to validate the maturity method and ensure the structural integrity of the concrete during the early stages of curing. For the purposes of this study the maturity index was calculated using the Temperature-Time Factor and the weighted maturity approaches.

Time-temperature factor (TTF)

The TTF method, recognized as the Nurse-Saul maturity function, represents the inaugural maturity method established in the early 1950s. This approach was formalized in 1987 by ASTM C1074 [9]. Nonetheless, the TTF maturity methodology enjoys broader adoption among state highway agencies, primarily due to its straightforward nature. The equivalent age can be understood as the total days or hours at a given temperature necessary to reach a maturity value that matches the value obtained from a curing period at temperatures that differ from the specified one. The TTF maturity testing process fundamentally involves two steps: creating the maturity calibration curve and assessing the maturity of the in-place concrete. The Nurse-Saul maturity function, widely recognized in the field, is defined in ASTM standard as follows [9, 36]:

$$M(t) = \Sigma(T_a - T_d) \cdot \Delta t \quad (1)$$

where: $M(t)$ – the temperature-time factor at age t (ºC-h), T_a – average concrete temperature during time interval (ºC), T_d – the datum temperature at which cement hydration stops (ºC), Δt – time interval (h).

In the context of Equation 1, deriving most variables requires only a basic level of complex analysis. The average concrete temperature during the time interval (T_a) is measured at specific intervals using a maturity monitoring system. The time interval (Δt), determined by the measurement frequency of the maturity meter, usually lasts 1 hour, 30 minutes, or shorter durations. The datum temperature (T_d) is the only variable that needs to be estimated or calculated. To achieve improved precision, T_d can be established through laboratory testing in accordance with ASTM C1074 standards, although it is frequently estimated to be around 0 °C, -5 °C, or -10 °C for practical purposes. ASTM C1074 suggests a datum temperature of 0°C for Type I cement without admixtures, cured within a temperature range of 0 °C to 40 °C. Choosing a 0 °C datum temperature is typically considered a cautious approach, based on the premise that concrete does not achieve strength gains when temperatures fall below freezing. This suggests that conditions where $(T_a - T_d) \leq 0$ result in no strength gain, represented as M(t) = 0, since the hydration process does not negatively impact the concrete's strength [9].

Weighted maturity

An alternative method for calculating maturity is the weighted maturity approach, which was first introduced by Papadakis and Bresson in the 1970s and further improved by de Vree in 1979. While not widely used in North America, it is currently standardized in the Netherlands [37] and widely accepted throughout Europe. The weighted maturity method, outlined in Equation 2, shares similarities with the Nurse-Saul equation, with $t_k T_k$ representing the area under the temperature curve and C^{nk} serving as a correction factor [9, 37, 38]:

$$M_w = \sum t_k - T_k C^{nk} \tag{2}$$

where: M_w – weighted maturity (°C-h), T_k – hardening time of concrete (h), t_k – hardening temperature interval, C – C-value of cement, nk– temperature-development parameter for T_k.

Using this equation is impractical due to the temperature-dependent nature of the nk factor. To simplify calculations, a discontinuous function can be employed for determining the n parameter in the proposed linear equation (Equation 3). Therefore, the equation for weighted maturity can be simplified by incorporating the C^{nk} values from the datum temp. (-10 °C) to the average temperature. This is now represented as Equation 4, which includes a continuous n function.

$$N = 0.1 \cdot T - 1.245 \tag{3}$$

$$M_w = \sum[(10 \cdot (C^{0.1 \cdot T-1.245} - C^{-1.245}) / lnC] \cdot \Delta t \tag{4}$$

where: Mw – weighted maturity (°C-h), T – average temperature during the time interval, C – C-value of cement, Δt – time interval (h).

The C-value, a characteristic specific to cement, denotes the cement's sensitivity to temperature. It can be acquired either directly from the cement manufacturer or through the standardized procedure outlined in NEN 5790 [37]. Typically, the value ranges between 1.25 to 1.75 [9]. Table 1 presents the C-values of the cement binders used, based on the percentage of clinker content in the binder.

