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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**APPLICATION OF PIEZOELECTRIC MATERIALS TO
MONITOR MODULUS AND STRENGTH DEVELOPMENT
OF CEMENTITIOUS MATERIALS**

LU XUBIN

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2018

**APPLICATION OF PIEZOELECTRIC MATERIALS TO
MONITOR MODULUS AND STRENGTH DEVELOPMENT
OF CEMENTITIOUS MATERIALS**

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Abstract

Strength monitoring of early-age concrete improves the efficiency of construction as it provides information on the optimum time for shoring removal and pre-stress transferring. Electromechanical impedance (EMI) technique has been proven to be a useful tool for strength monitoring of cementitious materials. One of the key limitations of this technique is the lack of physical models, which resulted in its strong reliance on statistical measures to quantify the strength of structure being monitored.

As the key originality of this thesis, a novel concept of “Smart Probe” is proposed to parametrically estimate the modulus and strength development of cementitious materials using the principle of EMI technique, overcoming the critical shortcoming of the traditional EMI technique. Instead of directly bonding a lead zirconate titanate (PZT) patch on the host structure, a PZT was first surface-bonded on a pre-fabricated aluminium beam termed Smart Probe, which was then partially embedded into cementitious materials for strength monitoring. The structural resonance frequencies of the Smart Probe can be identified from the conductance signatures throughout the curing process serve as strength indicator. An analytical model is developed to predict the dynamic modulus of elasticity of cementitious materials based on structural resonance frequencies. Experimental study was carried out on a mortar slab specimen to verify the model and to investigate the performance of the Smart Probe. It was found that the dynamic modulus of elasticity of the host structure could be predicted from the conductance signatures using the proposed model. Compressive strength assessment was achieved by establishing an empirical relation with the dynamic modulus. The proposed technique for strength monitoring of cementitious materials is parametric with high repeatability.

The analytical model of the Smart Probe is further improved by explicitly formulating the distributed stiffness and mass of the embedded segment of the Smart Probe in the governing equations, allowing more realistic predictions of the actual dynamic characteristics of the coupled Smart Probe-cementitious material system. A 3-D

coupled field finite element (FE) model is also established to predict the conductance spectrum. Multiple resonance peaks in the conductance spectrum computed by FE simulation are in good agreement with the experimental data. The effectiveness of both models in characterizing the resonance peaks are verified with experiment. Parametric study of the Smart Probe shows that the dimensions and position of the PZT patch on the Smart Probe influence the magnitude and the sharpness of the resonance peaks in the admittance spectrum.

In order to overcome the shortcomings of the traditional resonant frequency method (RFM) to measure dynamic modulus of concrete, such as the requirement of bulky and expensive equipment, this thesis proposes a new EMI technique for determining the dynamic modulus of cementitious materials, based on similar working principle of RFM. In this technique, a PZT patch is surfaced-bonded on a specially designed specimen of cementitious material, termed “Miniature Prism”. Experimental results show that, combining the technique with FE analysis, the dynamic modulus of the cementitious materials can be non-destructively measured. The technique possesses advantages, such as simplicity of data acquisition procedure and higher repeatability of measurement, that make it suitable for real-time monitoring.

List of publications

Lu X., Soh C. K. and Avvari P. V. (2015). Lamb wave propagation in vibrating structures for effective health monitoring. SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring: 94381Z-94381Z-94310.

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Chapter 1

Introduction

1.1 Background

Modern engineering structures (in civil, aerospace and mechanical engineering etc.) have become ubiquitous, and they play an essential role in the human society, providing basic welfare and protection. While human beings enjoy all the convenience and cosiness provided by various kinds of structures, safety of the structures is always a major concern.

1.1.1 Incidents of structural failures

Past incidents of structural failures vividly demonstrate the importance of structural safety.

The 2000 Commonwealth Avenue building (Figure 1.1), which was a cast-in-place concrete structure, underwent progressive collapse on the east side of the building during construction (Wigton 2009). Investigations revealed that the collapse could be caused by insufficiently developed compressive strength of the roof slab concrete, which resulted from insufficient curing of the concrete exposed in cold weather (Simpson Gumpertz & Heger 1971).

Figure 1.1 Structural failure of 2000 Commonwealth Avenue, Boston, USA in 1971 (Simpson Gumpertz & Heger 1971).

Although Singapore is small in area, it possesses a large quantity of densely distributed civil structures. Thus, Singapore is also not free of fatal structural failures that caused significant impact on the life of its people. One relatively recent incident is the collapse of the Nicoll Highway (Figure 1.2) on 20 April, 2004, which was caused by the collapse of a deep excavation for a subway station under construction. In fact, large deflections of the retaining wall were observed during the excavation, and one level of struts were overloaded. However, the loads measured in the struts were lower than expected, resulting in the project engineers' false judgment on the structural condition (Levey 2008).

Figure 1.2 Collapse of a stretch of the Nicoll Highway in Singapore (Hansford 2012).

The above-mentioned fatal disasters can be associated with two categories of safety defects, i.e. accumulated damage in the structure and insufficient capacity of structural members. Both these two types of defects may cause serious structural failures, which could lead to catastrophic consequences including loss of life and assets. Therefore, it is very important to inspect and monitor structures in real time, both during construction and in service, using advanced, reliable and robust techniques.

1.1.2 Monitoring of early age concrete structures

Concrete is one of the most widely used engineering materials in the construction industry. In general, strength of concrete is the controlling factor for design. It is known that concrete gains its strength gradually through hydration of its cement, in which multiple chemical reactions occur between water and the cement particles.

As mentioned in section 1.1.1, two types of defects could contribute to serious structural failures. Compared with structures built with other materials, such as steel, cast-in-place concrete structures could be more susceptible to insufficient strength

(capacity), as the strength development of concrete can be affected by many factors. Applying loads to a concrete structure with insufficient strength could lead to disasters (Figure 1.1).

Hence, real-time monitoring of the strength gain of early age concrete during the process of curing is as important as damage detection of the concrete during its service life. In construction engineering, having a good knowledge of the strength of the freshly placed concrete ensures the safety of the construction process. In addition, it can also provide information on the suitable time for shoring removal, which could, in turn, reduce the cost of the construction project by shortening the construction period. It also facilitates the determination of the appropriate time to apply prestressing force for prestressed concrete structures.

1.2 Overview of testing and monitoring properties of concrete

Concrete quality, such as the actual strength of in-situ concrete, can be accurately assessed by performing compressive strength tests on specimens drilled out from the structure. Other than the most common conventional compressive strength test, which is destructive in nature, a wide range of non-destructive testing (NDT) techniques are also available for strength estimation of concrete structures. Surface hardness methods (rebound hammer test), X-ray diffraction, ultrasonic pulse velocity (UPV) test and resonant frequency methods etc. are among the commonly used NDT techniques (Malhotra and Carino 2004, Bungey et al. 2006). In spite of their popularity, these methods suffer from some common shortcomings such as labour-intensive, time-consuming and difficult to apply in inaccessible regions of the structure (Lim et al. 2016). In addition, the results of some NDT techniques, such as the rebound hammer test, may not be satisfactorily repeatable (Soh and Bhalla 2005).

The emergence of smart materials, such as Lead Zirconate Titanate (PZT), provides possibilities for developing alternative inspection and monitoring techniques. The electromechanical impedance (EMI) technique, for instance, are able to overcome most of the above-mentioned shortcomings of the traditional testing techniques. In

this technique, PZT patches are installed on the host structure to measure the electromechanical impedance of the coupled system, in which the mechanical status of the structure can be reflected. The advantages of this technique include low cost, simplicity of sensor installation, minimal intrusion and can be permanently attached to the host structure. In terms of the purpose of real-time monitoring application, the EMI technique could be more advanced than the conventional counterparts, as it possesses remote and autonomous monitoring capability.

Application of the EMI technique to damage detection and integrity evaluation in various structures has been widely studied (Park et al. 2000, Annamdas and Radhika 2013, Lim and Soh 2013, Zuo et al. 2017). Based on similar principle to damage detection, researchers have been investigating the feasibility of employing EMI techniques to monitor hydration and strength development of concrete (Shin and Oh 2009, Tawie and Lee 2010, Yang et al. 2010, Wang et al. 2014, Talakokula and Bhalla 2016).

However, most previous studies using the EMI technique to monitor strength development have major shortcomings that limit their application. One of the key drawbacks is that the mechanical properties of the concrete cannot be parametrically related to the signals (electric admittance or impedance) measured from the PZT transducers. Hence, the technique highly relies on statistical measures for monitoring of concrete properties. Furthermore, in previous studies, reproducing the results on identical specimens has always been challenging. This can be attributed to the fact that the resonant frequencies extracted from the conductance spectrum are overly sensitive to the bonding layer of the transducers, which is highly difficult to be controlled in practice. In view of the shortcomings of the previous studies, there is a strong need to develop more advanced monitoring techniques which are able to provide parametric quantification of the mechanical properties of concrete more effectively.

It is known that increase in the strength and the hardening of fresh concrete mainly come from hydration of the cementitious materials, and the ensuing bond-developing in the hydration products. In this research, focus will hence be placed on more

effective applications of the EMI based technique to monitoring of strength development in fresh cementitious materials.

1.3 Research objectives and original contributions

This study aims to significantly improve the performance of the EMI technique in monitoring the modulus and strength development of cementitious materials throughout the curing process. The objectives of this research include:

- a. To develop novel monitoring approaches to real-time assessment of the mechanical properties of fresh cementitious materials, based on the electromechanical impedance principle; and
- b. to develop analytical and numerical models to relate the electromechanical admittance spectrum of the PZT transducers, which are installed on the cementitious material for active sensing, to the mechanical properties of cementitious materials.

The original contributions of this study are as follows:

- a) A novel "Smart Probe" based approach, adopting the principle of EMI, was proposed for real-time monitoring of the modulus and strength development in cementitious materials. In this approach, the mechanical properties of the cementitious material are indirectly reflected in the admittance/impedance spectrum of the Smart Probe, which is partially embedded in the cementitious material. The usage of the Smart Probe circumvents the adverse influence of the PZT bonding layer on the admittance signatures, which is one of the major challenges in previous studies. This is accomplished by using the movement of the resonance peak of the Smart Probe in the conductance spectrum as strength development indicator. Further, as the introduction of the Smart Probe establishes an indirect connection between the PZT transducer and the cementitious material, there is no need to bond the PZT onto the cementitious

material. Hence the data acquisition process can commence virtually immediately after the casting or placement of the cement paste for very-early-age monitoring, providing better knowledge of the construction progress for the engineers.

- b) A simplified analytical model was first developed to describe the electromechanical response of the partially embedded Smart Probe. The cementitious material is modelled as an equivalent Winkler foundation, which supports the embedded Smart Probe. The dynamic modulus of the cementitious material is identified by matching the structural resonance peak computed by the analytical model with that measured from the Smart Probe. Strength evaluation of the cementitious material is achieved by establishing an empirical relation between the identified dynamic modulus and the compressive strength determined from standard compression tests.
- c) The analytical model for the Smart Probe partially embedded in cementitious materials was further improved by explicitly incorporating the distributed stiffness and mass of the embedded segment of the Smart Probe into the governing equations. The improved analytical model enables more realistic representation of the dynamic characteristics of the integrated system.
- d) 3D coupled field finite element (FE) modelling of the cementitious material - Smart Probe system was carried out to predict the electric conductance spectrum. The conductance spectrum corresponding to various values of the modulus of the cementitious material was computed using the FE model, simulating the monitoring of the hydration process. The effects of various parameters, such as the sizes and bonding position of the PZT patch, on the conductance spectrum were studied using both the FE and the improved analytical model for the Smart Probe. In particular, results showed that Poisson's ratio of the cementitious material had limited effect on the conductance spectrum.
- e) Another EMI based technique was developed for strength development monitoring, which makes use of a specially designed cementitious material

specimen, termed Miniature Prism. This technique uses the resonance frequencies of the Miniature Prism to monitor the hardening process of the cementitious material and is superior to the traditional EMI technique which employs the resonance peaks of the PZT. The dynamic modulus of the cementitious material is determined by using the Miniature Prism in conjunction with 3-D finite element method (FEM) modelling. In addition, the technique serves as a promising alternative to the traditional resonant frequency method, as it is suitable for autonomous and real-time monitoring without the involvement of skilled technicians.

