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Review

Methodology for Determining the Correct Ultrasonic Pulse Velocity in Concrete

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Abstract: Quite often, concrete strength parameters must be determined in the shortest possible time. Due to the strong correlation between concrete's mechanical and acoustic properties, ultrasonic devices can be used for this purpose. However, the ultrasonic pulse velocity (UPV) is influenced by a variety of factors, including the curing and exploitation conditions of the concrete, the presence of reinforcement, and other various physical factors. Ignoring these factors may contribute to the misinterpretation of the measurement data when determining the strength of the concrete. Typically, all these factors are analyzed independently. This publication consolidates the findings obtained from our research efforts and field expertise over the past two decades. It outlines the elaborated UPV measurement methodology based on the integration of a four-argument function: the hydration process phase of the hardened cement paste (or concrete aged three days and older), hardening (curing) condition, concrete moisture level, and ambient temperature. To understand the interactions of the key factors, different ultrasonic devices were used to measure the velocities of longitudinal and surface waves in concrete by applying direct and indirect transmission methods when concrete specimens were tested under different moisture and temperature conditions.

Keywords: concrete; ultrasonic pulse velocity (UPV); curing; moisture; temperature; frost

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1. Introduction

The increase of new building and engineering structures, with concrete and reinforced concrete used as the base materials, coincides with the degradation of the technical conditions in previously built constructions. Consequently, there is a substantial increase in the number of structures requiring investigation and testing, necessitating a prompt evaluation of the test results in the short term. Therefore, there is a preference for using nondestructive test methods to ascertain the technical conditions of structures efficiently.

In practice, the strength of concrete is often chosen as a key parameter for characterizing the technical condition of a reinforced concrete structure. Various ultrasonic measuring devices can be applied to determine the concrete's strength in reinforced concrete structures. While there are existing standards outlining the preconditions for the correct performance of ultrasonic measurements and the interpretation of the results, rather insufficient information is given. The data obtained from the investigation on various construction sites indicate a significant impact of moisture and other factors on the ultrasonic pulse velocity (UPV). Ignoring these affecting factors can lead to misinterpretation of the measurement data. In general, there exists an inherent lack of assurance regarding the precision of the measurement data, even with a careful investigation into each distinct factor and its consequential impact. This uncertainty arises from the failure to consider the influence of these specific factors and their interactions on the UPV during the data selection process. Without a comprehensive understanding of these factors, civil engineers often interpret the measurements in a superficial manner, resulting in an inaccurate assessment of the properties of the tested concrete, thus leading to potential mistakes in the safety assessments of concrete structures. For example, neglecting the properties of concrete ingredients can result in a change in the concrete compressive strength of up to 50% with only a 5% change in the UPV [1,2].

The UPV of concrete is influenced by a variety of factors, including the properties of the raw materials [3], mix proportions [4,5], age, curing and exploitation conditions, moisture content [6], the embedded reinforcement, and various other physical factors. So far, all of them have been analyzed independently. For instance, it is often mentioned that the UPV increases in the areas of the reinforcement bars when testing reinforced concrete [1]. Additionally, the most significant influence is provided by the surface areas near the reinforcements. Ambient temperatures in the range of +5 °C to +30 °C do not influence the UPV of concrete [7,8]. In turn, changes in the standard moisture and temperature conditions, as interrelated factors, can significantly influence the UPV of concrete [9]. However, the moisture factor influence on the UPV of concrete is much more significant [9,10]. In previously conducted research on negative temperature influence on the UPV of concrete, the indicated influence level differs [11,12]. The maximum possible increase in the UPV of frozen concrete in relation to air-dry concrete is set at 18% [9]. However, the standard currently in force in the European Union does not provide specific guidance on accounting for the negative temperature influence on the UPV of concrete [13]. On the other hand, the standard of the Russian Federation [14] describes some features of measurements in frozen concrete. Namely, it is indicated that the correlation relationships between the UPV and strength of the concrete, established at a concrete temperature below 0 °C, are not allowed to be used at positive temperatures.

The impact of the moisture level on the UPV of concrete varies widely, ranging from negligible to a substantial level of 16% [9,10,15–17]. The nature of the correlation "ultrasonic velocity–concrete moisture" is also valued differently. While some research outputs characterize the relationship as linear [18], a majority of research studies acknowledge the use of exponential models [10,19]. The references within the standards of different states show uncertainty on this matter [13,14,20–22]. Notably, the reviewed literature lacks information concerning potential changes in the UPV due to moisture influence, particularly in relation to the age of the tested concrete and the quality of curing during the hardening process. Despite a few relatively similar interpretations and recommendations regarding the effects of moisture content and temperature on the UPV of concrete, there is no clear consensus between the available up-to-date research output and the existing standards [23]. Moreover, the latest research output simply indicates that there is still a notable absence of studies focused on ultrasonic monitoring where moisture content is considered [17,24,25].

This publication consolidates insights obtained from a number of different authors' research and field expertise outcomes within the last twenty years, with the goal to identify the interdependence among the main physical factors when subjected to testing for the same concrete compositions. After applying different ultrasonic measurement devices, it was revealed that the concrete moisture level has the most substantial impact on the outcome from the measurements. Variations in the moisture content largely determine the influence degree of the rest of the physical, mechanical and other factors on the UPV of concrete. Furthermore, it is rather significant whether concrete is tested at an early age or a later one in its exploitation lifespan.

The aim of this research was to formulate a correlation for obtaining accurate UPV data using direct and indirect transmission methods when concrete specimens were tested under different moisture and temperature (from −20 °C to +30 °C) conditions. The elaborated UPV measurement methodology [1,2] integrated a four-argument function which includes the phase of the hydration process of the hardened cement paste (or concrete age), hardening (curing) condition, concrete moisture level, and ambient temperature.