Carbon footprint analysis

The investigation of the early-strength development of the ready-mix concrete was supported by the carbon footprint analysis of tested mixtures. The carbon footprint assessment of concrete materials evaluates the environmental impacts across all stages of their life cycle: production (stage A), utilization (stage B), disposal (stage C), and recycling (stage D), using one cubic meter of concrete as the functional unit [40]. The methodology adopted in this study encompasses three stages: raw material extraction (A1), transportation (A2), and manufacturing (A3). These stages are critical for assessing the environmental impact, energy consumption, and emissions associated with the production process. The limitation of this life cycle analysis stems from a lack of information regarding the durability performance of the investigated mixtures, which will be crucial for the B stage. Additionally, it is assumed that the disposal and recycling stages are similar for all types of ready-mix concrete. Therefore, this analysis focuses exclusively on the production stage, with particular emphasis on the environmental impact of the materials used. The carbon footprint analysis was conducted using OneClick LCA software (One Click LCA© Version: 0.30.0, Database version: 7.6) [41], which leverages precise and validated data sourced from industry reports and Environmental Product Declarations (EPDs). The carbon footprint values of the ingredients in the concrete mixtures, as described in the EPDs, are expressed as the Global Warming Potential (GWP) in kilograms of CO_2 equivalent per functional unit of each material. For the cement binders and concrete admixtures, the GWP values were taken directly from the EPDs provided by the manufacturer. For the aggregates and water, generic mean values from the OneClick LCA software, based on its worldwide database, were used.

TEST RESULTS AND DISCUSSION

Heat of hydration

In Figure 1, the results of the heat of hydration test for the cement binder used are presented.

Table 1. The C – values according to clinker content [39]

Clinker content	Above 65%	50–64%	35–49%	20–34%
C – value	1.3	1.4	1.5	1.6

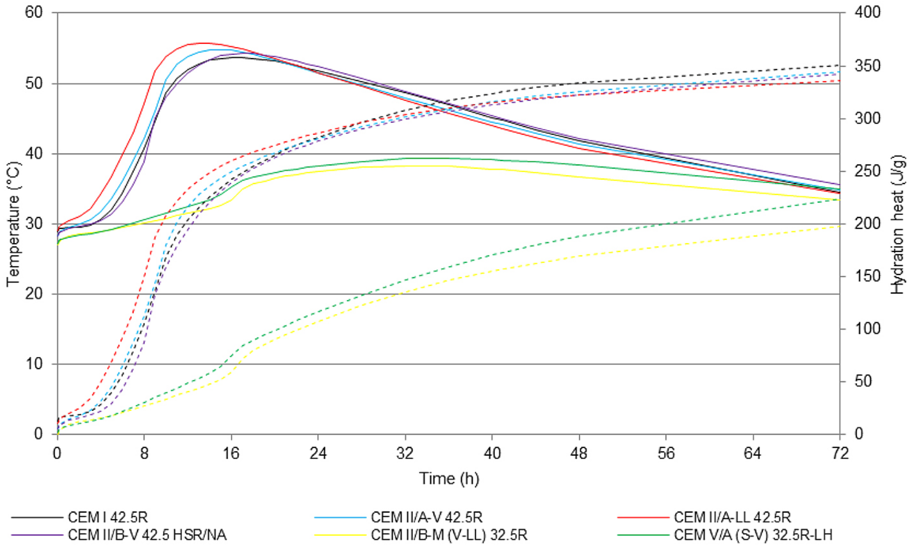

Figure 1. Test result of the heat of hydration test for the analysed cement binders (—— temperature (°C), – – – – hydration heat (J/g))

This test produces two graphs: the temperature development of the tested mortar and the heat released during the hydration reaction.

The obtained results clearly show differences in temperature development and hydration heat between the CEM 42.5 binders and the CEM 32.5 binders. For all CEM 42.5 cement binders, the maximum measured hydration heat values are approximately 350 J/g, with maximum temperatures ranging from 50 °C to 55 °C, achieved 10 to 12 hours after mixing with water. Within this group, the highest heat of hydration was recorded for CEM I 42.5R at 350 J/g, while the lowest was 336 J/g for CEM II/A-LL 42.5R. In contrast, for the CEM 32.5 binders, the maximum measured hydration heat values were 198 J/g for CEM II/B-M (V-LL) 32.5R and 223 J/g for CEM V/A (S-V) 32.5R-LH. Moreover, the maximum temperatures were 38 °C and 39 °C, respectively, achieved between 32 and 36 hours after mixing with water. Additionally, for the CEM 32.5 binders, the temperature development and the increase in hydration heat show no evidence of rapid growth at a specific time point, which is clearly observed in all CEM 42.5 binders.