It should be highlighted that the most critical drawback of the existing EMI based technique for strength monitoring of cementitious materials is that the technique is non-parametric and relies on statistical metrics. Thus, as the key originality of this thesis, the novel concept of “Smart Probe” which adopts the EMI principle, is proposed to parametrically estimate the dynamic modulus of elasticity and strength of cementitious materials in real time.

1.4 Thesis outline.

This thesis comprises six chapters including this introductory chapter.

Chapter 2 reviews the literature concerning techniques for monitoring and testing of concrete, with focus on reviewing the applications of impedance based methods in structural health monitoring and concrete curing monitoring.

Chapter 3 presents the development of a novel EMI based technique for strength development monitoring of cementitious materials based on the concept of “Smart Probe”. Also, the derivation of an analytical model of the Smart Probe embedded in the cementitious material is elaborated. The model is then employed to predict the dynamic modulus of elasticity of the cementitious materials based on the resonance frequency experimentally measured from the Smart Probe.

In Chapter 4, the analytical model of the Smart Probe is improved by directly formulating the embedded segment of the Smart Probe in the equation of motion. A 3-D coupled FE model is developed as well in the general purpose FEM software ANSYS for simulation of the EMI based strength development monitoring. The effectiveness of both models are verified with the experiment results presented in Chapter 3. The two models are then used to conduct parametric study of the technique.

Chapter 5 first investigates the performance of the proposed Miniature Prism based EMI technique, when working together with the FEM model, in determining the dynamic modulus and assessing the strength development of cementitious materials. The strength estimation capability of the Miniature Prism is then compared with the traditional EMI technique, rebound hammer tests and the Smart Probe based technique, by conducting a series of experiments.

Chapter 6 concludes the research and provide recommendations for further study.

Chapter 2

Literature review

In this chapter, the literature related to techniques for structural health monitoring and testing of concrete is reviewed. First, general methods for concrete property testing, in the lab or in situ, are briefly introduced. The subsequent text then focuses on reviewing the applications of piezoelectric materials to structural health monitoring and concrete curing monitoring, particularly using the impedance based methods.

2.1 Common approaches to testing of concrete

This section briefly reviews some of the common methods that have been widely used in practice for testing the mechanical properties of concrete.

2.1.1 Compression test for determination of strength and modulus of elasticity

Compressive strength is one of the most critical properties of concrete that is specified by designers to guarantee the load-resisting capacity of the structure (Mamlouk and Zaniewski 2011). The direct way to obtain compressive strength is to conduct the standard compression test. Figure 2.1 shows a compression testing machine that is commonly used in the laboratory.

Compression tests can be conducted on concrete cylinders with a diameter of 150 mm and 300 mm high, complying with ASTM C39. 100 by 200 mm cylinders are permitted for test as well. If compression tests are intended to be used for monitoring the strength development in the structural concrete, which can be used to determine the time for form removal, the standard test cylinders need to be field-cured. This monitoring strategy is considered inferior in terms of efficiency, as the cylinders have to be transported to a lab for testing and data acquisition interval thus becomes

extremely large. It apparent that compression tests are not suitable for real time monitoring purpose.

Figure 2.1 Machine for standard compressive strength tests.

When the strength obtained from compression tests on cylinders could not satisfy the specification, cores may need to be drilled out from the concrete in the structure. Then the cores are prepared and tested in a way similar to that for testing standard cylinders (Wight et al. 2012), which can be found in ASTM C42. The strength measured from such drilled cores should be considered the closest to the actual strength of the concrete in the structure. However, the measured strength could be affected by a number of factors and there are limitations associated with core tests, as discussed by Neville (2001).

The modulus of elasticity of concrete is another crucial material property to be considered in design of concrete structure. Engineers use elastic modulus to predict

the structure's deflection and dynamic response to seismic loading. This parameter largely controls the serviceability of a concrete structure. In addition, the modulus of elasticity of concrete has been shown to be strongly related to the strength (Pauw 1960, Tomosawa and Noguchi 1993, Neville 2011).

In generally, the modulus of elasticity is defined as the ratio between the stress and strain in the linear elastic range of a material. Concrete is not an elastic material, but approximately exhibits linear elastic behaviour in low stress range, based on which the secant modulus (static modulus) can be obtained (Neville 2011). In order to experimentally measure the static modulus of elasticity, the stress-strain relation for concrete in compression need to be obtained. It follows that a deformation measuring device, such as linear variable displacement transducer (LVDT), as shown in Figure 2.2, is required in compression tests if the modulus of elasticity is to be determined. Standard testing procedure for static modulus of elasticity can be found in ASTM C469.

Figure 2.2 A linear variable displacement transducer (LVDT) with 10 mm range.

The actual strength of a certain material, for example a concrete with certain mix proportions, cannot be determined until the material is loaded to failure. So compression tests on testing cylinders (or cores) offer the most accurate evaluation of the strength of concrete. However, this test is completely destructive and repetition of the test on the same specimen is impossible. Also, it is extremely time consuming and labour intensive.

2.1.2 Non-destructive Testing (NDT)

Techniques for determining structural integrity can be generally classified as global and local methods (Fan and Qiao 2011). Local methods normally refer to NDT techniques, although most of the structural integrity identification methods, including global methods, are "non-destructive" in nature. Non-destructive testing methods can be used to inspect structural members and identify defects in structures (Fan and Lowe 2012, Helal et al. 2015) while causing negligible or minimal damage to the structures.

2.1.2.1 Surface hardness

The hardness of concrete is one of the properties associated with its quality. Therefore, surface hardness methods have been developed to test this property. Two types of surface hardness methods were developed, which are indentation methods and rebound tests (Helal et al. 2015).

In the indentation methods, the concrete surface to be tested is impacted by an object with known mass and with known kinetic energy. The hardness of the concrete surface can then be assessed by measuring the dimensions of the indentation caused by the impact. These techniques, however, have never been globally accepted (Bungey et al. 2006).

In the rebound method, similar to the indentation methods, an impact is applied to the concrete surface. But what is measured in this method is how high the mass has rebounded after impacting on the concrete surface. The rebound hammer, invented by Ernst Schmidt in the 1940s, became very popular and is being widely used in engineering practice.

One reason for the popularity of Schmidt rebound hammer could be that its operation is relatively easy. To carry out the test, the operator just holds firmly the hammer perpendicular to the concrete surface and presses steadily against the concrete (Figure 2.3). After the mass impacts on the concrete and rebounds, a reading, which is termed rebound number, will be displayed on the device. The hammer can be placed

horizontally or vertically during the test, corresponding to testing of concrete walls or slabs, respectively. The estimated strength can be obtained from the conversion curve for a particular impact direction, which is provided by the manufacturer.

Figure 2.3 A Schmidt rebound hammer in operation.

Despite the popularity of the rebound hammer test, it suffers from certain limitations and should be employed carefully in engineering practice. In fact, there are a number of factors that considerably influence the test results. These factors include type of cement, type of coarse aggregates, cement content, age of the concrete, the mass of the structural member (or specimen) being tested and the smoothness of the test surface (Malhotra and Carino 2004, Bungey et al. 2006). It is conceivable that the rebound hammer test itself would not be adequate for strength estimate of in-place concrete and it should be used along other testing methods.

Although rebound test is classified as non-destructive testing methods, the concrete will still be damaged slightly after being subjected to a significant number of impacts. Therefore, this test method should be characterized as minor-destructive testing techniques.

2.1.2.2 Ultrasonic pulse velocity (UPV)

In general, travelling waves (mechanical waves that can propagate along a solid) can be generated in solid medium when the solid is excited by external time-varying loads in appropriate frequency range. Three types of mechanical waves can be present: surface waves (Rayleigh waves), longitudinal waves (compressional or P-waves) and transverse waves (shear or S-waves). Among them, the longitudinal waves and transverse waves are often used in ultrasonic testing of concrete.

In the ultrasonic testing of concrete, electronic pulses are generated by a pulse generator and converted into mechanical waves, which are then transmitted into the concrete by a transmitter. The receiver (can be separate transducers or the transmitter itself, depending on the measuring configuration) receives the mechanical waves travelled through the concrete and converts the mechanical energy to electronic signals again. The time that the ultrasonic pulse spends to travel through the concrete is known as the time of flight (TOF). Provided the distance the ultrasonic pulse travelled is known, the pulse velocity can then be obtained, which is related to the dynamic modulus of elasticity of the concrete.

The UPV technique has good capability in measuring the uniformity of concrete members, from which the strength variations of the concrete can be characterized (Bungey et al. 2006). Also, the UPV test is relatively straightforward to be carried out and can be applied to in-place structural members or specimens in the field. However, if higher reliability of the results is required, careful operation by skilled technicians is necessary. For example, the transducer face has to be appropriately

coupled to the concrete surface using greasy medium to transmit the mechanical energy with minimal loss. Therefore, one of the drawbacks of the UPV technique is related to the involvement of intensive skilled labour. Furthermore, another limitation lies in the fact that the technique could not be applied in situation where accessibility is only limited to one side of the concrete.

2.1.2.3 Resonant frequency methods

In accordance with vibration theory, the resonant frequencies of an elastic prismatic specimen with known geometry are largely determined by the modulus of elasticity and density. As the mechanical behaviour of concrete is approximately linear elastic when the deformation is small, this relation may be applied to concrete with acceptable accuracy. In other words, the modulus of elasticity of the concrete can be derived from the resonant frequencies of a concrete specimen, which can be experimentally measured. Note that the modulus of elasticity of concrete determined by resonant frequency methods is termed dynamic modulus, which is usually higher than the static modulus of concrete.

Both flexural and longitudinal vibration modes have been employed to determine the dynamic modulus of concrete. For a long straight rod, the fundamental frequency of flexural mode of vibration, f_{0L} , can be expressed as

$$f_{0L} = \frac{\pi}{2L^2} \sqrt{\frac{EI}{\rho A}} \quad (2-1)$$

where

E = dynamic modulus of elasticity

I = moment of inertia of the cross-sectional area of the rod

ρ = density of the material being tested

A = area of the cross-section

L = length of the rod

From Equation (2-1), one is able to calculate the dynamic modulus of elasticity for a measured resonant frequency, f_{0L} , as other variables are constant for a given concrete specimen. Malhotra and Carino (2004) proposed an equation similar to Equation (2-1) based on which the dynamic modulus is expressed. According to similar working principles, the dynamic modulus can also be determined from fundamental frequencies of longitudinal and torsional modes of vibration. ASTM C215 provides the standard testing procedures associated with resonant frequency methods using all the three modes of vibration.

One critical drawback of these testing methods is that the resonant frequency would be considerably affected by the boundary conditions, which is related to the support characteristics. Another drawback of these methods lies in that the testing procedure, including placement of the specimen on the appropriate supports and installation of the driving unit and sensors, is complicated and requires skilled technicians. The test equipment for this technique is bulky and expensive, limiting its employment in in-situ monitoring of concrete.