2. Measuring Devices and Concrete Specimens

Three devices were used to measure the UPV: the ultrasonic tester "UK-1401", ultrasonic flaw detector "A1220 Monolith", and an oscillograph "UKB-1M".

The ultrasonic tester "UK-1401" ("Acoustic Control Systems" company, Moscow, Russian Federation) was applied for the measurements of propagation velocities of longitudinal ultrasonic waves in concrete by using an indirect measurement method (Figure 1a). The main technical parameters of the device "UK-1401" are as follows: the measurement base (constant distance between the built-in dry point contact (DPC) transducers) of 150 ± 1 mm, an operational frequency of 70 kHz, an indication discreteness of the propagation time and velocity of ultrasonic waves of no more than ±1 %, and an operation temperature range from −20 °C to +50 °C.

(**a**) (**b**)

Figure 1. (**a**) Measuring process with the portable ultrasonic tester "UK-1401"; (**b**) low-frequency ultrasonic flaw detector "A1220 Monolith" [1].

A portable low-frequency ultrasonic flaw detector "A1220 Monolith" ("Acoustic Control Systems" company, Moscow, Russian Federation) with two DPC transducers T1802 (frequency: 50 kHz) was used to determine the longitudinal ultrasonic waves by applying direct transmission (see Figure 1b). This device is usually used to search for foreign object inclusions, cavities, and cracks in products and constructions made of reinforced concrete, stone, plastics, and similar materials in case of one-sided access to a control object; the measurement of the thickness of concrete; and the examination of the internal structures of coarse materials. The device is intended for operation under a temperature ranging from −30 °C to +55 °C and a relative air humidity up to 95% at a maximal temperature of +35 °C. The results of the UPV test were obtained in the A-scan mode (propagation method). The measuring error for the device "A1220 Monolith" is considered to be equal to the tester "UK-1401".

An oscillograph, "UKB-1M" (AO "Introskop", Chisinau, Moldova), was also applied to measure the UPV. This portable measuring device (see Figure 2) was equipped with two DPC exponential-type piezoelectric transducers with an operating frequency of 100 kHz. It is designed to determine the strength and identify concealed defects through the measurement of the propagation velocity of vibrations, evaluating the degree of their attenuation and analyzing the envelope pulse shapes. The technique relies on measuring the pulse propagation velocity and determining the value of the desired parameters using calibration charts or through a comparison with reference specimens. The information regarding the mode and time of ultrasonic wave propagation is reproduced in the form of an oscillogram. Both direct and indirect transmission methods are applied to determine the longitudinal and surface impulses.

To verify the effects of moisture and an elevated temperature on the UPV of concrete, 27 concrete specimens with dimensions of 150 × 150 × 150 mm^3 were manufactured. At the age of 2 days, nine demolded specimens were placed in the standard moist room at +20 °C and 95% RH, while eighteen specimens (nine demolded and nine molded) were placed in the climatic chamber [26,27]. It must be emphasized that in the climatic chamber with constant ventilation and humidity control, the following cyclic conditions were maintained over 24 h: for 17 h at a temperature of +10 °C and for 7 h at +30 °C, with the air humidity changing within the 20–50% range subject to temperature alterations.

Figure 2. The oscillograph "UKB-1M" device applied for the measurement of a reinforced concrete specimen [1].

For the determination of the negative temperature effect on the UPV of concrete, two different concrete mixes were manufactured using the same raw materials but with different water contents. A total number of twenty-eight cubic-shaped specimens with dimensions of 150 × 150 × 150 mm^3 were manufactured: the first mix had a water-to-cement (w/c) ratio of 0.54 and concrete compressive strength (f_c) of 53.7 MPa at 28 days, while the second mix had a w/c ratio of 0.61 and an f_c of 36.7 MPa [28].

It must be noted that the present paper summarizes the outcomes of the main results from previous research [2,26–30]. For more detailed information about the manufactured specimens, readers are encouraged to refer to the aforementioned sources.

The main characteristics of the concrete specimens, used in the research, are as follows [2]:

(1) Compressive strength of concrete: 20–60 MPa;
(2) Concrete density in an air-dry condition: 2200–2350 kg/m^3;
(3) The material of the coarse aggregates in the concrete mix: granite and dolomite; the size of the gravel and shingles did not exceed 30 mm;
(4) The particle size of the various mineral admixtures, used in the concrete mix, was not smaller than 10 µm.

3. Results

It is crucial to emphasize that initially, the influence reinforcement must be established during the determination of the UPV of reinforced concrete structures. Ignoring the possible effect of reinforcement on the UPV during testing can obscure the analysis of any other factors influencing the UPV objectively. The experimentally determined influence of reinforcement on the UPV of concrete may differ from the data found in various scientific papers and state standards. The particular information about this influence can be found in a previous research publication [29]. The methodology for the determination of the UPV of concrete structures considering the effects of moisture and reinforcement was developed by Lencis [1,2]. This methodology offers valuable insights into the significance of testing structural concrete. It underlines the necessity of considering both complex reinforcement and moisture factors, without favoring one over the other, as both indicate significant impacts. The method for measuring the UPV is presented in Figure 3 in the form of a flowchart, where the effects of corresponding factors are arranged in a hierarchical order of exclusion from top to bottom. The present publication summarizes the results of the moisture and ambient temperature factor influences on the UPV of concrete. The complex effects of these factors in relation to the concrete hardening environment and the cement hydration process phase (or concrete age) are determined.