Maturity monitoring

To establish the maturity index, temperature monitoring of the investigated concrete mixtures was performed alongside compressive strength tests conducted at specific time intervals. Figure 2 shows the temperature development of the analysed concrete mixtures, while Figure 3 presents

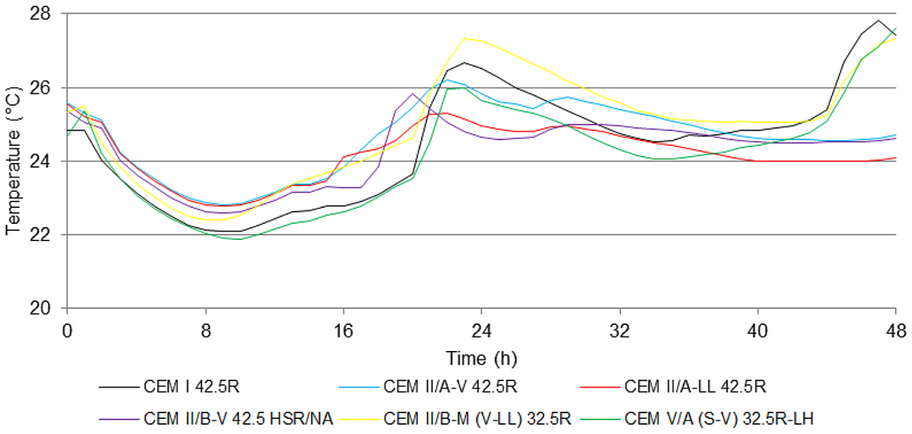

Figure 2. Temperature development of the concrete mixtures

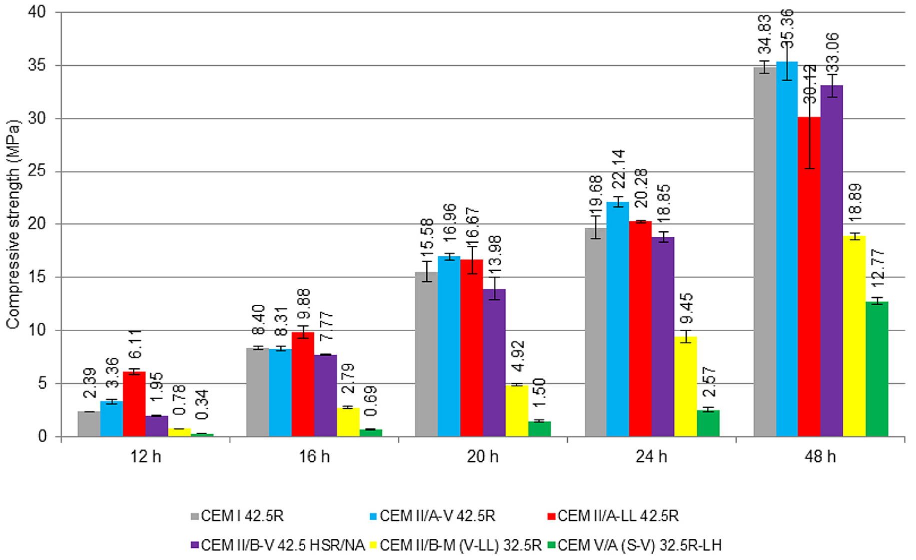

Figure 3. Test result of the compressive strength test

the compressive strength test results after 12 h, 16 h, 20 h, 24 h, and 48 h of curing.