All the NDT methods discussed above require operators to be present in the field. However, access to critical structural regions may not be always guaranteed during the construction or service span of the structure. In addition, most of these techniques often involve expensive and bulky testing equipment or probes, which further worsens the inaccessibility. The testing procedures related to these techniques are relatively too time consuming, considering the requirement of a real-time monitoring system. Also, operators must have a good knowledge of the testing technique and know the factors that may affect the testing results. All these factors prevent the techniques from being used in a real-time, autonomous and efficient monitoring system.

2.2 Piezoelectric materials and their application

2.2.1 Types of piezoelectric materials

Smart materials are materials that are able to change their properties in a controlled manner by external conditions or stimuli. Piezoelectric materials are a type of smart materials being widely applied in the areas of structural health monitoring (SHM). Its merit lies in the fact that the piezoelectric effect is a reversible process, i.e., electrical charge is generated in the material when external stress is applied, and strain (deformation) develops in the material when external electric field is applied. Man-made piezoelectric materials are commercially available nowadays and come in various forms, including piezoelectric ceramics, piezoelectric polymers and piezoelectric composites (Dineva et al. 2014).

The advantages of piezoelectric ceramics include low cost, ease of fabrication and low rate of energy dissipation (Gururaja 1992). The piezoelectric ceramic that is most widely used in SHM is lead zirconate titanate (PZT). PZT has very good electromechanical properties, such as high dielectric constants and considerably high piezoelectric coefficients (Webster and Eren 2014). PZT can be made into transducers of various shapes and sizes, as shown in Figure 2.4. It can also be fabricated as piezoelectric diaphragms (Murata Manufacturing Co. 2017) by adhering a piece of thin metal onto the piezoelectric ceramic (Figure 2.4). However, PZT also exhibits some undesirable properties, such as high acoustic impedance, brittleness and being fragile in tension, which narrow its application. One typical problem associated with PZT is the poor coupling with curved surfaces.

Figure 2.4 PZT transducers of various shapes and sizes.

After the discovery of piezoelectric ceramics, the phenomenon of piezoelectricity was also observed in some polymers (Webster and Eren 2014). A piezoelectric polymer that has been introduced to SHM and ultrasonic testing is polyvinylidene fluoride, or known as PVDF. The most favourable feature of PVDF films is their flexibility, which enables them to be easily bonded onto curved surfaces in structures (Monkhouse et al. 1997, Su et al. 2006, Su and Ye 2009). However, compared with PZT, PVDF has considerably poorer electromechanical properties and its energy efficiency is much lower as well (Gururaja 1992).

Piezoelectric composites, which are actually a combination of piezoelectric ceramics and polymers, have been developed to overcome the drawbacks of those two types of monolithic piezoelectric materials (e.g., PZT and PVDF). Though the cost of piezoelectric composites is lower than PVDF, they have higher electromechanical coupling coefficients and medium dielectric constants. They are flexible and hence

show excellent conformability to curved structural surfaces (Figure 2.5). However, some piezoelectric composites are shown to be less effective in actuating and collecting of guided waves than PZT transducers of the same sizes (Raghavan and Cesnik 2007). This may be attributed to the fact that the electromechanical coupling performance of piezoelectric composites largely depends on the content of PZT contained. Another fact to be considered is that piezoelectric composites, such as Macro Fibre Composite (MFC)(SMART MATERIAL 2017), as shown in Figure 2.5, are still significantly more expensive than piezoelectric ceramics (e.g. PZT).

Figure 2.5 A MFC piezoelectric composite transducer mounted on a curved structural surface.

2.2.2 Overview of application of piezoelectric materials to identification of structural properties

Due to the remarkable reversible electromechanical characteristics, piezoelectric materials have been utilized in various areas including vibration control and structural health monitoring (Duan et al. 2010). Making use of piezoelectric materials, the electromechanical impedance (EMI) technique has been developed and studied

extensively in the past over two decades (Annamdas and Radhika 2013) to serve as a potential alternative to the conventional NDT techniques. In addition, the EMI technique can also be used alongside the wave propagation (WP) technique, using the same PZT transducers to obtain more physical information (Song et al. 2007, Lim et al. 2016, Dumoulin and Deraemaeker 2017, Hong et al. 2017, Lim et al. 2017, Zhu et al. 2017) for better characterization of the structural condition.

The piezoelectric material that has been most widely used for transducers in the EMI technique is PZT. This is mainly attributed to the fact that PZT transducers possess strong electromechanical coupling capabilities, and they are light weight and non-intrusive to the host structure. The strong electromechanical coupling of PZT transducers enables them to act as both actuators and sensors (Yun and Min 2011), which complies with the principle of EMI technique.

2.3 Key developments in impedance based structural monitoring

In the field of SHM, the impedance-based technique has been applied to structural identification and damage detection (Lim et al. 2006, Annamdas and Radhika 2013) in various structures, including fatigue crack prediction (Lim and Soh 2011, Lim and Soh 2014a), corrosion monitoring (Talakokula and Bhalla 2014) and stress monitoring (Lim and Soh 2012, Lim and Soh 2013).

One of the earliest studies on the use of PZT transducers and the impedance principle in identification of structural integrity was conducted by Sun et al. (1995a). In their experiment, PZT patches were bonded on the nodes of an aluminium truss and the electric admittance of the PZT patches were measured, which also contained the mechanical impedance of the truss. The integrity of the truss, related to the damage location and severity, was then assessed through a damage indicator derived from the difference of the signature patterns between different states of structural health. Compensation for the signal variation resulting from thermal effect was attempted by the researchers as well (Sun et al. 1995b).

The structural integrity of the tail section of a real airplane was monitored using PZT patches which were bonded on the support brackets of the fuselage (Chaudhry et al. 1995b). As the impedance of the aircraft structure was measured in a high frequency range (> 50 kHz), the sensing area was significantly localized and even slight damage within the sensing zone was detected. The impedance based technique was also extended to monitoring the health state of metallic structures repaired with composite patches (Chaudhry et al. 1995a). The changes in the electrical impedance measured from the PZT transducers were used to qualitatively monitor the de-bond of the repair patch from the structure. Their experimental results also showed that the technique could be used to detect the propagation of an existing crack in the original structure, which was covered by the composite repair patch.

One of the earliest applications of the impedance-based monitoring technique to civil structures was reported by (Ayres et al. 1998). Qualitative real-time structural integrity monitoring using bonded PZT transducers was performed on a quarter-scale truss bridge joint, which was a massive structure compared with those in earlier studies of the technique. They proposed a damage metric that was able to detect the increasing level of damage of the structure, which was simulated by loosening the bolts progressively.

Park et al. (2000) then conducted more comprehensive experimental studies on the capability of the EMI technique to monitor the integrity of civil structural components. The proof-of-concept experiments for damage detection were carried out on composite-reinforced concrete walls, a 1/4-scale steel bridge joint and a civil pipe joint under various ambient conditions. The experimental results illustrated the potential of the technique for estimating damage locations in civil structures. The technique was also shown to possess adequate resistance to adverse ambient conditions, such as low-frequency vibrations in the structure, external loadings and temperature variations.

Soh et al. (2000) investigated the performance of PZT patch transducers in monitoring the crack development of a prototype reinforced concrete bridge structure under cyclic loading. The 'smartness' of the PZT patches was illustrated by their

capability to predict imminent damage in the structure. Their study brought the impedance-based technique one step closer to its application to real-life civil structures.

Inman et al. (2001) proposed the use of a single set of hardware, consisting of a single PZT patch transducer and a fibre optic sensor, for both structural health monitoring and vibrational control of aircraft panel simultaneously. Their study demonstrated the capability of PZT transducers to reduce vibrations of metallic structures in the normal control bandwidth.

A series of comprehensive works by Giurgiutiu et al. (2002a) examined the feasibility of integrated use of the EMI technique and the wave propagation technique for health monitoring of real aging aircraft structures (Giurgiutiu et al. 2002b, Giurgiutiu et al. 2004). The results demonstrated the complementarity between the EMI technique and the wave propagation technique, which can both employ a same set of PZT transducers.

An interesting exploratory study was conducted to investigate the performance of the impedance based technique in the on-site monitoring of the ground structures for space shuttles (Peairs et al. 2004a). It was suggested that the impedance-based technique has potential for long-term monitoring of NASA's ground structures. However, results from the study showed that low excitation force was observed in the tests, which could be caused by the use of MFCs, instead of PZT patches, as actuators and sensors.

Recently, an in-situ practical application study was conducted by Annamdas and Yang (2012), in which the impedance technique was employed to monitor the temporary underground support structures during soil excavation for a Mass Rapid Transit (MRT) station. No damage in the supporting structures was found during the monitoring period. On the other hand, it was reported that the fluctuations of the loadings on the supporting structures resulting from soil excavation was detected by the EMI technique.

Song et al. (2013) proposed a new EMI measurement technique in which a dual PZT transducers was used. The dual PZT transducer consisted of two concentric but separate PZT patches, of which one was annular and the other circular. Their results suggested that the dual PZT technique is better tolerant to temperature variation and possesses high signal-to-noise ratio, which makes the technique suitable for measuring the impedance of large-sized structures.

A novel EMI measurement configuration was proposed by Na and Lee (2013) to monitor multiple areas using only one single shot of frequency sweep. This technique involved the use of multiple PZT patches of different dimensions that were connected to various areas to be monitored using steel wires. Since the PZT patches have different resonance frequencies, the multiple resonance peaks were used to monitor different specific regions in the structure in a single impedance/admittance spectrum. Their study suggested that this technique could potentially reduce the cost of the EMI monitoring technique.

More recently, applications of the EMI technique have been extended to monitoring of bond-line integrity in adhesively bonded joints of aircrafts (Zhuang et al. 2016). Their studies showed that the EMI signatures measured from PZT transducers embedded in the adhesive joints were very sensitive to bond-line degradation (Zhuang et al. 2017), implying that the EMI technique is an excellent tool for monitoring of aircraft structures and could potentially contribute to the development of aerospace engineering.

A number of review papers can be found in the literature that summarise the key developments in the field of impedance-based structural monitoring employing piezoelectric materials (Park et al. 2003, Park and Inman 2007, Park et al. 2008, Annamdas and Radhika 2013, Annamdas et al. 2017).

2.4 Practical considerations associated with implementation of EMI technique

The common impedance analyser used in EMI technique offers many functions that may not be necessary for structural health monitoring, making the device over functional for monitoring purpose. Simplifying the electrical impedance measurement process in the EMI technique is an issue worth studying that relates to the actual application of the technique. Peairs et al. (2004b) developed a low-cost amplifier-based device which could serve as the impedance analyser for the EMI technique. The device was tested with experiment carried out on three types of structures, bolted joints, pipeline structures, and composite beams. Experimental results indicated that the impedance measured using the low-cost device was similar to previous results, implying that the device was somewhat comparable to its traditional counterpart for impedance based monitoring.

Stable performance of the PZT transducers, especially on a long-term basis, is a prerequisite for a reliable monitoring strategy. A study under taken by Yang et al. (2008a) showed that no marked change can be observed in the electric impedance measured from PZT patches kept under indoor conditions for as long as 1.5 years. Lin et al. (2010) experimentally investigated the responses of PZTs exposed to various external conditions, including variational temperature, fluid submergence, outdoor environment, large strains and cyclic loading. It was found that PZT can sustain large strain (typically $> 0.3\%$) and remained operational after 12 million cycles of fatigue loading. However, the PZT patches were susceptible to high temperature.