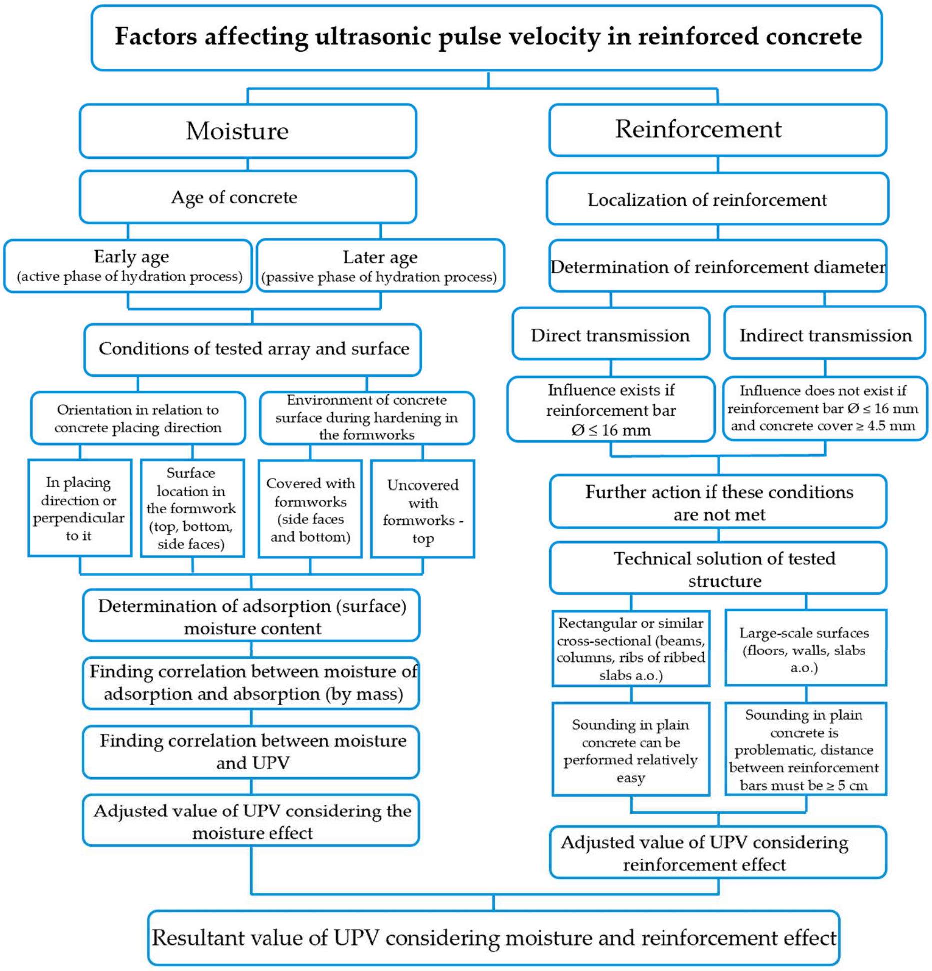

Figure 3. Flowchart outlines the steps involved in detecting and analyzing the effects of moisture and reinforcement when performing the UPV measurements in reinforced concrete structures [2].

3.1. The Influence of Moisture

The most influential factor on the UPV measurement results is moisture. The variations in the moisture content determine the extent to which other physical and mechanical characteristics of concrete, such as the temperature and elasticity properties, impact the UPV of concrete.

The data presented by Lencis et al. [27] indicate that concrete of varying strengths did not show any noticeable UPV variation character associated with the degree of water saturation. Despite differences in the strength, all specimens demonstrated a maximum water absorption falling within the range of 5.2–5.6%. Notably, the observed changes in the UPV for specimens in completely dry and maximum water-saturated conditions averaged around 19%. Through the application of indirect transmission, a significant increase in the longitudinal wave velocity was identified at the moment when the water absorption caused a mass increase in the concrete specimen of less than 0.1% per day, signifying the near-maximum saturation of concrete with water. The most significant changes were observed in concrete that was subjected to a hardening process in an environment with elevated temperatures, where an increase in the moisture by 0.1% by mass corresponds to a 9% increase in the UPV (see Figure 4).

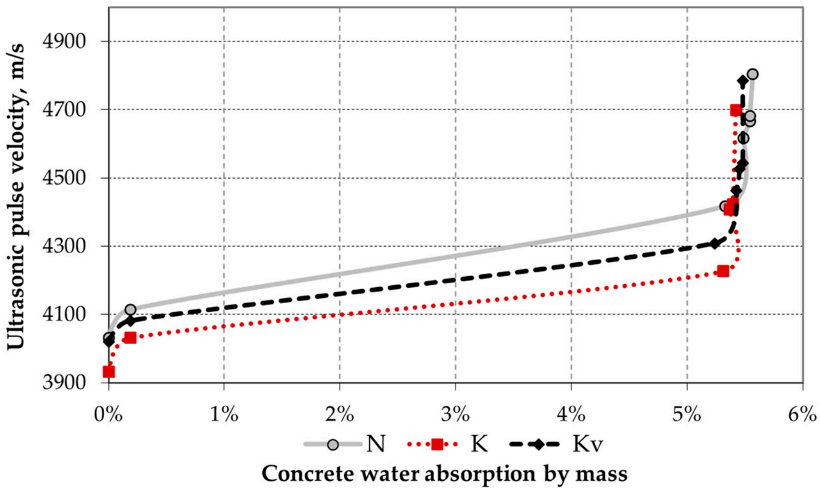

Figure 4. Correlations between ultrasonic pulse velocity and concrete water absorption by mass for specimens hardened in various environments: *N*—in the standard moist room; *K*—in the climatic chamber (demolded); and K_V—in the climatic chamber (molded) [2,26,27].

The results obtained clearly demonstrate the non-linear character of the correlation between the UPV and moisture content of the material, as determined in the concrete specimens. This is also confirmed in [31]. The mathematical and physical models developed by Fadragas and Gonzalez [10] show that this relationship is best described using an exponential model. Furthermore, it was determined that the most significant changes in the UPV occur during the initial stages of saturation.