The measured temperatures for the concrete mixtures ranged between 22 °C and 28 °C during the investigated time period. The temperature curves are very similar for all tested mixtures and are characterized by reaching the maximum temperature approximately 24 hours after casting. The temperature increase observed in the three types of concrete mixtures 46 hours after casting may have resulted from the uncontrolled exposure of the samples to sunlight passing through the laboratory windows, which likely occurred over a period of approximately two hours. Although the temperature evolution of the fresh concretes is comparable, significant differences in early strength development are observed. After 12 hours of curing, the maximum compressive strength was achieved by the concrete with the CEM II/A-LL 42.5R binder, while the minimum compressive strength was observed in the concrete with the CEM V/A (S-V) 32.5R-LH binder. The respective values were (6.11±0.28) MPa and (0.34±0.05) MPa. After 16 hours of curing, the maximum compressive strength was achieved by the concrete with the CEM II/A-LL 42.5R binder, while the minimum compressive strength was observed in the concrete with the CEM V/A (S-V) 32.5R-LH binder. The respective values were (9.88±0.62) MPa and (0.69±0.02) MPa. After 20 hours of curing, the maximum compressive strength was achieved by the concrete with the CEM II/A-V 42.5R binder, while the minimum compressive strength was observed in the concrete with the CEM V/A (S-V) 32.5R-LH binder. The respective values were (16.96±0.30) MPa and (1.50±0.07) MPa. After 24 hours of curing, the maximum compressive strength was achieved by the concrete with the CEM II/A-V 42.5R binder, while the minimum compressive strength was observed in the concrete with the CEM V/A (S-V) 32.5R-LH binder. The respective values were (22.14±0.45) MPa and (2.57±0.21) MPa. After 48 hours of curing, the maximum compressive strength was achieved by the concrete with the CEM I 42.5R and CEM II/A-V 42.5R binders, while the minimum compressive strength was observed in the concrete with the CEM V/A (S-V) 32.5R-LH binder. The respective values were (35.36±1.82) MPa and (12.77±0.31) MPa. Based on the obtained strength results, two distinct ready-mix concretes can be distinguished, analogous to the hydration heat test. One group consists of concretes made with CEM 42.5 binders, where the compressive strength values are comparable at most time points of the mechanical test, except for the first measurement at 12 hours of curing. The second group includes concretes made with CEM 32.5 binders; however, a significant discrepancy in the gain of compressive strength over time is observed. Interestingly, higher compressive strength values were achieved for the concrete with the CEM II/B-M (V-LL) 32.5R binder, even though this binder exhibited lower hydration heat compared to the CEM V/A (S-V) 32.5R-LH. Considering that the recommended demoulding compressive strength can vary from

10 to 17 MPa [42], deshuttering will be possible after 20 hours of curing for concrete elements made with CEM 42.5 binders. In the case of CEM 32.5 binders, demoulding could be performed after at least 48 hours of curing.

To highlight the contrast between the investigated cement types, Figure 4 presents a comparison of the hydration heat of cement binders and the compressive strength development of the concrete mixtures with CEM I 42.5 and CEM V/A (S-V) 32.5R-LH. The rapid early strength development is achieved due to the high-clinker content of the cement binder, which is associated with the high value of the heat of hydration.

Time-temperature factor (TTF)

Figure 5 shows the maturity indexes calculated using the TTF method. The results confirm the previous observations. Ready-mix concretes with CEM 42.5 exhibit similar maturity paths, in contrast to concretes with CEM 32.5, which have significantly lower maturity indexes. To achieve the minimum compressive strength required for demoulding, the TTF maturity index for CEM 42.5 concretes is approximately 400 °C-h. In comparison, for concrete with CEM II/B-M (V-LL) 32.5R, it is around 600 °C-h, and for concrete with CEM V/A (S-V) 32.5R-LH, it reaches

