Construction and Building Materials 162 (2018) 802–815

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Monitoring early-age setting of silica fume concrete using wave propagation techniques

Nikita Bhalla [a], Sandeep Sharma [b], Shruti Sharma [a,*], Rafat Siddique [a]

[a] Civil Engineering Department, Thapar University, Patiala, India
[b] Mechanical Engineering Department, Thapar University, Patiala, India

HIGHLIGHTS

- Early age setting properties of silica fume modified concrete are presented.
- Non-destructive methods involving wave propagation characteristics are used.
- Compressive strength, SEM, and EDS analysis of silica fume concrete is reported.

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 14 October 2017
Accepted 5 December 2017

Keywords:
Concrete
Setting
Silica fume
Ultrasonic pulse velocity
Guided waves
Acoustic emission
Compressive strength

ABSTRACT

It is imperative to investigate and monitor young and plastic concrete as soon as it is poured into the moulds from both, technical as well as economic considerations. It would facilitate to detect any anomalies in concrete and to undertake any remedial action at an early stage and avoid the hardship of dismantling solidified concrete later. The focus of the study is to investigate the effectiveness of wave propagation based Non-Destructive Techniques (NDT) of Ultrasonic Pulse Velocity (UPV), Ultrasonic Guided Waves (UGW) and Acoustic Emission (AE) to determine their efficacy in analysing the setting behaviour of concrete made with 6–12% replacement of cement by Silica Fume (SF). Test results indicate that a judicious combination of the three NDT techniques utilizing wave propagation characteristics of UPV, discrete UGW and continuous AE monitoring give a good indication of the setting mechanism of normal concrete as well as SF modified concrete. The three techniques applied in-situ in the field gives an early indication of the quality and efficiency of normal as well as SF modified concretes by studying the changes in UPV, transmitted UGW signal strength and AE hits with the setting of concrete. The research effort proposes an in-situ set-up for early age monitoring of green concrete as soon as it is poured into moulds utilizing these wave propagation techniques.

1. Introduction

Most widely used construction material worldwide is cast in situ Reinforced Concrete (RC) due to its ease in formation and mouldability into any typical shape. It is designed with various kinds of admixtures to meet specific design purposes and various performance parameters. It can only be ascertained after a particular curing period whether the prepared concrete meets the desired characteristics and if it is found to be deficient, then it has to be discarded and rebuild. This problem can be easily addressed if the setting and hardening patterns of the poured concrete are investigated within first 24 h of pouring it into the mould. Setting and hardening of concrete is closely related to hydration of cement. It can be broadly classified into two phases namely initial and final setting. In the initial setting stage, concrete transforms from liquid to solid state and it is important to precisely estimate the initial setting time so that the successive layers of concrete placed in the formwork forms a monolithic component with the previously placed concrete. The final set indicates time when concrete strength development and stiffening has started. Setting is influenced by use of certain admixtures and plasticizers etc. which are commonly used in construction these days in order to achieve desired characteristics. In case of inadequacy found (like contamination in material, faulty mix design or lack of supervision) during initial monitoring, it helps take corrective measures to redesign and reconstruct rather than waiting for curing period to get over and makes taking decisions (accept deficiency or demolish and rebuild). Hence, the early age monitoring of young concrete can help in deciding appropriate time for formwork removal and

* Corresponding author.
E-mail address: shruti.sharma@thapar.edu (S. Sharma).

https://doi.org/10.1016/j.conbuildmat.2017.12.032
0950-0618/

application of loads. Monitoring of young and plastic concrete is hence, beneficial from both, technical as well as economic considerations.

Nowadays, Supplementary Cementitious Materials (SCM) are commonly used in concrete since they improve the microstructure and durability of concrete. They may be in the form of natural pozzolans or industrial by-products and one such commonly used SCM is Silica Fume. High rise buildings demand the use of high performance concrete (HPC) and ultra-high strength concrete (UHSC) in construction work as they lead to reduction in the size of structural elements and silica fume is the key ingredient of HPC and UHSC. SF is a by-product of silicon and ferrosilicon industry produced in electric arc furnaces during production of alloys containing silicon. During reduction of pure quartz to silicon SiO_2 vapours are produced at temperature in excess of 2000 °C which when subjected to low temperatures, oxidize and condense to fine particles of non-crystalline silica. Previous research carried out shows that 10–15% SF is the optimum replacement of cement as further no significant increase in strength is observed. It is mainly attributed to extremely fine particles of SF which might lead to agglomeration and hence, drop in strength is observed [1,2]. Thus optimum replacement of SF not only modifies the fresh properties like reduced bleeding and increased cohesion but also improves the hardened properties of early compressive strength, tensile strength, flexural strength and modulus of elasticity with increased toughness and higher bond strength [3–6]. Through the pore size refinement by SF, reduction in thickness of interfacial transition zone (ITZ) along with reduction in orientation of calcium hydroxide (CH) crystals in ITZ and reaction with free lime improves durability properties of sulphate resistance [3,7,8], permeability to chloride and water intrusion [9], increased abrasion resistance on decks, floors, overlays and marine structures [10], high electrical resistivity, superior resistance to chemical attack from chlorides, acids and nitrates and good fire resistance [9,11]. Portland cement is nowadays primary material used in construction and previous research work shows that silica fume has enhanced both mechanical and durability properties of Portland cement concrete [12–16].