Park et al. (1999) suggested that the effect of temperature on the EMI monitoring technique can be diminished by applying an empirical temperature compensation technique. Huynh and Kim (2014) developed a device known as PZT interface to investigate the temperature effect in a study involving the monitoring of prestress using EMI. They then employed an algorithm based on effective frequency shift (EFS) to separate the effect of temperature on the impedance signatures from the prestress-loss effect, which was being monitored (Huynh and Kim 2017).

One advantage of the EMI technique lies in that, the impedance signature usually would not be affected by operational vibrations of the host structure (Park et al. 2003). However, in their investigation into the effect of external excitation on the EM admittance spectrum measured from PZT transducers, Yang and Miao (2008) found that external vibrations in the frequency range comparable to that of the PZT actuation could considerably affect the admittance signatures. Campeiro et al. (2017) reported that chirp signals, which is often associated with rotating machinery, could induce deviations in the electromechanical impedance signatures. They suggested that compensation for the effect of external vibration or noise can be made by raising the actuation signal level.

Structures are built to support various types of loadings, being static or dynamic, change in which alters the stress distribution in the members and may influence the application of the EMI technique. Abe et al. (2000) are among the earliest who employed the EMI technique for stress prediction in 1-dimensional (1-D) and 2-dimensional (2-D) thin structures. They used the concept of wave propagation to derive the influence of stress on the behaviours of thin structures. Experimental results showed that tensile stress in thin structures tends to raise the resonance frequencies. Another study suggested that the susceptance spectrum measured from PZT patches could perform better than the electric conductance in identifying stresses in the host structure on site (Annamdas et al. 2007).

2.5 Modelling for EMI technique

2.5.1 Analytical approach

Preliminary modelling approaches have been proposed in the initial development of the EMI technique (Crawley and De Luis 1987, Lalande 1995, Fairweather 1998).

One of the most famous models that made substantial contribution to the impedance based monitoring technique was proposed by (Liang et al. 1994a, Liang et al. 1994b, Liang et al. 1996). The model considered only the axial deformation of a PZT patch

interacting with the host structure and is hence usually referred to as 1-D model. In this model, the host structure was represented by a single-degree-of-freedom (SDOF) dynamic system, which has a particular mechanical impedance denoted by Z . The parameters of the SDOF system included lumped mass, stiffness and damping, as shown in Figure 2.6. The PZT patch was modelled as a bar vibrating in the axial direction with its end connected to the SDOF host structure. Using the force boundary conditions for the PZT actuator, which was defined at the interface between the PZT and the host structure, and the constitutive relation for piezoelectric materials, the electromechanical response of the above-mentioned coupled system was characterized by the electromechanical admittance (Liang et al. 1994a)

$$Y = i\omega \frac{w_A l_A}{h_A} \left(\bar{\epsilon}_{33}^T - \frac{Z}{Z_A + Z} d_{31}^2 \bar{Y}_{11}^E \right) \quad (2-2)$$

where ω is the angular frequency of actuation, w_A , l_A and h_A are the width, length and thickness of the PZT actuator, respectively. l_A is measured along the axis of the bar model for the PZT, as shown in Figure 2.6. $\bar{\epsilon}_{33}^T$ is the complex dielectric constant measured with zero stress, d_{31} is the piezoelectric constant, $\bar{Y}_{11}^E$ is the complex Young's modulus of the PZT, and Z and Z_A denote the mechanical impedance of the structure and the PZT respectively.

This model was further extended by (Giurgiutiu and Zagrai 2000, Giurgiutiu and Zagrai 2002) to predict the electromechanical response of PZT transducers mounted on 1-D structures, e.g. a simple beam. The host structure (as the SDOF system in the Liang's model) connected to the ends of the PZT actuator was represented by the dynamic structural stiffness, which was determined from both the longitudinal and transverse vibrational responses of the host structure using vibration theory. Experimental results indicated that the admittance spectra predicted by their model were representative of the electromechanical response of the coupled system with satisfactory agreement between calculated and experimental results.

Figure 2.6 Sketch of a single-degree-of-freedom mechanical system driven by a PZT transducer.

In another 1-D model proposed by Bhalla and Soh (2003) to account for damage diagnosis, the properties of the host structure associated with the driving point of the PZT was defined through an equivalent SDOF system, which was comprised of specific stiffness, mass and damping. A complex damage metric was then proposed to quantitatively depict damage based on the parameters of the SDOF. They experimentally demonstrated that the proposed damage metric performed better than traditional approaches.

In the succeeding studies of modelling for the EMI technique, the PZT-structure electromechanical interaction was analysed in a 2-D manner. In the 2-D model proposed by Zhou et al. (1995), the concept of direct impedance (Z_{xx} and Z_{yy}) and cross impedance (Z_{xy} and Z_{yx}) was proposed to account for both the longitudinal and lateral constraining forces of the host structure. The model was then applied to predict response of PZT transducers mounted on various structures, including beams, thin plates and shells, and the results were experimentally verified (Zhou et al. 1996). It can be expected that the performance of this model is limited in damage diagnosis

problems as the system of equations for the impedance turns out to be underdetermined (Annamdas 2007).

Bhalla and Soh (2004b) made improvements to the 2-D EMI model by incorporating the effective mechanical impedance into the PZT-structure interaction model. Based on this model, they proposed a new approach to damage detection and structural identification, which was successfully applied to lab-sized aerospace and civil structural members (Bhalla and Soh 2004c). The model was also employed to analyse the shear lag effect when thick bonding layers were present (Bhalla and Soh 2004a).

Annamdas and Soh (2007a) further extended the 2-D models to consider 3-dimensional electromechanical effect by defining the “directional sum impedance”. The model was then applied to study the influence of PZT properties on the performance of the EMI technique in damage identification (Annamdas and Soh 2007b). As a sensor network is required for monitoring of large structural areas, modelling of interactions of multiple PZT patches was also explored (Cheng and Lin 2005, Annamdas and Soh 2008, Zuo et al. 2017).

2.5.2 Numerical approach

Finite element method (FEM) has proven to be a useful tool for the modelling of the EMI technique (Madhav and Soh 2007, Yang et al. 2008b). Liu and Giurgiutiu (2007) applied the finite element method in the EMI techniques for both freely suspended piezoelectric wafer active sensors (PWAS) and 1-D beam structures with installed PWAS. They explored two approaches to the FEM simulation of the 1-D beam-PWAS system, i.e. 2-D analysis using shell elements without electro-mechanical coupling and direct modelling of the structure-PWAS interaction using 3-D coupled field elements. Comparison of results from the two approaches indicated that admittance signatures given by the coupled field 3-D simulation were closer to the experimental results.

Lim and Soh (2011) developed a proof-of-concept semi-analytical damage model which incorporated finite element (FE) simulation and linear elastic fracture

mechanics theory into the EMI technique. Experimental studies on a lab-sized 1-D beam structure showed that the EMI technique is capable of identifying fatigue crack propagation and the damage model could be used for estimating the remaining life of the structure. Park et al. (2006) conducted FE simulations to verify their experimental study in which progressive surface damage were induced on a concrete beam and the impedance signatures measured from multiple PZT transducers were used for damage monitoring. Their predictions of damage with FE simulation showed consistent trend with the experiment in terms of the change in the impedance signatures.

2.6 Application of EMI technique to concrete strength monitoring

Traditionally, the integrity or quality of concrete is inspected by performing compression tests or employing NDT techniques, as discussed in the previous sections. The emergence of piezoelectric materials provides opportunities for developing new approaches to evaluating properties of concrete.

As described earlier in this chapter, studies have shown that the EMI technique, employing the piezoelectric effects or energy transduction capability of PZT transducers, is an excellent tool for identification of properties in metallic structures. Therefore, it can be conceived that application of the technique to testing and monitoring of concrete would be no exception.

Soh and Bhalla (2005) are among the earliest to propose the use of EMI technique for strength prediction of concrete. They established an empirical relation between the cube compressive strength of concrete and the first resonant frequency of the PZT surface bonded on the concrete cube.

Shin and Oh (2009) further extended the application of EMI to early age monitoring of concrete strength development. Their work showed that the EMI sensing technique is capable of tracking the strength gain of early age concrete by evaluating the root mean square deviation (RMSD) of the conductance signatures.

Shin et al. (2008) conducted a series of tests on concrete cylinders under different curing conditions to verify the effectiveness of the EMI technique for strength gain monitoring. Their study suggested that the resonant frequency shift index of the EMI technique can be a more sensitive indicator for strength monitoring between day 3 and day 14 than the methods based on wave velocity. It was also found that the adhesive bonding condition significantly affected the baseline signatures and they suggested the root mean square deviation (RMSD) could be a good indicator for strength growth in the case where tight bonding was present.

Tawie and Lee (2010) carried out an investigation into the application of the EMI technique to on site monitoring of concrete strength development by comparing the performance of various statistical measures, including RMSD, mean absolute percentage deviation (MAPD) and correlation coefficient deviation (CCD). Their study showed that a better correlation between MAPD and the strength can be found, compared with RMSD.

In addition to surface-bonded PZT transducers (Bhalla et al. 2012), studies on EMI technique for strength monitoring of concrete or cementitious materials using embedded PZT patches have also been reported (Annamdas and Rizzo 2010, Narayanan et al. 2017). Wang and Zhu (2011) demonstrated the feasibility of concrete strength gain monitoring using embedded PZT transducers wrapped with asphalt lacquers. Analyses were performed with MAPD and RMSD of the admittance. The MAPD and RMSD of the real admittance were found to be better correlated with the compressive strength of concrete cubes. Employing the concept of effective mechanical impedance, Wang et al. (2014) recently proposed a 3-D EMI model characterizing the interaction between concrete and embedded PZTs for strength monitoring. The correlation coefficient of the mechanical impedance obtained using the model was found to be a good indicator for compressive strength monitoring. Saravanan et al. (2015) studied the performance of different types of embedded smart aggregates to monitor the strength gain of early age concrete. Kim et al. (2015) proposed an approach to concrete curing monitoring, which make use of the correlation between the curing status and the gradient of the susceptance spectrum

measured from embedded PZTs. The merit of this approach lies in that one no longer needs to identify the resonance peaks from the admittance signatures.

Talakokula et al. (2018) proposed a non-dimensional hydration parameter for early-age hydration monitoring of reinforced concrete, which was derived from admittance signatures of a PZT patch bonded on the rebar. The experimental results showed that the impedance-based non-dimensional hydration parameter could provide evaluation of the extent of hydration of the concrete effectively.

The integration of wireless systems and PZT transducers has also been reported in some recent literatures (Providakis and Liarakos 2011, Quinn et al. 2011, Quinn et al. 2012). Providakis and Liarakos (2014) proposed a wireless based EMI technique which employed a generalized extreme value (GEV) statistical measure to perform quantitative monitoring of concrete curing. Their study suggested that a strong relation exist between the number of GEV outliers and the concrete strength gain.

Some researchers have made further improvements to the EMI-based monitoring techniques by investigating the feasibility of applying reusable PZT transducers to strength development monitoring of concrete (Divsholi and Yang 2009, Yang et al. 2010, Tawie and Lee 2011). Tawie and Lee (2011) proposed a novel reusable PZT sensor, comprised of a bolt and a PZT patch attached on it. The sensor was installed on the rod embedded in the cement mortar and can be taken off for reuse after measuring the electromechanical impedance. Experimental studies demonstrated that the reusable PZT sensors were able to monitor the setting of cement mortar and detect progressive damage.