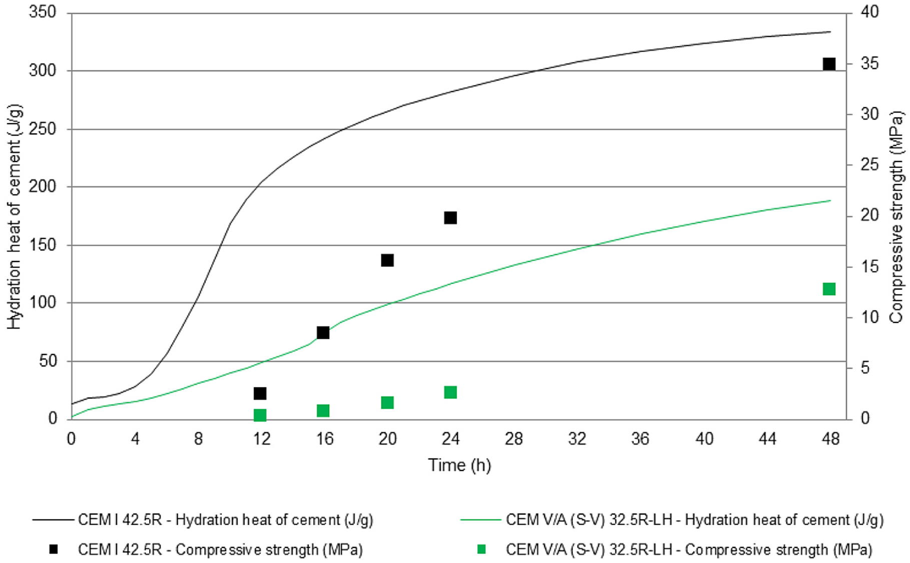

Figure 4. Comparison of the hydration heat of cement and the compressive strength development for CEM I 42.5 and CEM V/A (S-V) 32.5R-LH

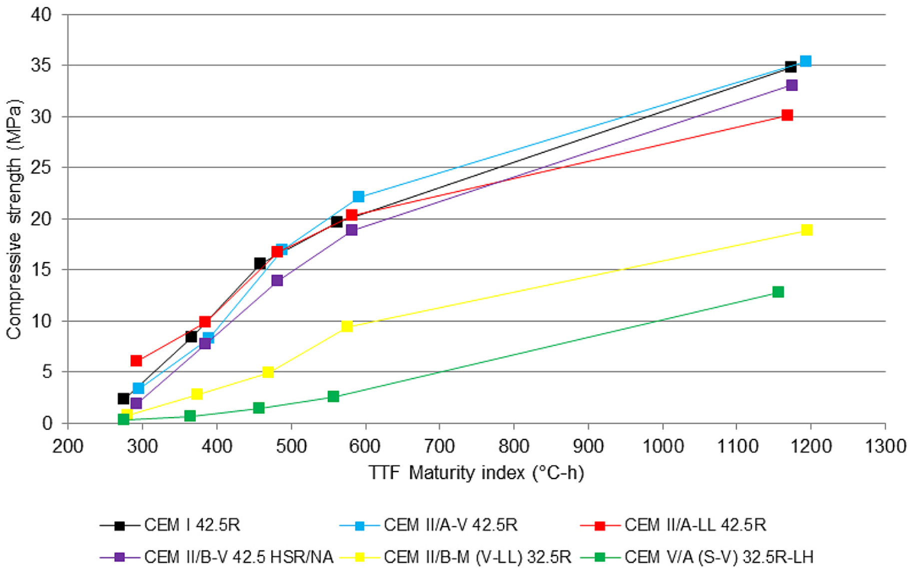

Figure 5. Maturity index calculated based on the TTF method

nearly 1000 °C-h. In engineering practice, this necessitates either longer curing times or higher temperatures in curing chambers.

Weighted maturity

To evaluate the weighted maturity index, the C-value of cement should be experimentally determined. However, for the purpose of this paper, the C-values reported in the literature have been adopted. Table 2 presents the C-values of the cement binders used, based on the percentage of clinker content in the binder.

Figure 6 illustrates the maturity indexes calculated using the weighted maturity method. To achieve the minimum compressive strength required for deshuttering the concrete element, the weighted maturity index for CEM 42.5 concretes is approximately 400 °C-h, while for concrete with CEM II/B-M (V-LL) 32.5R, it exceeds 600 °C-h, and for concrete with CEM V/A (S-V) 32.5R-LH, it approaches nearly 1000 °C-h. It is clearly evident that the obtained maturity indices and maturity paths show similar values and trends to those obtained using the TTF method.

Carbon footprint analysis

To assess the environmental impact of the concrete mixture in relation to its early strength development, the carbon footprint of the investigated ready-mix concretes have been calculated. In Table 3, the values of the GWP (stage A1-A3) of the used materials are presented. The GWP values of the cement binders vary between 0.664 eqkgCO_2/kg for CEM I 42.5 and 0.323 eqkgCO_2/kg for CEM V/A (S-V) 32.5R-LH. This factor is strongly affected by the amount of clinker in the binder material. To reduce the negative environmental impact of the cement binder, many alternative binder materials are used, such as limestone (LL), blastfurnace slag (S), and fly ash (V), in particular.

