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Utilizing Ultrasonic Guided Waves for the Early Age Assessment of Concrete Strength and Hardening: Review Paper

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Abstract - **Monitoring the early age strength and hardening of concrete plays a crucial role in ensuring the structural integrity and durability of concrete structures. Ultrasonic guided waves have emerged as a promising non-destructive testing technique for assessing concrete properties. This review paper aims to provide an overview of the utilization of ultrasonic guided waves for the early age assessment of concrete strength and hardening. The paper begins by discussing the fundamental principles of ultrasonic guided waves and their interaction with concrete materials. It highlights the advantages of using guided waves, such as their ability to propagate over long distances and penetrate through concrete structures. The review then explores various techniques employed for generating and detecting guided waves, including piezoelectric transducers, air-coupled transducers, and laser-ultrasonics. Furthermore, the paper presents a comprehensive analysis of the different parameters that can be extracted from ultrasonic signals to assess the early age strength and hardening of concrete. These parameters include wave velocity, attenuation, reflection, and scattering characteristics. The influence of various factors, such as moisture content, temperature, and mixture proportions, on the ultrasonic response of concrete is also discussed. Moreover, the review discusses the challenges and limitations associated with the application of ultrasonic guided waves in early age concrete assessment. It addresses issues such as signal interpretation, wave dispersion, and the presence of air voids. Additionally, recent advancements in signal processing techniques and data interpretation methods are highlighted. In conclusion, the utilization of ultrasonic guided waves for the early age assessment of concrete strength and hardening shows great promise. This review paper provides valuable insights into the current state-of-the-art in this field and offers recommendations for future research directions.**

Keywords: Early age concrete assessment, Ultrasonic guided waves, Concrete strength, Concrete hardening, Non-destructive testing, Signal processing.

I. INTRODUCTION

The setting and hardening of fresh concrete are critical phases in construction, as they greatly impact the properties and performance of concrete structures throughout their service life. The transition of the concrete mixture from a fluid state, important for placement into formworks, to a solid state with desired properties is essential. Monitoring and controlling the hardening process allow for determining the optimal time to remove formwork or apply structural loads, thus ensuring proper behavior and functionality. Having accurate and effective testing methods for determining the properties of young concrete is of utmost importance for both technical and economic reasons. Traditional testing methods, such as the slump cone test, flow table test, penetration needle test, Vicat apparatus test, hydration temperature measurement, and pull-out test for young concrete, have limitations, particularly in providing continuous measurement data. Rheological testing methods using viscosimeters are often unsuccessful as they subject fresh concrete to shear forces that can disrupt the microstructure during the early stages of hydration. Among various non-destructive testing (NDT) methods, ultrasound testing has proven to be successful in accurately determining the properties of fresh and young concrete. Ultrasound-based techniques offer advantages in terms of precise property evaluation. These methods utilize ultrasonic waves to analyze and assess the concrete's characteristics. By transmitting and receiving ultrasonic signals, parameters related to the setting and hardening of concrete can be extracted, providing valuable insights into the material's behavior and properties. In summary, ultrasound testing methods have shown promise in achieving more accurate and reliable determination of the properties of fresh and young concrete. These techniques overcome the limitations of conventional testing methods and offer continuous measurement capabilities, making them highly valuable for assessing and monitoring concrete during its critical early stages of development.

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II. SETTING AND HARDENING OF CONCRETE

Setting time refers to the moment when fresh concrete undergoes a transition from a fluid state to a plastic state, marking the stiffening of the material after it has been placed. Although the concrete may no longer be fluid, it may still exhibit considerable weakness, making it unsuitable for bearing loads or supporting foot traffic. The setting process is primarily attributed to the formation of early-stage calcium silicate hydrates.

The terms "initial set" and "final set" serve as arbitrary definitions for early and later stages of the setting process, respectively. Laboratory methods involve the use of weighted needles that penetrate the cement paste to determine these set points. These procedures allow for the measurement and determination of the specific times at which the concrete transitions from its initial plastic state to a more solidified form. In summary, setting time is characterized by the transition of fresh concrete from a fluid to a plastic state, signifying the material's stiffening. It is important to note that while setting occurs, the concrete may still lack sufficient strength for various applications. The terms "initial set" and "final set" provide benchmarks for early and later stages of setting, and laboratory techniques utilizing weighted needles enable the determination of these set times in cement paste. The transition from a fluid state to a solid state in fresh concrete can vary in duration, ranging from less than one hour to as long as 24 hours.