The approaches based on the principle of wave propagation, including travelling wave (derived from ultrasonic testing) and standing wave, have also been extensively used in conjunction with piezoelectric transducers for concrete monitoring (Gu et al. 2006). These piezoelectric transducers can be installed in the form of simply embedding (Song et al. 2007), “smart aggregates” (Song et al. 2008b, Xu et al. 2017) or surface bonding (Lim et al. 2016). While the EMI technique employs one transducer as both actuator and sensor, the WP technique requires separate actuator

and sensor in most cases, which may increase the cost for certain monitoring applications.

Although a considerable amount of work has been conducted in using the EMI technique to monitor concrete strength, the technique is still facing critical limitations that hinder its potential practical application. The testing results of the current EMI curing monitoring technique are hardly reproducible on identical specimens mainly due to inconsistent bonding conditions of the transducers. In addition, no parametric models have been developed to quantitatively predict mechanical properties of concrete. Hence, previous studies generally rely on statistical analysis of the impedance signatures. The historical key developments of the EMI-based monitoring technique can be illustrated by a tree diagram as presented in Figure 2.7.

Figure 2.7 Development of the EMI technique.

Chapter 3

Strength development monitoring and dynamic modulus assessment of cementitious materials using “Smart Probe” based EMI technique

3.1 Introduction

Techniques capable of monitoring the strength gain of cementitious materials in real time during the process of curing is highly sought-after in construction engineering as it provides information concerning the safety of structures and the progress of construction projects. Being autonomous and cost-effective, the EMI technique has been shown to be a promising approach to damage detection and strength development monitoring of cementitious materials and concrete on a real-time basis (Soh and Bhalla 2005, Tawie and Lee 2011, Na and Lee 2012). However, most of the previous studies, which are reviewed in Chapter 2, have limitations that hinder them from being commercialized. One of the key issues associated with the EMI technique lies in the difficulty of relating the electrical conductance to the mechanical properties of the cementitious materials. In other words, a lack of physical models renders the technique highly dependent on statistical analysis. In addition, repeatability of the conductance spectrum is also an important concern. This is especially true for EMI technique using direct surface bonded PZT patches, as the resonance peaks in the conductance spectrum are overly sensitive to the bonding condition. Controlling the bonding thickness is very difficult, if not impossible, rendering the technique essentially unrepeatable.

In this chapter, a proof-of-concept study is presented, which aims to overcome the abovementioned difficulty by introducing a novel concept known as Smart Probe. The Smart Probe is partially embedded in the cementitious material, which can be mechanically treated as an equivalent elastic foundation supporting the Smart Probe.

Considering elastically small deformation of the cementitious material, the modulus of the equivalent elastic foundation can be associated with the dynamic modulus of elasticity of the cementitious material. The introduction of ‘Smart Probe’ as an interface between the cementitious materials and the PZT transducer facilitated the establishment of an analytical model, which is capable of mathematically describing the electromechanical behaviours of the coupled system including the Smart Probe and the equivalent elastic foundation. This enables the mechanical properties of the cementitious materials to be predicted, in particular, the dynamic modulus of elasticity, which is closely related to the compressive strength. Further, the proposed Smart Probe ensures high repeatability of the conductance signature as compared with the conventional EMI techniques. Since the hardening of cement paste is the main source of the strength development of concrete (Popovics 1992), the performance of the proposed technique in cement mortar is investigated in this chapter.

3.2 Physical Principle behind EMI monitoring technique

Most structural health monitoring techniques based on impedance employ both the direct and converse piezoelectric effect of the piezoelectric material. The converse piezoelectric effect is used for actuating the structure, while the direct piezoelectric effect is used for sensing.

In the EMI technique, a PZT transducer is usually surface-bonded on or embedded in concrete structures (Annamdas et al. 2009, Tawie and Lee 2011). The PZT transducer acts as collocated actuator and sensor. To perform the EMI based active sensing, a sinusoidal varying voltage is applied to the PZT patch, the PZT vibrates and thus excites the concrete structure through the strain transfer across the bonding layer. The vibrational behaviour of the host structure will simultaneously affect the vibration of the PZT patch, as the deformation of the patch is constrained by the host structure. The electric current through the PZT patch will hence be dependent on the mechanical behaviour of the host structure. Consequently, the electrical impedance/admittance

of the PZT will be modulated and can be measured by an impedance analyser, which carries information pertaining to the mechanical properties of the host structure.

The above-mentioned working principle can be further illustrated by examining the model developed by Liang et al. (1994a). As can be seen in Equation (2-2), the electric admittance Y is simultaneously determined by the mechanical impedance of the host structure Z , and that of the PZT Z_a . In the case of monitoring throughout the curing process of cementitious materials, change in the mechanical properties, in particular, increase in stiffness and strength, and reduction in damping can be indirectly reflected in the electromechanical conductance spectrum.

3.3 Concept of “Smart Probe”

As mentioned in the Introduction, the concept of “Smart Probe” is introduced to overcome the existing shortcomings of the EMI technique in monitoring of cementitious materials. Instead of directly attaching a PZT transducer to the host structure, the transducer is surface bonded on an aluminium beam with known geometry and mechanical properties. This device is termed Smart Probe. In the proposed application, the Smart Probe is partially embedded in the structure made of cementitious materials during casting. The entire system couples the mechanical properties of the host structure and the electromechanical properties of the Smart Probe. As the electromechanical properties of the Smart Probe can be assumed to remain constant during the hydration process, any changes in the impedance signature are induced by the changes in mechanical properties of the structure. This feature of the Smart Probe is used for monitoring the strength development process of the cementitious material.

In the EMI techniques, conductance (real part of admittance) signatures are found to be effective in SHM (Park et al. 2003). Therefore, the conductance signatures are used for monitoring and estimation of strength in this study. While the peaks of the conductance signatures indicate the resonant frequencies of the Smart Probe (Giurgiutiu and Zagari 2002, Lim and Soh 2014b), the resonant frequencies are

significantly influenced by the boundary conditions of the Smart Probe. However, no attention has been paid to the effect of different boundary conditions in the literature. The boundary conditions of an embedded Smart Probe are determined by the confinement from the host cementitious material. Therefore, the physical property, specifically the dynamic modulus of elasticity of the host structure during the curing process, can be associated to the resonance frequencies of the Smart Probe. In the following section, a theoretical model is developed to correlate the dynamic modulus of elasticity of the cementitious material to the conductance signatures of the Smart Probe.

3.4 EMI based Strength Development Monitoring of Cementitious Materials using Smart Probe – Development of Theoretical Model

This section presents the mathematical development of a theoretical model for the proposed Smart Probe in strength development monitoring of cementitious materials. First, the general expression of the admittance output from a Smart Probe with rectangular cross section is derived in Sections 3.4.1 and 3.4.2. Next, Sections 3.4.3 and 3.4.4 deal with the case where the Smart Probe is partially embedded in the cementitious material. The cementitious material is modelled as an elastic foundation and provides elastic supports for the Smart Probe. Subsequently, the mechanical properties of the cementitious materials are correlated with the modulus of the elastic foundation model in Section 3.4.5. Finally, the relation between the dynamic modulus and the compressive strength of the cementitious materials is presented in Section 3.4.6.

3.4.1 Theoretical modelling of electrical response of end-constrained PZT sensor

Smart Probe can be modelled as a one-dimensional structure as its bending motion is dominant. Therefore, the admittance expression of a PZT patch in one-dimensional

motion is first derived. A surface bonded PZT is constrained by the structure, simplified as stiffness (Giurgiutiu and Zagrai 2000). Consider a PZT patch of length L_{PZT} , width b_{PZT} and thickness t_{PZT} , and is constrained in the x -direction as shown in Figure 3.1. The external electric field is applied along the poling direction, which is through the thickness. The constraints from the structure are assumed to be linear elastic and are denoted as K_{str1} and K_{str2} .

Figure 3.1 PZT transducer constrained by the host structure.

The equation of motion for the longitudinal free vibration of the PZT patch can be expressed as

$$\ddot{u}_a = c_a u_a'' \quad (3-1)$$

where u_a is the displacement in the x -direction. $\dot{u}_a = \frac{\partial u_a}{\partial t}$ and $u_a' = \frac{\partial u_a}{\partial x}$ denote differentiation with respect to time and spatial variable x , respectively. $c_a = \frac{E_a}{\rho_a}$ is the velocity of the longitudinal wave, E_a is the Young's modulus and ρ_a is the density of the PZT patch. The solution is assumed to take this form (Bottega 2014)

$$u_a = \hat{u}_a(x) e^{i\omega t} \quad (3-2)$$

where $\hat{u}_a(x)$ denotes the modal functions, depending only on x and can be expressed as

$$\hat{u}_a = C_1 \cos(k_a x) + C_2 \sin(k_a x) \quad (3-3)$$

where $k_a = \frac{\omega}{c_a}$. The coefficients C_1 and C_2 will be determined from the mechanical and the electrical boundary conditions of the PZT patch.

The constitutive relations of the piezoelectric materials under the one-dimensional assumption can be expressed as (Giurgiutiu 2008)

$$S_1 = s_{11}^E T_1 + d_{31} E_3 \quad (3-4)$$

$$D_3 = d_{31} T_1 + \epsilon_{33}^T E_3 \quad (3-5)$$

where S_1 is the strain in x direction, T_1 is the stress and E_3 is the electric field in the thickness direction. $s_{11}^E = \bar{s}_{11}^E (1 - \eta \cdot i)$ is the complex mechanical compliance at zero electric field, d_{31} is the piezoelectric constant, D_3 is the electric displacement and $\epsilon_{33}^T = \bar{\epsilon}_{33}^T (1 - \delta_\epsilon \cdot i)$ is the complex permittivity at zero stress. The mechanical loss factor η and electric loss factor δ_ϵ represent the mechanical and electrical damping of the system, respectively. The electric field takes the form $E_3 = \hat{E}_3 e^{i\omega t}$.

The boundary conditions as shown in Figure 3.1 can be given as

$$T_1 \left(\frac{1}{2} L_{PZT} \right) b_{PZT} t_{PZT} = -K_{str2} u_a \left(\frac{1}{2} L_{PZT} \right) \quad (3-6)$$

$$T_1 \left(-\frac{1}{2} L_{PZT} \right) b_{PZT} t_{PZT} = K_{str1} u_a \left(-\frac{1}{2} L_{PZT} \right) \quad (3-7)$$

Note that the sign of tensile stress is taken as positive and compressive stress as negative. Substituting the general form of the modal functions (Equation (3-3)) into Equations (3-4), (3-6) and (3-7) gives

$$\begin{aligned}
& C_1 \left[-k_a \sin \left(\frac{1}{2} k_a L_{PZT} \right) + r_2 \cos \left(\frac{1}{2} k_a L_{PZT} \right) \right] \\
& + C_2 \left[k_a \cos \left(\frac{1}{2} k_a L_{PZT} \right) + r_2 \sin \left(\frac{1}{2} k_a L_{PZT} \right) \right] = d_{31} \hat{E}_3 \\
& C_1 \left[k_a \sin \left(\frac{1}{2} k_a L_{PZT} \right) - r_1 \cos \left(\frac{1}{2} k_a L_{PZT} \right) \right] \\
& + C_2 \left[k_a \cos \left(\frac{1}{2} k_a L_{PZT} \right) + r_1 \sin \left(\frac{1}{2} k_a L_{PZT} \right) \right] = d_{31} \hat{E}_3
\end{aligned} \tag{3-8}$$

where

$$\begin{aligned}
r_1 &= \frac{K_{str1}}{b_{PZT} t_{PZT}} S_{11}^E \\
r_2 &= \frac{K_{str2}}{b_{PZT} t_{PZT}} S_{11}^E
\end{aligned} \tag{3-9}$$

Let $\varphi = \frac{1}{2} k_a L_{PZT}$. Coefficients C_1 and C_2 can be determined by solving Equation (3-8):

$$\begin{aligned}
C_1 &= \frac{d_{31} \hat{E}_3}{\Delta} (r_1 \sin \varphi - r_2 \sin \varphi) \\
C_2 &= \frac{d_{31} \hat{E}_3}{\Delta} (-2k_a \sin \varphi + r_2 \cos \varphi + r_1 \cos \varphi)
\end{aligned} \tag{3-10}$$

where Δ is the determinant of the coefficient matrix of Equation (3-8).