Figure 7 shows the total GWP (A1-A3) values for the performed concrete mixtures. The highest GWP value was reached by the concrete with CEM I 42.5R, and the lowest GWP value by the concrete with CEM V/A (S-V) 32.5R-LH, with values of 223.8 eqkgCO_2/m^3 and 114.7 eqkgCO_2/m^3, respectively. Moreover, in all analysed cases, the cement binder is responsible for around 90% of the total GWP (A1-A3) value, while

Table 2. The C – values of the analysed cement binders

Material	CEM I 42.5R	CEM II/A-V 42.5R	CEM II/A-LL 42.5R	CEM II/B-V 42.5 HSR/NA	CEM II/B-M (V-LL) 32.5R	CEM V/A (S-V) 32.5R-LH
Clinker content [43, 44]	Above 90%	80–94%	80–94%	65–79%	65–79%	40–64%
C – value [39]	1.3	1.3	1.3	1.3	1.3	1.5

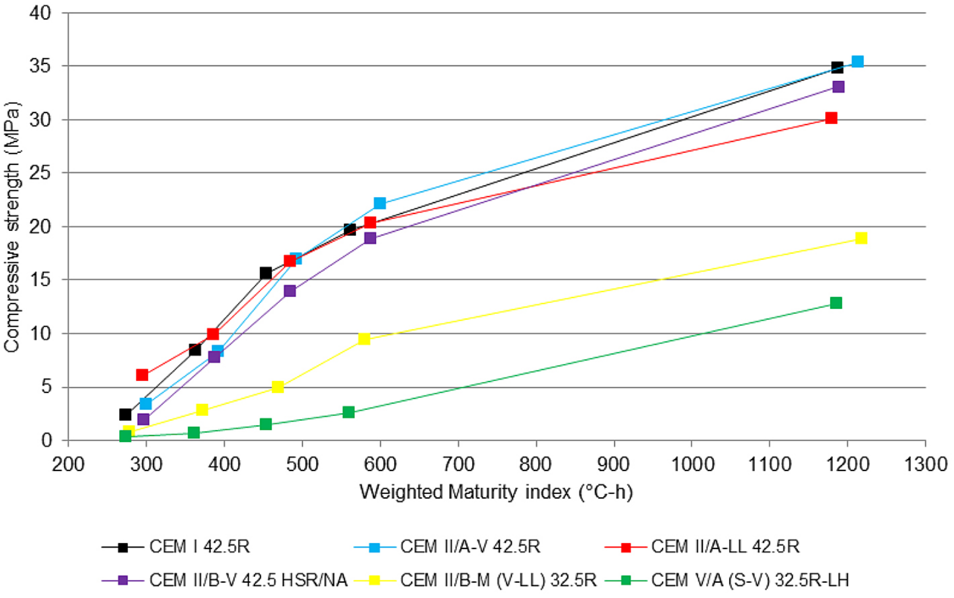

Figure 6. Maturity index calculated based on the weighted maturity method

Table 3. Values of the GWP (stage A1-A3) for the analysed materials

Material	CEM I 42.5R	CEM II/A-V 42.5R	CEM II/A-LL 42.5R	CEM II/B-V 42.5 HSR/NA	CEM II/B-M (V-LL) 32.5R	CEM V/A (S-V) 32.5R-LH
GWP (eqkgCO$_2$/kg)	0.664 [45]	0.562 [46]	0.597 [47]	0.516 [48]	0.439 [49]	0.323 [50]

Material	Water	Sand (0/2)	Fine gravel	Coarse gravel	Superplasticizer
GWP (eqkgCO$_2$/kg)	0.0003 [41]	0.00232 [41]	0.00378 [41]	0.00378 [41]	1.53 [51]