The initial set of cement paste is defined as the point at which the paste has acquired enough rigidity to cease being in a fluid state. On the other hand, the final setting time occurs when the rigidity of the paste has increased to the extent that it becomes a solid material with very low strength. Typically, cement exhibits an initial set within 2 to 4 hours and a final set within 5 to 8 hours. Following the final set, there is a significant increase in strength, marking the beginning of the hardening stage.

Hardening refers to the process of strength development in concrete and can continue for weeks or even months after the concrete has been mixed and placed. The primary mechanism behind hardening is the formation of calcium silicate hydrate as the cement hydrates. The hardening time signifies when the concrete possesses sufficient bearing capacity to support construction loads. The duration of concrete hardening can vary, ranging from a few hours to as long as 2 to 3 weeks.

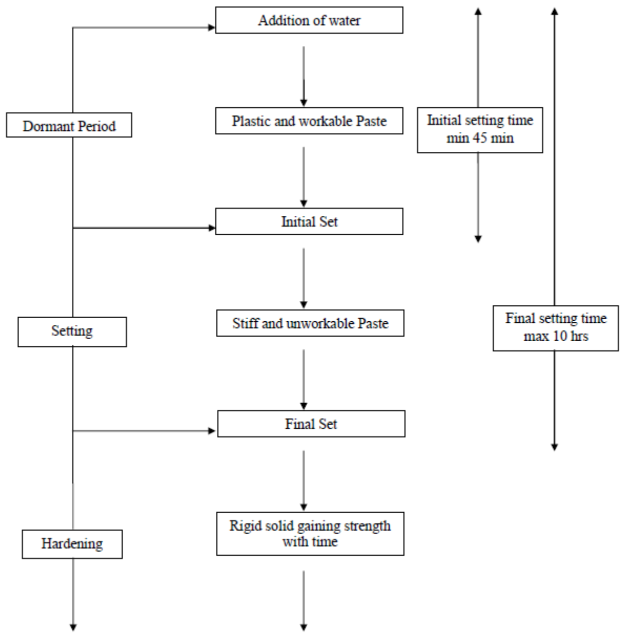

Figure 1: Schematic description of setting and hardening of a cement paste

III. FACTORS THAT AFFECT THE SETTING AND HARDENING TIME INCLUDE, BUT ARE NOT LIMITED TO

The factors that influence the setting and hardening of concrete include:

- Type and quantity of cementitious materials, such as cement and fly ash.
- Water content in the concrete mixture.
- Presence of admixtures like accelerators, air entrainers, and water reducers.
- Volume of concrete being placed.
- Properties of the surrounding soil, including permeability and degree of saturation.
- Ambient temperature at the construction site.
- Curing conditions applied to the concrete after placement.

IV. LITERATURE SURVEY

The aim of this study is to investigate the setting and hardening properties of concrete through the utilization of ultrasonic guided waves. In this section, a comprehensive literature review is presented, encompassing various methods and techniques employed for monitoring the early age strength (within the first 24 hours of hydration) and the hardening process (during concrete specimen curing). This review provides insights into the research conducted in this field over the past decade, offering an overview of the advancements achieved thus far.

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Darquennes et al. (2009) conducted a comparative study to investigate the setting and hardening of concrete using three different techniques: (1) ultrasonic monitoring with the FreshCon system, (2) a resistivity method, and (3) the mechanical Kelly-Bryant method. The experimental tests were performed on two slag cement concretes to compare the effectiveness of these methods and evaluate their capability to continuously monitor the setting and hardening process of concretes with varying slag content in the cement. The results showed that the initial setting age values obtained from the three methods were in good agreement overall. However, only the non-destructive methods, namely ultrasonic and electric methods, were able to determine the final setting time. It was concluded that all three methods were complementary to each other, and the non-destructive methods provided additional information regarding the hydration process of cementitious materials, including chemical reactions and stiffness evolution. These non-destructive techniques were also effective in capturing the differences in the setting behavior attributed to variations in the slag content in the cement. Darquennes et al. (2009) demonstrated the complementary nature of the three studied methods for monitoring the setting and hardening of concrete. The non-destructive techniques, particularly ultrasonic monitoring and resistivity measurement, offered valuable insights into the hydration process and provided a means to assess the effects of slag content on the setting behavior of cementitious materials.