3.2. The influence of an Elevated Temperature

When evaluating the influence of an elevated temperature on the UPV of concrete at various phases of the cement hydration process, it should be considered that the term “elevated temperature” is related to the hydration processes ongoing in concrete. Thus, a temperature is considered elevated when it exceeds the normal concrete curing environment temperature (+18 ± 2 °C).

The primary objective in [26] was to evaluate the impact of an elevated temperature on the UPV within the depth of the concrete mass and to determine the depth of the surface layer where, under respective hardening conditions, the development of microcracks in the upper layers of a specimen has no significant effect on the UPV of concrete. The categorization of the concrete specimens was based on the hardening environment, resulting in three primary groups: *N* (the standard moist room), *K* (climatic chamber, demolded), and K_V (climatic chamber, molded). Each of these three groups was further subdivided into three subgroups. Specifically, for particular concrete specimens, the hardening process was discontinued, followed by their release from the formwork and the side faces cut off at the three distinct ages of 7, 14, and 28 days. This surface layer removal aimed to access the potential impact of the shrinkage process on the UPV of concrete below the excised layer, with testing conducted both before and after the cutting procedure. Ultrasonic tests were carried out at the ages of 2, 7, 14, 64, and 84 days. Prior to the removal of the tested surface layer, the moisture content was determined. Subsequent to this, measurements were carried out using the ultrasonic tester “UK-1401”. Following the initial measurements, the specimens’ dimensions and mass were measured to determine the density. This preliminary sequence of actions was necessary due to the penetration of moisture into the concrete during cutting. While a specimen dried, it was necessary to control the two following parameters: surface moisture and density. This was carried out to guarantee the restoration of these two parameters to the initial levels established before the cutting process. Once the surface moisture and density had returned to their pre-cutting levels, UPV measurements were carried out again [14].

Initially, a surface layer with an average thickness of 1.5 mm was removed from the side face of the concrete specimen. Subsequently, one day later, a repeated cutting procedure was carried out, resulting in the removal of an average total surface thickness of 15 mm from each specimen. After removing a 1.5 mm thick surface layer from the side face of the 7-day-old concrete, a minor increase in the UPV was observed for the K-group specimens (see Table 1). In cases, where a 15 mm thick surface was removed, K-group specimens, which were released from the formwork before the cycling process and hardened in an elevated temperature environment, showed a much more substantial increase in the UPV results, by ~200 m/s or 5% on average. Similarly, the specimens of group K_V, which hardened in a similar environment despite being kept in the formwork, also demonstrated an increase in their UPVs (see Table 1). It should be noted that, in concrete that hardened in normal conditions, no increase in the UPV was observed after the removal of the surface layer [26].

Table 1. UPV changes determined for the surface layers of various thicknesses by cutting off the side faces of the 7-day-old concrete specimens [2,26].

Designation of Specimen	Specimen Group	Cut Thickness, [cm] *	UPV before Cutting [m/s]	UPV after Cutting [m/s]	UPV Difference		Cut Thickness [cm] *	UPV after Cutting [m/s]	UPV Difference	
					[m/s]	[%]			[m/s]	[%]
4.[7]		0.31	4258	4337	+78	+1.8	1.69	4624	+366	+8.6
13.[7]	*K*	0.19	4489	4537	+47	+1.1	1.45	4524	+35	+0.8
18.[7]		0.15	4326	4354	+29	+0.7	1.55	4517	+192	+4.4
		Average			+51	+1.2			+197	+4.6
22.[7]		0.09	4648	4679	+31	+0.7	1.63	4722	+74	+1.6
25.[7]	K_V	0.15	4620	4617	−3	−0.1	1.37	4641	+21	+0.4
27.[7]		0.23	4608	4642	+34	+0.7	1.78	4750	+142	+3.1
		Average			+21	+0.4			+79	+1.7
10.[7]		0.05	4598	4564	−33	−0.7	1.42	4614	+17	+0.4
16.[7]	*N*	0.10	4599	4544	−56	−1.2	1.39	4545	−54	−1.2
17.[7]		0.09	4637	4612	−24	−0.5	1.35	4589	−48	−1.0
		Average			−38	−0.8			−29	−0.6

Note: 1. Designation according to the hardening environment of the concrete specimen: *N*—in the standard moist room; *K*—in climatic chamber, demolded; K_V—in climatic chamber, molded; 2. *—thickness of the surface layers cut off the side faces of the concrete specimens.

In a comparable experiment conducted with 14- and 28-day-old concrete, specimens that were demolded and underwent hardening in the climatic chamber showed an even greater increase in their UPV: approximately 300 m/s or 7% for the 14-day-old concrete specimens and 450 m/s or 10% for the 28-day-old concrete specimens.

The findings indicate that when concrete undergoes a hardening process in an environment with an air temperature of +30 °C, an elevated porosity and/or the presence of microcracks in the upper layers contribute to a delay in the propagation of ultrasonic waves. Consequently, when applying the indirect transmission method for UPV measurements on concrete, the correlation between the acoustic and mechanical properties is significantly affected by the materials' hardening conditions. Moreover, the conditions determined for the upper layer of the concrete may not necessarily provide an accurate representation of the overall condition of the concrete [2].

3.3. The Influence of a Negative Temperature

The influence of a negative temperature on the UPV was determined for air-dry and water-saturated concrete. The duration of freezing of the concrete specimens is based on references provided in the standards for determining the frost resistance of concrete [32–37]. These standards specify the required duration for a concrete specimen with specific dimensions to freeze completely through its entire volume.