Substituting Equation (3-10) into Equation (3-2) gives the resulting displacement, and the corresponding strain can be obtained from the relation

$$S_1 = \frac{\partial u_a}{\partial x} \quad . \tag{3-11}$$

The electric displacement field can be obtained by substituting Equation (3-11) into Equations (3-4), and subsequently (3-5):

$$D_3 = \hat{D}_3 e^{i\omega t} = \left\{ \left[\frac{k_a}{\Delta} (B_2 \cos k_a x - B_1 \sin k_a x) - 1 \right] k_{31}^2 + 1 \right\} \epsilon_{33}^T \hat{E}_3 e^{i\omega t} \quad (3-12)$$

where

$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E \epsilon_{33}^T}$$

$$B_1 = r_1 \sin \varphi - r_2 \sin \varphi$$

$$B_2 = -2k_a \sin \varphi + r_2 \cos \varphi + r_1 \cos \varphi$$

The total electric charge can be obtained by integrating the electric displacement over the area:

$$Q = \hat{Q} e^{i\omega t} = \int_{-\frac{1}{2}b_{PZT}}^{\frac{1}{2}b_{PZT}} \int_{-\frac{1}{2}L_{PZT}}^{\frac{1}{2}L_{PZT}} \hat{D}_3 dx dy \cdot e^{i\omega t} \quad (3-13)$$

$$= \left[\left(\frac{2B_2}{\Delta L_{PZT}} \sin \varphi - 1 \right) k_{31}^2 + 1 \right] \epsilon_{33}^T \hat{E}_3 L_{PZT} b_{PZT} \cdot e^{i\omega t}$$

The electric current flow in the PZT is determined by differentiating the electric charge with respect to time:

$$I = \frac{dQ}{dt} = \frac{d(\hat{Q} e^{i\omega t})}{dt} = i\omega \hat{Q} e^{i\omega t} = \hat{I} e^{i\omega t} \quad (3-14)$$

The admittance is defined as the ratio of electric current to the applied voltage and can be expressed as:

$$Y = \frac{\hat{I} e^{i\omega t}}{\hat{V} e^{i\omega t}} = \frac{\hat{I}}{\hat{E}_3 t_{PZT}} = \left[\left(\frac{2B_2}{\Delta L_{PZT}} \sin \varphi - 1 \right) k_{31}^2 + 1 \right] \frac{\epsilon_{33}^T L_{PZT} b_{PZT}}{t_{PZT}} i\omega. \quad (3-15)$$

3.4.2 Dynamic response of Smart Probe subject to PZT actuation

To obtain the electric admittance, the structural stiffness of the Smart Probe needs to be determined. The dynamic structural stiffness K_{str1} and K_{str2} of a rectangular beam (Smart Probe) are derived in this section. The stress transferred from an ideally bonded PZT patch can be mechanically modeled as in-plane surface traction along

the edges of the PZT (Crawley and De Luis 1987). In this case, the excitation from the PZT transducer can be simplified as a pair of forces acting in opposite directions on the surface of the Smart Probe, as shown in Figure 3.2. Considering force equilibrium and adopting the “plane sections remain plane” assumption, the forces can be replaced by a pair of axial forces acting along the neutral axis and a pair of couples (Figure 3.2). Although both longitudinal and transverse vibrations will be excited in the Smart Probe, transverse motion is dominant in terms of contribution to the electric output of the PZT (Lim 2012). Therefore, only transverse vibration of the beam is considered in this study.

Following the coordinate system depicted in Figure 3.2, The equation of motion of the Smart Probe based on uniform Euler-Bernoulli beam theory can be written as (Bottega 2014)

$$EI \frac{\partial^4 w(x, t)}{\partial x^4} + \rho A \frac{\partial^2 w(x, t)}{\partial t^2} = - \frac{\partial m(x, t)}{\partial x} + f(x, t) \quad (3-16)$$

where $E = \bar{E}(1 + \mu \cdot i)$ is the complex Young’s modulus, I is the moment of inertia of the cross section, ρ is the density, and A is the cross section area of the Smart Probe. The mechanical loss factor μ represents the viscous damping of the Smart Probe. w represents the transverse displacement (in y -direction) of the neutral surface of the Smart Probe. $m(x, t)$ is the distributed body couple and $f(x, t)$ is the distributed transverse force.

Figure 3.2 Aluminum beam driven by a surface-bonded PZT transducer.

The modal functions of the beam can be obtained by solving the equation for free vibration (the terms on the right of Equation (3-16) vanished). The general form of the modal functions for Euler-Bernoulli beams can be written as

$$W(x) = A_1 \cos \beta x + A_2 \sin \beta x + A_3 \cosh \beta x + A_4 \sinh \beta x \quad (3-17)$$

where

$$\beta^4 = \frac{\rho A \omega^2}{EI} \quad (3-18)$$

The constants, the parameter β and the natural frequency ω will be determined from the boundary conditions.

The steady state response of the Smart Probe to external excitations can be obtained using mode superposition principle. Using this method, the displacement is expressed by modal expansion

$$w(x, t) = \sum_{n=1}^{\infty} W_n(x) q_n(t) \quad (3-19)$$

Substituting Equation (3-19) into Equation (3-16) and making use of the orthogonality of the modal functions yields

$$\ddot{q}_n(t) + \omega_n^2 q_n(t) = \frac{f_{pn}(t)}{M_{pn}} \quad (n = 1, 2, 3 \dots) \quad (3-20)$$

where

$$f_{pn}(t) = \int_0^L W_n(x) \left(-\frac{\partial m(x, t)}{\partial x} + f(x, t) \right) dx \quad (3-21)$$

$$M_{pn} = \int_0^L W_n(x) \rho A W_n(x) dx \quad (3-22)$$

and ω_n is the n th natural frequency of the beam for flexural modes. Consider harmonic excitation from the PZT transducer.

As shown in Figure 3.2, the beam is subjected to a pair of concentrated moment and the transverse force is zero. Thus, the forcing term in Equation (3-16) becomes

$$-\frac{\partial m(x, t)}{\partial x} = -\frac{\partial}{\partial x} \{ \hat{M}_{PZT} [\delta(x - x_{a1}) - \delta(x - x_{a2})] \} e^{i\omega t}, \quad (3-23)$$

where $\delta(x)$ is the Dirac Delta function, x_{a1} and x_{a2} represent the coordinates of the two edges of the PZT on the beam. Thus, we have the modal force

$$\begin{aligned} f_{pn} &= \hat{f}_{pn} e^{i\omega t} \\ &= \int_0^L W_n(x) \left(-\frac{\partial m}{\partial x} \right) dx = \hat{M}_{PZT} [W'_n(x_{a1}) - W'_n(x_{a2})] e^{i\omega t} \end{aligned} \quad (3-24)$$

The magnitude of the couple is given by

$$\hat{M}_{PZT} = \hat{T}_{PZT} \frac{h}{2}, \quad (3-25)$$

where $\hat{T}_{PZT}$ is the magnitude of the driving force from the PZT as shown in Figure 3.2.

As the input is harmonic, we seek a solution to Equation (3-20) of the form

$$q_n(t) = Q_n e^{i\omega t}. \quad (3-26)$$

The amplitude of the modal response can be obtained by substituting Equation (3-26) into Equation (3-20)

$$Q_n = \frac{\hat{f}_{pn}}{M_{pn}(\omega_n^2 - \omega^2)}, \quad (3-27)$$

where $\hat{f}_{pn}$ can be evaluated with Equation (3-24). The total transverse displacement is given by combining all the modes as per Equation (3-19).

To obtain the structural stiffness, the x -direction (horizontal) displacement on the beam surface in contact with the PZT patch is required. In flexural motion, this is induced by the rotation of the cross section of the Smart Probe. Thus, the horizontal displacement can be expressed as (Giurgiutiu 2008)

$$u_f(x, t) = -\frac{h}{2} \frac{\partial w(x, t)}{\partial x}. \quad (3-28)$$

The dynamic structural stiffness K_{str1} and K_{str2} are defined as the ratio of the applied force to the displacement

$$K_{str} = \frac{F_{PZT}}{u_f}, \quad (3-29)$$

where $F_{PZT} = \hat{T}_{PZT}e^{i\omega t}$ is the driving force from the PZT patch. Substituting Equations (3-19) and (3-28) into Equation (3-29) yields the expression for the dynamic structural stiffness

$$K_{str1} = \frac{-\hat{T}_{PZT}e^{i\omega t}}{\hat{u}_f(x_{a1})e^{i\omega t}} = \left\{ \left(\frac{h}{2}\right)^2 \sum_{n=1}^{\infty} \frac{[W'_n(x_{a1}) - W'_n(x_{a2})]}{M_{pn}(\omega_n^2 - \omega^2)} W'_n(x_{a1}) \right\}^{-1} \quad (3-30)$$

$$K_{str2} = \frac{\hat{T}_{PZT}e^{i\omega t}}{\hat{u}_f(x_{a2})e^{i\omega t}} = \left\{ -\left(\frac{h}{2}\right)^2 \sum_{n=1}^{\infty} \frac{[W'_n(x_{a1}) - W'_n(x_{a2})]}{M_{pn}(\omega_n^2 - \omega^2)} W'_n(x_{a2}) \right\}^{-1} \quad (3-31)$$

Note that the above dynamic structural stiffness is frequency dependent. The dynamic structural stiffness represented by Equations (3-30) and (3-31) can be used to evaluate the admittance output, as described in Section 3.4.1. The above solutions are also applicable to the Smart Probe with different boundary conditions.

3.4.3 Dynamic response of Smart Probe partially embedded in cementitious-material based structures

As mentioned in the previous section, the constants of the modal functions need to be determined from specific boundary conditions. In the proposed technique, the Smart Probe is partially embedded in the cementitious materials (Figure 3.3(a)). Assuming the material is linear elastic and the displacement is small, the cementitious material is modelled as an elastic foundation. The elastic foundation can be simplified as equivalent elastic supports as shown in Figure 3.3(b). The boundary conditions for the specific beam are given as

$$W''(0) = 0 \quad (3-32)$$

$$W'''(0) = 0 \quad (3-33)$$

$$EIW'''(L) = k_t W(L) - m_e \omega^2 W(L) \quad (3-34)$$

$$EIW''(L) = -k_r W'(L), \quad (3-35)$$

where k_r is the stiffness of the linear rotation elastic support, and k_t is the stiffness of the linear translation elastic support. m_e is an equivalent lumped mass which takes into account the embedded portion of the Smart Probe (Figure 3.3).

Figure 3.3 (a) A Smart Probe partially embedded in cementitious materials and (b) a free beam model with elastic supports subjected to surface traction.