Robeyst .Nicolas & De Belie. Nele (2009)In their study, Robeyst et al. (2009) observed that previous research on ultrasonic methods for monitoring the setting of concrete primarily focused on wave velocity as a useful parameter. To explore the application of wave energy as a measurement parameter, they conducted the ultrasonic wave transmission technique on various concrete and mortar samples. These samples contained increasing proportions of blast-furnace slag or fly ash as replacements for ordinary Portland cement. The transmitted ultrasonic wave energy was calculated by summing the squared amplitudes of the received signal and dividing it by the reference energy (E/Eref). The results showed that the increase in energy during the setting process was delayed when blast-furnace slag or fly ash was used as a replacement for ordinary Portland cement. The final setting, as determined by the standard penetration resistance test, occurred shortly after the peak in the derivative curve of the ultrasonic energy. Furthermore, the study proposed the values E/Eref = 0.02 and 0.15 as thresholds for easily calculating the initial and final setting times based on the ultrasonic energy measurements. However, the sensitivity of the energy measurement to the quality of the sensor contact was noted, suggesting the need to minimize drying shrinkage of the cementitious samples in order to ensure accurate results. In summary, Robeyst and De Belie (2009) introduced the concept of using ultrasonic wave energy as a parameter for monitoring the setting of concrete. They observed that the energy increase during setting was affected by the incorporation of blast-furnace slag or fly ash. The study proposed specific threshold values for initial and final setting based on ultrasonic energy measurements and emphasized the importance of maintaining proper sensor contact to minimize measurement inaccuracies caused by drying shrinkage.

Lee .H.K. &Tawie R. (2010)In the study conducted by Lee and Tawie (2010), they focused on the advancements in piezoelectric materials to develop new nondestructive evaluation and monitoring techniques. Specifically, they embedded piezoceramic (PZT) sensors into concrete by bonding them onto steel reinforcing bars, enabling nondestructive monitoring of the concrete. To assess the performance of the PZT sensors and the electromechanical impedance (EMI) sensing technique, a series of experiments were conducted. The objective was to monitor the bond development between the steel rebar and concrete by measuring the electrical response of the PZT sensors bonded to the steel rebar using an impedance analyzer. Through the EMI measurements, the researchers were able to detect the gradual adhesion between the steel rebar and fresh concrete by observing changes in the conductance spectra of the PZT sensors. These changes indicated the development of bond strength, which could be attributed to the transformation of the concrete from a liquid to a solid state controlled by the hydration of cement. By monitoring the hydration of concrete over time, they were able to estimate the bonding status between the steel rebar and the concrete. The results of the study demonstrated that various factors, such as varying water-cement ratio, low curing temperature, and poor compaction, influenced the early-age development of bonding between the steel rebar and the concrete. In summary, Lee and Tawie (2010) employed PZT sensors and the EMI sensing technique to monitor the bond development between steel rebar and concrete. Their findings highlighted the impact of factors like water-cement ratio, curing temperature, and compaction on the early-age bonding process. These nondestructive evaluation and monitoring techniques offer potential for assessing the quality and performance of concrete structures.

Pazdera et al. (2010) conducted a study on concrete properties during the early age process, with a particular focus on fissuring that predominantly occurs during this stage. To assess and monitor these properties, the researchers applied nondestructive testing methods, including the Acoustic Emission Method and Nonlinear Spectroscopy. The results of the study revealed interesting findings. It was concluded that techniques such as Acoustic Emission, Non-linear (ultrasonic) spectroscopy, and Impedance spectroscopy prove to be

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suitable tools for monitoring the structural behavior of concrete throughout its lifespan. These methods provided valuable insights into the micro changes occurring within the concrete structure from the time of its production. Overall, the simultaneous use of these nondestructive testing methods enabled a more comprehensive evaluation of the concrete structure, allowing for a better understanding of its properties and behavior from its early stages of formation.

Zhu et al.(2015) The authors of this study propose an ultrasonic guided wave method that utilizes guided waves in a steel rebar to monitor the hardening process of the surrounding cement paste and mortar. The specific guided wave mode employed is the longitudinal L(0,1) mode, which is excited in the rebar using an EMAT sensor and received by a piezoceramic P-wave ultrasonic transducer. Continuous measurements were conducted during the hydration of the cement to monitor the attenuation of the longitudinal guided wave, resulting from leakage from the rebar into the surrounding cement paste or mortar. Additionally, shear wave velocities in the cement materials were simultaneously monitored. The experimental setup included four cement paste samples and three mortar samples. The results of the experiments revealed a strong correlation between the attenuation of the guided wave leakage and the shear wave velocity for all the tested samples. Moreover, both parameters exhibited an increasing trend with the age of the cement materials, indicating a relationship between the hardening process and the measured ultrasonic properties. In summary, the study demonstrates the effectiveness of the proposed ultrasonic guided wave method for monitoring the hardening process of cement materials. The correlation observed between the guided wave leakage attenuation and shear wave velocity suggests that these parameters can serve as indicators of the material's age and structural changes during the hardening process.