It has been ascertained that the main factor during a short-term exposure to frost is the moisture content of the tested concrete. The impact of frost on the UPV shows a notable uniformity across different testing methods, which is particularly noteworthy during the active phase of the cement hydration process. It is known that as the age of concrete increases, these changes in the UPV decrease. More precisely, at the ages of 3, 7, 14, and 28 days, the average UPV increase for frozen concrete is 13%, 7%, 4%, and 0%, respectively [30]. This leads to the conclusion that by the 28th day, the influence of frost becomes negligible on the concrete that has undergone curing in a standard environment.

To understand whether low temperatures affect the UPV of hardened cement paste differently during the active and passive phases of the hydration process, specimens aged slightly over 3 years at the time of testing were examined. It is important to note that these specimens were originally manufactured to study the effects of moisture and elevated temperatures on the UPV of concrete. These specimens were stored in an air-dry environment for 3 years prior to further research. The mass and surface moisture of the specimens were measured, after which they were tested with ultrasonic equipment and placed in a climatic chamber.

After removing the specimens from the climatic chamber, the UPV of concrete was measured again. Subsequently, the specimens were submerged in water for six days, followed by a cycle of freezing and thawing. Throughout the research, the specimens underwent the following sequence of actions: (1) stored at the room temperature conditions (+20 ± 2 °C for more than 3 years); (2) stored in the climatic chamber (−18 °C for 4.5 h); (3) stored at the room temperature conditions (+20 ± 2 °C for 2.5 h); (4) stored in water (+18 ± 2 °C for 6 days); (5) stored in the climatic chamber (−18 °C for 4.5 h); and (6) stored at the room temperature conditions (+20 ± 2 °C for 2.5 h). At the end of each phase, the UPV was determined.

The following results were obtained:

- No changes in the UPV were established after freezing the 3-year-old concrete specimens at air-dry conditions.
- The maximum increase in the UPV reached 34% for concrete specimens saturated with water and then frozen (see Table 2).
- Furthermore, the differences in the UPV change are related to the concrete curing environment. Namely, the longer the concrete is exposed to elevated temperatures during the hardening process, the greater the impact of moisture and frost on the UPV. Consequently, the differences in the UPV will also be more pronounced.
- The increase in the UPV in the case of concrete that has hardened in a standard environment is determined to be 14–20%.

Table 2. Changes in the UPV in the active and passive phases of the hydration process of hardened cement paste, by comparing test data of frozen concrete specimens with corresponding values prior to freezing (data from [1]).

Phase of Hydration Process		**Active**				**Passive**					
Concrete age in days		3	7	14	28	1163			1169		
Curing environment		*N*				*N*	K_V	*K*	*N*	K_V	*K*
Surface moisture, %		>6				3.1	3.0	3.6	>6		
Indirect transmission	ΔV_l (%)	+13 (+26)	+9 (+11)	+4	0	+1	+1	0	+20	+25	+34
	ΔV_s (%)	+14 (+23)	+7 (+11)	+4	0	+1	+4	+1	+14	+17	+26
Direct transmission	ΔV_l [1] (%)	+11 (+20)	+6 (+11)	+5	0	+1	0	+1	+16	+18	+19
	ΔV_l [2] (%)	+12 (+21)	+7 (+11)	+5	+1	–	–	–	–	–	–
Average		+13 (+23)	+7 (+11)	+4	0	+1	+2	+1	+17	+20	+26

Notes: 1. Designation according to the hardening environment of the concrete specimen: *N*—in the standard moist room; *K*—in climatic chamber, demolded; K_V—in climatic chamber, molded; 2. ΔV_l and ΔV_s—changes in the UPV, measuring, respectively, the longitudinal and surface wave propagation velocities; 3. UPV is determined using the following equipment: [1]—"UKB-1M"; [2]—"A1220 Monolith"; 4. In the active phase of the hydration process, the results of the UPV changes for the 2nd concrete mix are given in the brackets.

Despite using the same types of raw materials for both concrete mixes, during the active phase of the hardened cement paste hydration process, for frozen concrete with a lower compressive strength and higher water amount, the changes in the UPV are determined to occur at a higher rate. In addition, the differences in the UPV are more pronounced in younger concrete specimens (see Table 2). This observation can be attributed to the decrease in the moisture levels in concrete during the hardening process.

Concrete subjected to long-term frost exposure during a period from 3 to 28 days exhibits an extremely significant difference in the UPVs for the frozen and thawed conditions. Namely, in frozen concrete, the UPV is abnormally high, which is approximately 2 times higher than the UPV determined in the thawed state. It is important to note that the actual value is reflected by the UPV determined in the thawed state. Therefore, when testing frozen concrete at an early age, correction coefficients can be multiplied the obtained the UPV of frozen concrete. These correction coefficients, determined through different testing methods, are summarized in Table 3.

Table 3. Correction coefficients for the UPVs of concrete exposed to long-term frost [2].

Age of Concrete in Days			3	7	14	28
Indirect transmission	Longitudinal w. [1]	Correction coefficients	0.50	0.49	0.55	0.57
	Surface w. [2]		0.52	0.50	0.55	0.58
Direct transmission	Longitudinal w. [2]		0.53	0.56	0.57	0.58
	Longitudinal w. [3]		0.51	0.55	0.56	0.59
Average			0.52	0.53	0.56	0.58

Note: ultrasonic equipment: [1]—"UK-1401"; [2]—"UKB-1M"; [3]—"A1220 Monolith".