Standard laboratory testing methods for determination of young mortars and concrete properties include penetration needle tests (for mortars only) [17,18], slump and flow table [19,20], hydration temperature measurement [21–24] and pull-out tests [25] for concretes. But these methods suffer from the drawback of continuous measurement data and are not reliable for in-situ monitoring since they are largely dependent on the technical measurement skills of the operator. Literature on variety of other assessment techniques relating to the measurement of volume changes, stress modifications and structural changes during the solidification of cementitious mixtures is also available [26–28]. Rheological testing methods which use different types of viscometers induce shear forces in fresh concrete destroying the microstructure of the hydrating cements and concretes and hence, are not recommended. There is a requirement of modern non-destructive, non-invasive and in-situ tools which can access the initial setting characteristics of concrete. More recently electrical resistivity [29–31], electromagnetic waves [32] and highly non-linear solitary waves [33] have also been suggested for non-destructive monitoring in hydrating concrete. These are specialized advanced assessment techniques which have limited practical applicability for in-situ monitoring of setting concrete.

Ultrasonic wave propagation has been suggested by the researchers to relate to degree of solidification of mortars and concrete. Ultrasonic wave velocity has been used for characterizing setting and early hydration of cement based materials [34–41]. The effect of water-cement ratio, various kinds of admixtures and superplasticizers in concrete [42–45] on the wave velocities has also been reported. More recently, the ultrasonic wave reflection [46–49], variation in resonant frequencies [50], signal amplitudes and a combination of velocities, frequencies and energy content [51] has also been able to discern the microstructural changes occurring due to solidification. However, ultrasonic bulk wave propagation has the limitation to be developed into a NDT method for civil structures since they experience large amount of attenuation in concrete.

In Reinforced Concrete (RC) structures, concrete is reinforced with steel bars, and the ultrasonic waves attenuate less in steel in comparison to concrete. Hence, the reinforcing bars have been suggested to be used as ultrasonic wave guides by some researchers for monitoring setting and early hardening of concrete using an ultrasonic wave guides between embedded steel and surrounding mortars and concrete [52–54]. Ultrasonic guided waves are more effective when specific wave structures or modes excited at varying frequencies are used to relate to specific problems. Researchers have identified specific surface sensitive low frequency ultrasonic guided wave modes which were utilized to investigate surface corrosion in reinforcing bars [55–57] and to the bond development between steel and concrete in RC structures. These modes could further easily relate to the variation in setting patterns of normal and self-compacting concrete [58,59]. Hence, low frequency specific guided wave modes have the potential to be used and developed into an in-situ, non-destructive and non-invasive monitoring technique for freshly poured young concrete.

Another wave propagation technique which has established itself as an NDT tool is Acoustic Emission (AE) technique which depends upon the energy initiated within the component or material under the test, thus being passive in nature. It has various advantages over conventional NDT techniques such as in-situ and continuous monitoring and potential to monitor the entire structure at once with limited number of sensors. It has been successfully applied for monitoring of damage induced cracks in civil structural applications like in steel bridges, prestressed concrete structures, and in RC structures [60–67]. It has also been perceived by several researchers to monitor setting in cement pastes and concrete during hardening. Chotard et al. [68] attributed increased AE activity to changes during the hydration of cement like dissolution of grains, appearance of new phases and draining of pores. Chotard et al. [66] also utilized AE technique to observe setting of calcium aluminate cement. They divided AE activity in various stages with no AE activity up to 3 h of mixing and strong variation in AE events between 3 and 6 h which was attributed to water consumption, change of state from liquid to solid and capillary pores being emptied. Skal's'kyi et al. [69] used AE to study solidification of concrete and concluded that initial 6 h are most active for acoustic signals which were attributed to completion of formation of crystal structure. Hydration products filled pores making structure compact and shielded the cement particle which leads to reduction in AE activity at later stages. Similar justifications were given for observed AE activity by solidifying concretes and mortars by Abeele et al. [70], Gabrijel et al. [71] and Lura et al. [72].

Hence, the wave propagation tools of ultrasonic guided waves and acoustic emission can related to the setting of cement and concrete as suggested by some researchers in the recent past. In this work, authors have utilized ultrasonic guided waves as an active monitoring tool and passive acoustic emission technique along with established ultrasonic pulse velocity measurements to investigate the various the different stages and phases of setting of concrete modified with Silica Fume (SF) as a replacement of cement in varying proportions. With increase in the use of SCMs in concrete, it becomes a necessity to validate the emerging NDT tools for the detection of changes in setting and hardening patterns. A vis-à-vis comparison has been attempted between the various NDT tools of UPV, UGW and AE to determine their efficacy in understanding the setting behaviour of SFC. The non-destructive