Lee et al.(2018) The aim of this study was to non-destructively monitor the hardening process of ultra-high performance concrete (UHPC) using a single embedded sensor system and focusing on the characteristics of guided waves, particularly the Lamb wave. The propagation of Lamb waves is influenced by the material properties of the medium and the boundary conditions. As the boundary conditions of the embedded sensor system change continuously during the hardening process of concrete, the measured characteristics of the propagating waves also exhibit variations. To gain a deeper understanding of these variations in wave propagation, the Lamb modes were decomposed utilizing the polarization characteristics of piezoelectric sensors. These sensors were employed to measure the wave responses and enable the analysis of the Lamb modes. In summary, the study aimed to monitor the hardening process of UHPC using a single embedded sensor system, with a specific focus on the characteristics of guided waves, such as the Lamb wave. By analyzing the polarization characteristics of piezoelectric sensors and decomposing the Lamb modes, the variations in wave propagation during the hardening process were investigated. This approach provides valuable insights into the evolving behavior of UHPC during the hardening stage.

Fodil et al.(2020) This study evaluates the applicability of a non-destructive testing device for assessing the strength of high-performance concrete (HPC), with the aim of enhancing on-site non-destructive strength assessment capabilities. Specifically, the focus is on HPC within a specified strength range. Cylindrical concrete specimens are manufactured and allowed to harden, followed by conducting ultrasonic pulse velocity (UPV) and compressive tests to establish a correlation model between UPV measurements and compressive strength. The developed model is then applied to estimate the strength of a separate HPC sample, using the same type of aggregates. The estimated strength is compared to the actual strength of the second HPC sample to evaluate the reliability of the developed model and the UPV testing method. In a subsequent stage, the proposed model is compared to existing models for assessing the strength of HPC. This comparison serves as a means to confirm or challenge the observations made in the initial part of the study. The results indicate that the UPV method employed in this study lacks sensitivity for accurately assessing the strength of HPC. Despite the variations in strength observed across different HPC samples considered in this study, as well as in existing literature, the UPV measurements remain confined within a narrow range of values. In summary, this study assesses the suitability of a non-destructive testing device for strength assessment of high-performance concrete. The research involves establishing a correlation model between UPV measurements and compressive strength, as well as comparing the proposed model to existing assessment methods. The findings highlight the limited sensitivity of the UPV method for accurately evaluating the strength of HPC.

Loseva et al.(2021) This article explores the application of an ultrasonic method for monitoring the strength of concrete in piles. The geotechnical conditions of the city territory where the study took place are outlined. The article describes the conditions under which the concrete mixture in the pile shaft hardens, as well as the standard conditions for hardening concrete samples. A comprehensive description of the control technique used in the study is provided. The article establishes a correlation between the age of the concrete in the piles and concrete samples and the propagation velocity of ultrasonic waves. By analyzing this relationship, the researchers were able to assess the strength of the concrete in situ. Based on the findings of the study, it was concluded that

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the strength of concrete in piles can be effectively monitored using the ultrasonic method. In summary, this article focuses on the implementation of an ultrasonic method for assessing the strength of concrete in piles. It highlights the geotechnical conditions, describes the hardening process of the concrete, and presents a detailed control technique. The study establishes a connection between the age of the concrete and the ultrasonic wave propagation velocity, ultimately demonstrating the feasibility of in-situ strength control for concrete in piles.

Maziejuk et al.(2021) This paper presents an analysis of research conducted on the compressive strength of cubic concrete samples during the early stage of curing, specifically after 7, 14, and 28 days. The study examines the influence of variable water-cement ratios on the concrete's strength and assesses statistical and strength parameters to determine the quality of the concrete produced. The authors verified whether the expected C25/30 concrete grade, as specified by the prefabrication plant recipe, was achieved. They adjusted the proportions of individual components to achieve the desired concrete grade. The article provides estimations of the concrete grade based on strength parameters observed at three different stages of the concrete curing process.