Several noteworthy findings were noticed during the investigation. It must be noted that when concrete undergoes a freezing process, it typically shows a decrease in its mass, resulting in a lighter composition. Perhaps this can be related to the lower density of ice (920 kg/m^3) compared to water (1000 kg/m^3). Additionally, freezing promotes a decrease in the surface moisture of concrete, which is relatively easy to measure for the exploited construction: it most often does not exceed 6%. Emphasizing the important role of the accurate determination of surface moisture for interpreting changes in the UPV, close attention is required in such cases. In the context of frozen concrete, the correlation between the UPV and concrete surface moisture content differs from that observed in unfrozen concrete. Ignoring this fact may lead to inaccurate estimates of UPV values. It should be noted that the correlation between the UPV and concrete surface moisture content is characteristic of both the active and passive phases of the hardened cement paste hydration process (for a comparison of the results, the research was performed on young and three-year-old concrete). However, it can be noted that in the passive phase, this feature applies only to concrete with surface moisture levels exceeding the air-dry humidity levels, which are approximately 3.5%.

For frozen concrete specimens in the early phase of the hardened cement paste hydration process, there is a comparatively high decrease in the surface moisture level, similar to that observed in moisture-saturated concrete, regardless of the age, while during the passive phase of the hardened cement paste hydration process, this decrease in the mass and surface moisture content of the specimens is smaller.

3.4. Methodology for Determining the Correct UPV of Concrete

This UPV measurement methodology [1,2] incorporates a UPV analysis for characterizing the concrete strength in structures. This analysis takes into account the interaction effect of the concrete hardening environment, age, moisture content, and ambient temperature factors. Various concrete mixes were applied to examine the subordination of these factors. The measurement results were found to be most significantly influenced by the concrete moisture content. Specifically, the changes in moisture levels predominantly determined the influence rates of physico-mechanical properties and other characteristics on the UPV of concrete.

The algorithm was developed for the most common testing method in practice, which is indirect transmission, particularly when using longitudinal and surface wave impulses in the investigation. The developed measurement methodology includes the UPV correction coefficient k_V function, which comprises four arguments: the concrete hardening environment c, cement hydration phase (or concrete age) t, concrete moisture W, and ambient temperature T:

$$k_V = f(c; t; W; T). \tag{1}$$

As it is experimentally proven that changes in the UPV are observable under certain circumstances, the k_V function for arguments is defined in following sub-headings:

- Concrete hardening environment c: (1) in normal conditions (at an ambient temperature +18 ± 2 °C and relative humidity of air 95–100%) c_n; (2) at elevated ambient temperature conditions (up to + 30 °C, relative humidity of air not exceeding 50%) c_d; and (3) reduced temperature conditions (air temperature of −18 ± 2 °C and relative humidity of air 65–75%) c_f;
- Concrete age t: (1) in the active phase of the cement hydration process, i.e., concrete at the ages of 3, 7, 14, and 28 days: t_3, t_7, t_{14}, t_{28}, respectively; and (2) at the passive phase of the cement hydration process for 56- and 1000-day-old concrete: t_{56} and t_{1000}, respectively;
- Concrete moisture by mass W: (1) air-dry concrete with a moisture content of 2–3%: W_2 and W_3, respectively; (2) wet concrete (4–5%: W_4 and W_5, respectively); and (3) maximally water-saturated concrete (5–6%: W_5 and W_6, respectively);
- Ambient temperature T: (1) −20. . .0 °C ($T_{-20...0}$): the range of the frost influence, or the cement hydration process has stopped; (2) +1. . .+9 °C ($T_{+1...+9}$): cement hydration process takes place in a lowered temperature; (3) +10. . .+ 20 °C ($T_{+10...+20}$): favorable temperature for cement hydration process; and (4) +21. . .+30 °C ($T_{+21...+30}$): temperature is contributing to shrinkage of hardened cement paste.

In the developed model, cases of dry concrete (with the moisture content ranging from 0 to 1 %) do not comply with the situation in practice. Additionally, the ambient temperature is directly related to the concrete temperature, which is particularly evident in cases of negative temperatures. During the experiment, concrete specimens were tested while frozen throughout their volume. Therefore, when applying the UPV correction coefficient value, special attention should be paid to relatively high negative ambient temperatures, especially in the range from −4 °C to +4 °C. It is crucial to ensure that the tested concrete has frozen fully throughout its volume, considering the geometrical parameters of the construction element and its likelihood to freeze at the corresponding air temperature.

The correction coefficients of the UPV are selected by comparing them with the actual UPV at a given day (t_3, t_7, t_{14}, t_{28}, t_{56}, and t_{1000}), which was determined during a 28-day concrete hardening period or until testing at the corresponding age of the active phase of the cement hydration process. Subsequently, when concrete is exposed to an air-dry environment during further exploitation, the selected correction coefficients are applied (c_n, c_d, or c_f).

For instance, under normal curing conditions (hardening environment: c_n) up to 28 days of age, it is assumed that the actual UPV (k_V = 1) corresponds to a concrete moisture level of W = 5%. However, at 1000 days of age, the concrete moisture is expected to decrease to 3%. The values for coefficients k_V = 1 may slightly differ for each hardening condition, but they are applicable within a favorable temperature range of $T_{+10...+20}$ during the cement hydration process. The occurrence of the four-argument function coefficient k_V = 1 for concrete in different hardening environments is as follows:

$$\begin{cases} k_V = f(c_n; t_3 \ldots t_{28};\ W_5; T_{+10\ldots+20}) = 1 \\ k_V = f(c_n; t_{56};\ W_4; T_{+10\ldots+20}) = 1 \\ k_V = f(c_n; t_{1000};\ W_2; T_{+10\ldots+20}) = 1 \\ k_V = f(c_d; t_3 \ldots t_{14};\ W_5; T_{+10\ldots+20}) = 1 \\ k_V = f(c_d; t_{28\ldots56};\ W_4; T_{+10\ldots+20}) = 1 \\ k_V = f(c_d; t_{1000};\ W_2; T_{+10\ldots+20}) = 1 \\ k_V = f\left(c_f; t_3 \ldots t_{28};\ W_5; T_{+10\ldots+20}\right) = 1 \\ k_V = f\left(c_f; t_{56};\ W_4; T_{+10\ldots+20}\right) = 1 \\ k_V = f\left(c_f; t_{1000};\ W_2; T_{+10\ldots+20}\right) = 1. \end{cases} \quad (2)$$