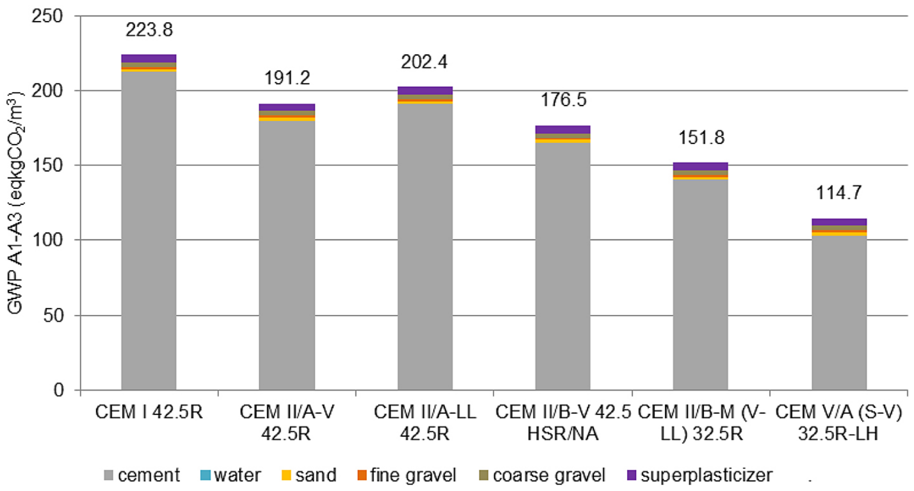

Figure 7. GWP (A1-A3) values for the analysed ready-mix concretes

accounting for only 10% of the volume. The results clearly show that the amount and type of cement binder play a crucial role in the carbon footprint of ready-mix concrete.

All the analysed ready-mix concretes with rapid early strength development are characterized by relatively high GWP values. Lower carbon footprints of the concrete mixtures correspond to lower early compressive strength values, resulting in a longer curing time for the concrete structure. However, it is noteworthy that concrete made with CEM II/B-V 42.5 HSR/NA has the lowest GWP impact among the CEM 42.5 concretes, with a value only 14% higher than that of ready-mix concrete made with CEM II/B-M (V-LL) 32.5R.

CONCLUSIONS

The maturity index, as determined by both approaches, consistently indicates the ongoing increase in concrete strength. This validates the core principle that the maturity of concrete, considering both time and temperature, is a reliable indicator of its compressive strength. The consistent increase in strength with maturity index across all cement types further confirms the effectiveness of the maturity model as a valuable tool in civil engineering practice. Despite slight variations in the maturity model, the TTF and Weighted Maturity methods consistently showed similar patterns in strength development. It appears that each method successfully captures the correlation between maturity and strength, even when there are no significant temperature changes.

Furthermore, the study presents a clear correlation between the maturity models TTF and weighted maturity) and the heat of hydration in various cement binders. There is a strong correlation between higher heat of hydration values and higher maturity indices, suggesting that these models are effective in predicting the strength development of concrete. The findings of this study provide strong evidence supporting the accuracy and effectiveness of the TTF and weighted maturity models in predicting the compressive strength of concrete. These models take into account the hydration characteristics of different types of cement, ensuring reliable forecasts.

In addition, the carbon footprint analysis of ready-mix concretes with different cement binders shows that concrete with CEM V/A (S-V) 32.5R-LH as a binder has the lowest carbon footprint, while CEM I 42.5R has the highest environmental impact. The significant reduction in emissions for blended cements (CEM V and CEM II variants) is primarily due to the lower clinker content and the inclusion of supplementary cementitious materials, such as blastfurnace slag, fly ash, and limestone. Therefore, using blended cements offers a more sustainable alternative for concrete production, reducing environmental impact, albeit at the expense of early strength development. The presented results are the outcome of a preliminary study assessing the carbon footprint of concrete mixtures in relation to their early strength development. The main objective of this study was to highlight the challenges of balancing the use of low-emission binders with the construction industry's demand for accelerated processes. The authors acknowledge the need for further investigation into the durability performance of concrete and an analysis of end-of-life scenarios to conduct a comprehensive life cycle assessment, including life cycle cost analysis. These topics are within the authors' scope of interest and will be explored in future research.

The decarbonisation of the cement-concrete industry through the use of low-emission cement binders is one of the biggest challenges of our time. On the contrary, particularly in the precast concrete industry, the additional energy consumption required for extended curing times in curing chambers increases the carbon footprint of the manufactured elements. In terms of cast-in-situ structures, longer curing times require more labour and delay the construction schedule, which also impacts the environmental impact of the building. A hybrid approach that integrates the maturity model of concrete to assess early strength development with carbon footprint analysis could represent a promising strategy for optimizing the construction process.

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