Tran et al.(2022)This article documents the significant advancements in the technology of ultrasonic guided waves in long bones over the past decade. It covers various topics related to this field, including the available data acquisition configurations for measuring bone guided waveforms, signal processing techniques applied to bone ultrasonic guided waves, numerical modeling of ultrasonic wave propagation in cortical long bones, formulation of inverse approaches to reconstruct bone properties based on observed ultrasonic signals, and clinical studies to establish the application and effectiveness of this technology. The review aims to provide a comprehensive overview of bone guided-wave ultrasound, particularly for individuals new to this scientific field. It highlights the key developments and research conducted in recent years, offering insights into the state-of-the-art techniques and methods employed in this domain. The article concludes by identifying specific challenging problems and proposing future research directions for further advancements in this area of study.

Araújo et al.(2022)The objective of this paper is to assess the effectiveness of the non-destructive ultrasonic pulse velocity (UPV) test method in determining the compressive strength of high-strength concrete (HSC) after exposure to fire. The compressive strength was determined using destructive cylinder tests as well as by measuring the ultrasonic pulse velocity. A total of 20 concrete samples were evaluated, and 10 different equations that correlate the compressive strength of concrete with UPV were examined. However, none of these equations proved to be well-suited for the case of HSC.

To address this limitation, the paper proposed a new equation that demonstrated better suitability for assessing post-fire damaged HSC using the UPV test method. The results indicated that the UPV test method could effectively evaluate the compressive strength of HSC after fire-induced damage. In summary, this paper evaluates the UPV test method for determining the compressive strength of HSC after exposure to fire. It examines several existing equations but finds them unsuitable for HSC. A new equation is proposed, which proves to be more appropriate for assessing post-fire damaged HSC using the UPV test method. The findings highlight the potential of the UPV test as a non-destructive tool for evaluating the strength of fire-damaged HSC.

Rahimi et al.(2023) This paper investigates the use of a particular type of Ordinary Portland Cement (OPC), specifically Iranian Qayen, in the preparation of concrete specimens treated with a Compound Curing Agent (CCA) and Water Base Curing (WBC). The CCA, a paraffin-based water emulsion, is applied to protect fresh concrete against rapid water evaporation. The study follows ASTM standards and focuses on determining the compressive strength of mortar cylinders. The experimental investigation begins with a slump test to assess the mixing efficiency of the concrete. Subsequently, concrete specimens are prepared using ASTM-graded sand, OPC, and varying water/binder ratios of 0.47. These specimens are then subjected to curing with WBC and CCA for 7 days, 14 days, 21 days, and 28 days before conducting compressive strength tests. The study examines the impact of the mortar's structural grade on the strength of the concrete, compares the compressive strengths achieved with different curing methods, and evaluates the technical effectiveness of concrete protection using the curing compounds in Kabul. The experimental results demonstrate that the compressive strength of the concrete specimens cured with water is slightly higher than those treated with a curing compound. However, the compressive strength data obtained from the compound-cured concrete specimens show better reliability compared to the water-cured specimens. Additionally, various hardening models are employed to fit the compressive strength test results of the concrete specimens. In summary, this paper investigates the use of OPC type-I Iranian Qayen in conjunction with CCA and WBC for concrete specimens. The study evaluates the compressive strength of the specimens using ASTM standards, compares different curing methods, and assesses the effectiveness of concrete protection using curing compounds. The findings indicate slight differences in compressive strength between water-

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cured and compound-cured specimens, with the latter showing greater reliability.

V. CONCLUSSION

This review paper focuses on the utilization of ultrasonic guided waves for the early age assessment of concrete strength and hardening. The authors provide a comprehensive overview of this non-destructive testing technique, exploring its principles, advantages, and various methods employed for generating and detecting guided waves. The paper discusses the parameters that can be extracted from ultrasonic signals to assess early age concrete strength, including wave velocity, attenuation, reflection, and scattering characteristics. Furthermore, the influence of factors such as moisture content, temperature, and mixture proportions on the ultrasonic response of concrete is examined. The review also addresses the challenges and limitations associated with the application of ultrasonic guided waves in early age concrete assessment, such as signal interpretation, wave dispersion, and the presence of air voids. The authors highlight recent advancements in signal processing techniques and data interpretation methods. They emphasize the potential of ultrasonic guided waves for early age concrete assessment, providing valuable insights into the current state-of-the-art in this field. The paper concludes by offering recommendations for future research directions to further enhance the accuracy and effectiveness of ultrasonic guided wave technology in assessing concrete strength and hardening during the early age stages. In summary, this review paper serves as a comprehensive guide to utilizing ultrasonic guided waves for the early age assessment of concrete strength and hardening. It provides an overview of the principles, methods, parameters, and challenges associated with this non-destructive testing technique. The paper showcases the potential of ultrasonic guided waves and highlights the need for further research in this area to improve concrete assessment methods.

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