The total number of functions included in the algorithm is 360. It should be noted that in 161 occurrences, the correlations of the arguments in the function are not subordinate to the basic principles of cement hardening as a hydraulic binder, in relation to the necessary water content and ambient temperature, nor do they adhere to the extreme hardening and ambient temperature ranges (c_d—$T_{-20\ldots0}$ and c_f—$T_{+21\ldots+30}$). Such occurrences only correspond to the modeling necessity within scientific research, and in this algorithm, such equation outcomes are formulated as *unrealistic case in practice*. The defined coefficient k_V = 1 occurrences amount to 18 (6 in each hardening environment, corresponding to concrete ages included in the function). Yet, there are 181 other numeral values of k_V. The experimentally obtained coefficient values, considering the ambient temperature at the hardening time, are summarized in Table 4.

The obtained UPV correction coefficient k_V must be multiplied by the corresponding UPV value V_{meas} measured at a certain age under specific testing conditions. It is assumed that values of the UPV values are determined in specific measurement units, such as m/s or km/s, but this estimation method in the formula shown below allows for the use of other UPV measurement units as well. The actual value of the UPV V_{act} is calculated using the following formula:

$$V_{act} = V_{meas} \cdot k_V \quad (3)$$

Consequently, by performing measurements in various conditions, including extreme ones, which may significantly differ from those observed in real cases of detecting UPVs, using the values of the UPV correction factor k_V enables the acquisition of correct UPV values in the tested concrete. This approach significantly reduces the risk of errors in assessing the strength properties of the tested concrete.

Table 4. Experimentally obtained values of the coefficients of change in the ultrasonic pulse velocity (data from [1]).

−20...0 °C			c_n					c_d					c_f		
	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6
t_3	×	×	×	0.86	0.73	×	×	×	×	×	×	×	×	0.50	0.49
t_7	×	×	×	0.91	0.78	×	×	×	×	×	×	×	×	0.50	0.49
t_{14}	×	×	×	0.96	0.84	×	×	×	×	×	×	×	×	0.55	0.52
t_{28}	×	×	0.99	0.98	0.86	×	×	×	×	×	×	×	×	0.57	0.55
t_{56}	×	1.01	0.99	0.98	0.85	×	×	0.99	0.98	0.85	×	0.99	0.98	0.98	0.65
t_{1000}	0.99	0.99	0.99	0.98	0.80	0.99	0.99	0.99	0.98	0.66	0.99	0.99	0.99	0.98	0.72
+1...+9 °C			c_n					c_d					c_f		
	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6
t_3	×	×	×	1.02	0.98	×	×	×	1.01	0.97	×	×	×	1.01	0.98
t_7	×	×	×	1.02	0.98	×	×	×	1.01	0.97	×	×	×	1.01	0.98
t_{14}	×	×	×	1.02	0.98	×	×	×	1.01	0.97	×	×	×	1.01	0.98
t_{28}	×	×	1.04	1.02	0.98	×	×	1.01	0.98	0.94	×	×	×	1.01	0.98

Table 4. *Cont.*

t_{56}	×	1.04	1.02	0.99	0.95	×	1.03	1.01	0.98	0.94	×	1.03	1.01	0.99	0.96
t_{1000}	1.02	0.99	0.97	0.94	0.90	1.01	0.99	0.97	0.94	0.90	1.01	0.99	0.97	0.94	0.91
+10…+20 °C			c_n					c_d					c_f		
	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6
t_3	×	×	×	1	0.96	×	×	×	1	0.96	×	×	×	1	0.97
t_7	×	×	×	1	0.96	×	×	×	1	0.96	×	×	×	1	0.97
t_{14}	×	×	×	1	0.96	×	×	1.03	1	0.96	×	×	×	1	0.97
t_{28}	×	×	1.03	1	0.96	×	1.02	1	0.97	0.93	×	×	×	1	0.97
t_{56}	×	1.02	1	0.97	0.93	×	1.02	1	0.97	0.93	×	1.02	1	0.97	0.94
t_{1000}	1	0.98	0.96	0.93	0.89	1	0.98	0.96	0.93	0.89	1	0.98	0.96	0.93	0.90
+21…+30 °C			c_n					c_d					c_f		
	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6	W_2	W_3	W_4	W_5	W_6
t_3	×	×	×	1.01	0.97	×	×	×	1.01	0.97	×	×	×	×	×
t_7	×	×	×	1.01	0.97	×	×	1.04	1.01	0.97	×	×	×	×	×
t_{14}	×	×	1.04	1.01	0.97	×	×	1.04	1.01	0.97	×	×	×	×	×
t_{28}	×	×	1.04	1.01	0.97	×	1.03	1.01	0.98	0.94	×	×	×	×	×
t_{56}	×	1.03	1.01	0.98	0.94	×	1.03	1.01	0.98	0.94	×	×	1.01	0.98	0.97
t_{1000}	1.01	0.99	0.97	0.94	0.90	1.01	0.99	0.97	0.94	0.90	1.01	0.99	0.97	0.94	0.91

Notes: The designations given in the table are explained above in the paper; here, ×—unrealistic case in practice.

4. Discussions

In order to minimize the occurrence of possible errors in the interpretation of the k_V values, a guide has been prepared for concrete testers. This methodology provides a guidance on selecting the relevant parameters based on specific test conditions, thus ensuring accurate interpretations.