Imposing the first two boundary conditions, Equations (3-32) and (3-33), on the general form of the modal function, Equation (3-17), results in

$$A_1 = A_3, \quad A_2 = A_4 \quad (3-36)$$

Imposing Equations (3-34) and (3-35) on Equation (3-17), and using Equation (3-36) gives

$$\begin{aligned} & A_1[EI\beta^3(\sin \beta L + \sinh \beta L) - (k_t - m_e \omega^2)(\cos \beta L + \cosh \beta L)] \\ & - A_2[EI\beta^3(\cos \beta L - \cosh \beta L) + (k_t - m_e \omega^2)(\sin \beta L + \sinh \beta L)] = 0 \end{aligned} \quad (3-37)$$

$$\begin{aligned} & A_1[EI\beta(\cos \beta L - \cosh \beta L) - k_r(\sin \beta L - \sinh \beta L)] \\ & + A_2[EI\beta(\sin \beta L - \sinh \beta L) - k_r(\cos \beta L + \cosh \beta L)] = 0. \end{aligned} \quad (3-38)$$

Setting the determinant of the coefficients to zero leads to the frequency equation

$$\begin{aligned} & (1 - \cos \beta L \cosh \beta L) - \frac{k_r}{EI\beta} (\cos \beta L \sinh \beta L + \sin \beta L \cosh \beta L) \\ & + \left(\frac{k_t}{EI\beta^3} - \frac{m_e \beta}{\rho A} \right) (\cos \beta L \sinh \beta L - \sin \beta L \cosh \beta L) \\ & + \left(\frac{k_r k_t}{(EI)^2 \beta^4} - \frac{k_r m_e}{EI \rho A} \right) (1 + \cos \beta L \cosh \beta L) = 0. \end{aligned} \quad (3-39)$$

Solving the above equation yields the parameter β , and hence the natural frequencies of the Smart Probe.

As the modal function (Equation (3-17)) describes the relative displacement of each mass element of the beam, either one of the two constants (A_1 and A_2) in Equation (3-37) is arbitrary. Without loss of generality, set the constant A_1 equal to one. Solving Equation (3-37) for A_2 and substituting the result and Eq. (3-36) into Eq. (3-17) gives the modal functions

$$W_n(x) = \cos \beta_n x + \cosh \beta_n x + \xi_n (\sin \beta_n x + \sinh \beta_n x) \quad (n = 1, 2, \dots) \quad (3-40)$$

where

$$\xi_n = - \frac{EI\beta_n(\cos \beta_n L - \cosh \beta_n L) + k_r(\sin \beta_n L - \sinh \beta_n L)}{EI\beta_n(\sin \beta_n L - \sinh \beta_n L) - k_r(\cos \beta_n L + \cosh \beta_n L)}$$

3.4.4 Stiffness of equivalent elastic supports

The expressions for the stiffness of the elastic supports k_r and k_t are derived in this section. To derive these parameters, the interaction between the embedded Smart Probe segment and the cementitious material is investigated. As the vibrating amplitude is low, it is assumed that the deformation of the Smart Probe and the host structure is small and stays in the linear elastic range. Another assumption is that the embedded part of the Smart Probe and the host structure are in good connection. Based on these assumptions, the embedded segment can be modelled as a beam on an elastic foundation, as shown in Figure 3.4 and Figure 3.5. The elastic foundation represents the elastic constraint on the beam segment from the host structure. Winkler foundation model is adopted in this study. In this model, the constant of the foundation k , which has dimension $kN/m/m$, is equal to the force applied on per unit length of the foundation in order to produce a unit displacement of the foundation (Timoshenko 1955). The stiffness of an elastic support is defined as the ratio between the applied force and the resulting displacement. To determine the stiffness of the elastic supports (k_t and k_r), the end displacements of the embedded beam segment when it is subjected to an end concentrated force and an end concentrated moment, respectively, are needed.

Figure 3.4 Embedded beam segment subjected to a concentrated force.

Figure 3.5 Embedded beam segment subjected to a concentrated couple.

Consider the embedded beam segment of length L_e , which is modeled as a beam on elastic foundation, as shown in Figure 3.4. A concentrated force F is applied at one end of the beam. By applying the method of initial conditions (Hetényi 1974), the transverse displacement at the loading point can be obtained

$$w(L_e) = \frac{8\alpha \cdot F [-A_w(\alpha L_e) \cdot D_w(\alpha L_e) + B_w(\alpha L_e) \cdot C_w(\alpha L_e)]}{EI \cdot \begin{vmatrix} 4\alpha^2 C_w(\alpha L_e) & 4\alpha D_w(\alpha L_e) \\ 4\alpha^3 B_w(\alpha L_e) & 4\alpha^2 C_w(\alpha L_e) \end{vmatrix}}, \quad (3-41)$$

where $\alpha = \sqrt[4]{\frac{k}{4EI}}$ and

$$\begin{aligned} A_w(\alpha x) &= \cosh \alpha x \cdot \cos \alpha x \\ B_w(\alpha x) &= \frac{1}{2} (\cosh \alpha x \cdot \sin \alpha x + \sinh \alpha x \cdot \cos \alpha x) \\ C_w(\alpha x) &= \frac{1}{2} \cdot \sinh \alpha x \cdot \sin \alpha x \\ D_w(\alpha x) &= \frac{1}{4} (\cosh \alpha x \cdot \sin \alpha x - \sinh \alpha x \cdot \cos \alpha x). \end{aligned} \quad (3-42)$$

By definition, the stiffness of the linear translation elastic support (Figure 3.3 (b)) is the ratio of the force to the resulting displacement at the loaded point

$$k_t = \frac{F}{w(L_e)} = \frac{EI \cdot \begin{vmatrix} 4\alpha^2 C_w(\alpha L_e) & 4\alpha D_w(\alpha L_e) \\ 4\alpha^3 B_w(\alpha L_e) & 4\alpha^2 C_w(\alpha L_e) \end{vmatrix}}{8\alpha [-A_w(\alpha L_e) \cdot D_w(\alpha L_e) + B_w(\alpha L_e) \cdot C_w(\alpha L_e)]} \quad (3-43)$$

Similar procedure is followed to derive the stiffness of the rotation elastic support. An end moment is applied to the beam segment as shown in Figure 3.5. The angle of rotation at the right end is found to be

$$\varphi(L_e) = \frac{8\alpha^3 \cdot M[4D_w(\alpha L_e) \cdot C_w(\alpha L_e) + A_w(\alpha L_e) \cdot B_w(\alpha L_e)]}{EI \cdot \begin{vmatrix} 4\alpha^2 C_w(\alpha L_e) & 4\alpha D_w(\alpha L_e) \\ 4\alpha^3 B_w(\alpha L_e) & 4\alpha^2 C_w(\alpha L_e) \end{vmatrix}}. \quad (3-44)$$

Subsequently, the stiffness of the linear rotational elastic support is given by

$$k_r = \frac{M}{\varphi(L_e)} = \frac{EI \cdot \begin{vmatrix} 4\alpha^2 C_w(\alpha L_e) & 4\alpha D_w(\alpha L_e) \\ 4\alpha^3 B_w(\alpha L_e) & 4\alpha^2 C_w(\alpha L_e) \end{vmatrix}}{8\alpha^3 [4D_w(\alpha L_e) \cdot C_w(\alpha L_e) + A_w(\alpha L_e) \cdot B_w(\alpha L_e)]} \quad (3-45)$$

3.4.5 Correlating elastic modulus of cementitious material with foundation constant

The Winkler model linearly correlates the deflection and the reaction forces of the foundation through a constant of the foundation k , based on which the stiffness of the elastic supports k_r and k_t are expressed in terms of k , as presented in the previous section. A relationship needs to be established between the dynamic modulus of the cementitious material E_c and the Winkler foundation constant k , so that the stiffness of the elastic supports k_r and k_t can be correlated to E_c .

The elastic settlement w of a foundation subjected to a uniform normal pressure q_0 can be expressed as (Holtz et al. 2011)

$$w = \frac{q_0 B}{E} (1 - \nu^2) I_s, \quad (3-46)$$

where E is the Young's modulus, ν is the Poisson's ratio, B is the characteristic dimension of the loaded area and I_s is the shape and rigidity factor.

From Equation (3-46), the modulus of Winkler foundation can be obtained by dividing the pressure by the settlement

$$k_0 = \frac{q_0}{w} = \frac{E}{B(1 - \nu^2)I_s}. \quad (3-47)$$

In the case where the Smart Probe is partially embedded in the cementitious material, the loaded area is considered rigid. B is taken as the width of the embedded segment.

Considering the width of the embedded segment of the Smart Probe, the constant of the equivalent Winkler foundation is given by

$$k = \frac{k_0 B}{I_m} = \frac{E_c}{(1 - \nu^2)I_s I_m}, \quad (3-48)$$

where E_c is the dynamic modulus of cementitious material and I_m is the equivalent foundation modification factor.

3.4.6 Identification of strength of cementitious material

For a given dynamic modulus of elasticity of the cementitious material, E_c and Poisson's ratio, ν , substituting Equation (3-48) into Equations (3-43) and (3-45) yields the corresponding elastic supports for the smart probe. Next, the resulting dynamic structural stiffness, as given by Equations (3-30) and (3-31), can be obtained by following the solution procedures described in Sections 3.4.2 and 3.4.3. Then, the electric conductance output corresponding to the given properties of the cementitious material can be determined using Equation (3-15). Therefore, we have analytically arrived at a physical model that quantitatively correlates the dynamic properties of the cementitious material and the conductance signatures of the PZT transducer. From the measured conductance signatures, the dynamic modulus of elasticity of the cementitious material being monitored can be identified with the proposed model.

To date, in spite of strong correlation between the dynamic modulus of elasticity and the strength of cementitious material, analytical relationship is inexistent. Various empirical relationships have been established such as the one proposed in ACI 318-14 (American Concrete Institute 2014), where the dynamic modulus of elasticity of concrete can be empirically associated with the compressive strength of concrete

$$E_c = \eta_c \sqrt{f_{cu}}, \quad (3-49)$$

where f_{cu} is the compressive strength (N/mm²), and η_c is the curve fitting proportionality constant.

3.5 Experimental study

3.5.1 Sample and transducer preparation, and experimental setup

In the experimental study, the proposed technique was used to monitor the curing process of a cement mortar. The mix proportion by weight of the mortar used in this study is 1:0.4:2 (cement: water: sand). A mortar slab with the dimensions of $600 \text{ mm} \times 600 \text{ mm} \times 100 \text{ mm}$ and 12 cylinders (diameter: 100 mm, height: 200 mm) were cast using the same mix. The cylinders were used to obtain the compressive strength after 1 day, 2 days, 3 days, 7 days, 14 days and 28 days of curing.

Three Smart Probes were prepared in this experiment. The Smart Probe consisted of an aluminium beam and a PZT patch manufactured by PI Ceramic (Figure 3.6). The aluminium beam is of 6061 alloy with dimensions of $2 \text{ mm} \times 10 \text{ mm} \times 200 \text{ mm}$. A PZT patch with dimension $10 \text{ mm} \times 10 \text{ mm} \times 0.3 \text{ mm}$ was surface bonded at the center of the Smart Probe using two parts epoxy. The three Smart Probes were labeled 'SLB-1', 'SLB-2' and 'SLB-3', respectively. The Smart Probes were partially embedded in the slab from the top surface of the slab with a fixed embedment length of 30 mm (Figure 3.7(a)). The Smart Probe was embedded immediately after casting and the slab surface was further compacted to ensure full contact between the Smart Probe and the mortar. An impedance analyser (Hioki IM3570, as shown in Figure 3.7(b)) was used to measure the electrical admittance of the PZT transducer with a 5V sinusoidal actuating voltage.