The most significant changes in the UPV can be observed in the presence of a negative temperature. Namely, there are 26 cases where the coefficient values fall within the range of 0.49–0.90, while occurrences of such coefficients at negative temperatures total 19 cases (see Table 4). In addition, when comparing the values of the coefficients of UPV changes that fall below 0.74 (indicating significant differences in the UPV results), such cases are exclusively observed at negative ambient temperatures. It should be emphasized that the smallest numerical values of the coefficients are determined when concrete freezes during the early stages of hardening. As can be seen in Table 4, a higher frequency of relatively lower coefficient values is observed in the case of maximum water absorption of concrete, corresponding to an absolute moisture content of 5–6%. In this case, it is not the ambient temperature that is important, but rather the age of the concrete: the older concrete, more noticeable the changes in the UPV are under the influence of moisture. In addition, for concrete that has undergone hardening at elevated ambient temperatures, changes in the UPV are notably more pronounced under the influence of moisture. Summarizing the above-mentioned details, it can be concluded that the most significant changes in the results of the UPV occur for wet and frozen concrete.

In order to facilitate the selection of argument positions and to understand the application of UPV change coefficients, detailed explanations are provided for each of them in the following description below:

If the hardening environment for concrete remains unknown until it reaches 28 days (with the first 14 days being crucial for the hydration of the hardened cement paste and its correlation with UPV propagation in concrete), it is recommended to conduct measurements under the conditions where the influence of the k_V factor will be minimized. The occurrence of the active or passive phases of the hydration process in the hardened cement paste of the tested concrete plays an important role. In the active phase, determining the age of the concrete is usually straightforward. On the other hand, during the passive phase, empirical data suggest the use of a concrete age of 56 days up to 6 months old, while an age of 1000 days is applicable for older concrete.

To determine concrete moisture levels, it is recommended to use measuring devices designed for determining the surface moisture content. These devices should have established correlations with the concrete moisture by mass, ideally determined through methods such as water absorption tests. In addition, such experiments should be performed with as many different concrete mixes as possible in order to establish the correlations applicable for a wider range of concrete compositions. It should be emphasized that for completely frozen concrete, surface moisture values are approximately 0.5–2 percentage points lower compared to thawed concrete. This difference tends to increase with the age and water saturation level of concrete. Therefore, when dealing with frozen concrete, it is essential to consider the surface moisture levels of thawed concrete as a reference.

The ambient temperature is directly related to the concrete temperature. Particular care should be taken when performing measurements at negative ambient temperatures. In the case of positive temperatures, the difference in the k_V values is generally less pronounced, unless the measurements are performed close to the freezing point. It should be noted that during the experiments, the concrete specimens should be uniformly frozen in their entire volume. Thus, special care should be taken in applying the values of the coefficient of variation of the UPV when testing at temperatures in the range from −4 °C to +4 °C. Namely, the researcher must be sure that the concrete to be tested has frozen in its entire volume. In this case, the main criterion is the geometric parameter of the tested concrete object in relation to its possibility of freezing at the relevant air temperature.

5. Conclusions

The complex effects of the phase of hydration process of the hardened cement paste (or concrete age), hardening (curing) condition, concrete moisture level, and ambient temperature on the ultrasonic pulse velocity in reinforced concrete structures are evaluated. By summarizing the research results, an ultrasonic pulse velocity correction coefficient algorithm is developed. The correct application of this algorithm would significantly reduce the risk of errors in the interpretation of ultrasonic pulse velocity measurement data in relation to concrete strength evaluations.

It has been determined that there is an average difference of 19% in the UPV for completely dry concrete compared to concrete in a state of maximum saturation with water. When testing with an indirect transmission method, an increase in the UPV of precisely 9% was obtained when the maximum saturation of concrete with water was achieved.

The experimental evidence indicates that during the hardening of concrete at an ambient temperature above +30 ± 2 °C, defects such as an increased porosity in the cement and/or the appearance of microcracks occur in the upper layers. These defects contribute to a delay in the propagation of ultrasonic waves, resulting in a potential decrease of up to 10% in the UPV of concrete.

In the active phase of the hardened cement paste hydration process, the measured UPV of frozen concrete is up to 13% higher than in thawed concrete. However, these changes in the UPV decrease with the increase in the age of concrete. It was found that at the age of 28 days, the effects of frost becomes insignificant on concrete that was subjected to standard environmental conditions during the hardening process. The moisture content of the tested concrete significantly impacts the assessment of the influence of low temperatures on the UPV. Under long-term exposure to frost between days 3 to 28, the UPV of frozen concrete is abnormally high, approximately two times higher than in the thawed state.

When freezing the 3-year-old concrete specimens under air-dry conditions, no changes in the UPV were observed. However, when these specimens were saturated with water and then frozen, the maximum increase in the UPV reached 34%. It was determined that the differences in changes in the UPV depend on the concrete curing environment. In particular, the longer the exposure to elevated temperatures during the hardening process of concrete, the greater the differences in the UPV will be, which are caused by moisture and frost. In this context, the increase in the UPV for concrete that hardened in a standard environment was determined to be 14–20%.

An algorithm was developed for a four-argument function, capable of processing multiple sets of UPV data. This function was created to evaluate the strength of concrete in structures. The algorithm includes the UPV correction coefficient k_V in a four-argument function, which comprises the concrete hardening environment, cement hydration process phase (or concrete aged three days and older), concrete moisture level, and ambient temperature in the range from −20 °C up to +30 °C, which allows us to obtain the correct UPV of the tested concrete, excluding the impacts of the main physical and physico-chemical factors.

The developed methodology can be considered as a guideline for generating the correct correlation, significantly reducing the possibility of misinterpreting UPV data in relation to determining the compressive strengths of reinforced concrete structures.

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