Figure 3.6 Pictorial representation of Smart Probe.

Note that although the aluminium used for the Smart Probe may react with the alkaline cementitious material paste during initial contact, the reaction was prevented soon after the protective layer was generated, which has limited influence on the results of the current experiment. However, in certain circumstances, corrosion of aluminium in cementitious materials could be prolonged and severe. For example, in reinforced concrete, corrosion may occur if aluminium is in direct contact with rebar. Thus, more suitable material for the interface should be determined in future studies.

(a)

(b)

Figure 3.7 Experimental setup for strength development monitoring of cementitious material with EMI smart probe: (a) Slab specimen with partially embedded Smart Probes and surface-bonded PZTs and (b) Impedance analyser.

3.5.2 Data acquisitions and frequency selection

The admittance measurements were first performed within the frequency range from 5 kHz to 450 kHz. Figure 3.8 shows a typical conductance signatures acquired within two different frequency ranges. The observed resonance peaks in the conductance signatures in Figure 3.8(a) corresponded to the natural modes of the Smart Probe. The advantage of taking measurement in this range lies in that the resonance frequencies of Smart Probe were not affected by the bonding condition (Yang et al. 2008a) of the PZT patch. The resonance peaks in the higher frequency range from 50 kHz to 450 kHz (Shin et al. 2008) as shown in Figure 3.8(b) correspond to the resonant frequencies of the PZT patch itself. The positions of these peaks in the conductance spectrum, on the other hand, can be significantly affected by the thickness and the adhesive type of the bonding layer, as suggested by Soh and Bhalla (2005).

(a)

(b)

Figure 3.8 Typical conductance signatures versus frequency: (a) 13 - 25 kHz and (b) 50 – 450 kHz.

3.6 Results and Discussions

3.6.1 Consistency of conductance signatures

The conductance signatures obtained from the three Smart Probes labelled as SLB-1, SLB-2 and SLB-3, under free-ended condition, are compared in Figure 3.9. The peaks of the conductance signatures indicate the resonance frequencies of the Smart Probe. It can be seen that the resonance frequencies obtained by the EMI technique are consistent for all three identical Smart Probes.

As the mortar hardened, the boundary condition of the embedded portion of the Smart Probe continuously changed. Figure 3.10 shows the conductance signatures of three Smart Probes measured 20 hours after casting. The resonance peaks of the Smart Probe are different from those under free-ended condition, indicating that there is a change in vibrational behaviour. Again, it can be observed that the resonance peaks among different Smart Probes are fairly consistent.

Figure 3.9 Conductance signatures versus frequency obtained from free Smart Probes.

This is an important observation – conductance signatures are highly repeatable among different Smart Probe. This overcomes one of the key shortcomings in the conventional EMI technique with direct surface bonded PZT transducer. In the conventional EMI technique, the electrical signatures are highly sensitive to the bonding condition, which is almost impossible to control in practice. This renders the conventional technique unrepeatable and highly dependent on statistical analysis for quantification, resulting in lack of reliability in real-life application.

3.6.2 Verification of analytical model under free-free boundary condition

The baseline conductance signatures measured from a free-free Smart Probe are compared with the analytical results in Figure 3.11 . As shown in the figure, within the lower frequency range from 5 to 25 kHz (for the particular dimensions of the Smart Probe adopted in this research), the resonance peaks of the analytical results agree closely with those obtained from the experiment, implying that the theoretical model is fairly accurate.

Note that the performance of the analytical model is not satisfactory in higher frequency range above 40 kHz. In addition, the proposed analytical model can not be used to predict the amplitude-dominant PZT peaks which normally occur above 100 kHz. This is attributed to the fact that this analytical does not include the resonance modes of the PZT patch, which is not the main concern of this study.

Figure 3.10 Conductance signatures versus frequency obtained from embedded Smart Probes 20 hours after casting.

Figure 3.11 Comparison between experimental and analytical conductance signatures under free-ended condition.

3.6.3 Structural resonance frequency as strength indicator

Figure 3.12 depicts the conductance signatures in different frequency ranges obtained from Smart Probe ‘SLB-1’ throughout the curing process of the mortar slab. The resonance peaks shifted rightward throughout the hydration process, which indicates the increase of stiffness of the mortar. Therefore, resonance frequency can be used as an effective indicator of stiffness change.

As mentioned earlier, the strength of the cementitious material can be correlated to its modulus of elasticity. Consequently, the resonance frequency also indirectly serves as a strength index. It should be pointed out that there are multiple resonance peaks that can be used for monitoring. As shown in Figure 3.12, resonance peaks in the three frequency ranges are all effective in monitoring the strength gain of the mortar. One advantage of the Smart Probe is that measurement can commence at a fairly early stage as required, which is not achievable for the conventional direct surface-bonded PZTs. It should be pointed out that within the first 5 hours of mixing, the damping effect is dominant such that resonance peaks can hardly be observed. The magnitude of the peaks after 1 day of curing were also found to be larger than the peak acquired after 5 hours of mixing. This is due to the fact that the mortar was “wet” and “soft” in the first few hours, thus possessed higher damping, which inhibited a strong resonance.

3.6.4 Determination of dynamic modulus

Determination of the dynamic modulus of the cementitious material is achieved by employing the analytical model developed in Section 3.4. Before this can be accomplished, the analytical model of the Smart Probe needs to be updated. Given the physical parameters of a Smart Probe, the conductance signatures can be evaluated using Equation (3-15). Then the analytical model is updated by comparing the analytical output with the data experimentally measured from a free-free smart probe. The dynamic modulus of the mortar at a particular stage is identified through the following procedures. First, the Poisson’s ratio of the mortar, as in Equation (3-48), is assumed to be a constant value 0.25 (Kaplan 1959). So for a given initial

value of the dynamic modulus E_c , the theoretical conductance signatures can be evaluated using the equations given in Section 3.4. Next, E_c is continuously updated to minimize the variance in terms of resonance frequency between the calculated theoretical result and the experimental result. Finally, the dynamic modulus is identified as the value that yields the best agreement. For the optimization of E_c , the experimental resonance frequency takes the average value of the three Smart Probes SLB-1, SLB-2 and SLB-3.

(a) 11.1 – 11.8 kHz

(b) 13.8 – 14.7 kHz

(c) 20.2 – 21.6 kHz

Figure 3.12 Conductance signatures versus frequency obtained from ‘SLB-1’ throughout the process of strength development.

Figure 3.13 shows the analytical conductance signatures computed for different dynamic modulus of the mortar. Apparently, the resonance peaks of the analytical signatures shift progressively to the right as the dynamic modulus increases. In terms of the movement of the resonance peaks, it is observed that the outcome of increasing the curing time in the experiment is similar to that of increasing the modulus of elasticity of the mortar in the model. Thus, the resonance peaks represent different ages of the mortar slab and a lower value of the dynamic modulus corresponds to an earlier age. The consistency of the observations between the theoretical and the experimental results qualitatively shows the validity of the proposed model. From the experimental results (Figure 3.12), it can be observed that the movement of the resonance peak is much larger during the early stage of curing (within the first day) than the later stage. On one hand, this is due to the fact that the hydration rate is the highest in the first 24 hours and slows down gradually. On the other hand, this can be accounted for by the similar pattern found in the analytical results, i.e. the resonance peak is more sensitive to the dynamic modulus in the lower modulus range. In other words, when the dynamic modulus reaches a large value, the same amount of increase in the modulus value causes relatively lesser amount of peak movement.

Figure 3.13 Conductance signatures versus frequency computed with the analytical model.

Figure 3.14 Frequency shift of various resonance peaks experimentally obtained from ‘SLB-1’ throughout the process of strength development.

Resonance peaks of the conductance signatures in higher frequency ranges are generally more sensitive to the changes in the mechanical properties of the structure and exhibit larger movement, which is graphically shown in Figure 3.14. On the other hand, the EMI model gives higher accuracy in lower frequency ranges. Considering both accuracy and sensitivity, the resonance peak between 14 and 15 kHz is thus selected for the monitoring purpose in this study. In this range, modeling of the EMI technique is relatively accurate and the sensitivity of the peak movement is considered moderate. To identify the dynamic modulus of the mortar at a particular age, an initial trial value of the dynamic modulus E_c was first used to compute the conductance signature using the analytical model and the model resonance frequency was determined. This model frequency was compared with the experimental frequency, which is usually different. If the model frequency was less than the experimental frequency, the trial dynamic modulus was increased and a new model frequency was determined using this updated E_c . By updating the E_c iteratively, the

discrepancy between the model and experimental frequencies would be minimized and the E_c of the mortar can thus be determined.

Table 3.1 summarizes the experimental resonant frequencies (14-15 kHz peak), the calculated theoretical resonant frequencies and the predicted dynamic modulus of the mortar. Figure 3.15 illustrates the experimental resonance frequencies (14-15 kHz peak) of the mortar at various ages and the corresponding model-calculated resonance frequencies. Good agreement can be observed between the experimental and the calculated results. As shown in the figure, a rapid increase in the resonance frequencies in the first seven days can be observed, attributed to the high rate of hydration. The rate of increase in resonant frequencies significantly reduced after seven days of curing.

Table 3.1 Resonance frequency and identified dynamic modulus at different curing time

Day	Experimental Resonance Frequency (kHz)				Theoretical Resonance Frequency (kHz)	Dynamic Modulus (GPa)
	SLB-1	SLB-2	SLB-3	Average		
5 Hours	14.182	14.223	14.200	14.202	14.202	13.9
1	14.298	14.365	14.341	14.335	14.336	18.4
2	14.320	14.405	14.379	14.368	14.368	20.3
3	14.335	14.430	14.392	14.386	14.387	21.7
7	14.362	14.477	14.417	14.419	14.418	24.8
14	14.371	14.488	14.426	14.428	14.428	26
28	14.378	14.491	14.438	14.436	14.436	27.1

Figure 3.16 shows the relationship between the dynamic modulus used for the computation in the model and the theoretical resonance frequencies which match the experimental results in Figure 3.15. The prediction of the dynamic modulus on various curing days were made from the above relation. Figure 3.17 presents the predicted dynamic modulus of elasticity of the mortar against curing time. As

reflected by the steep slope of the curve, the dynamic modulus ramped up significantly in the first seven days. It developed to more than 90% of its 28-day value in the first 7 days. The results are consistent with earlier studies (Lim et al. 2016) using the wave propagation technique, suggesting the validity of the proposed technique.

Figure 3.15 Comparison between average experimental resonance frequency at different curing time and model-calculated results.

Figure 3.16 Theoretical resonance frequency against dynamic modulus.

Figure 3.17 Dynamic modulus of elasticity versus curing time.

3.6.5 Strength estimation

The compressive strengths of the mortar slab on different curing days were determined through compression tests. The measured strength took the average value of the results obtained from two cylinder specimens tested on the same day. As mentioned earlier, an empirical relation can be found between the dynamic modulus of elasticity and the compressive strength using Equation (3-49).

Considering the form of Equation (3-49), the constant η_c can be evaluated by performing linear least square curve fitting analysis with the data obtained at different curing stages. As shown in Figure 3.18, the constant was found to be 3.65 for the cementitious material used in this study. With this relation, the compressive strength at various stages of curing can be predicted using the proposed model. It should be noted that the constant η_c may depend on the type of cement and the type of aggregates used (Lim et al. 2016). Once the constant η_c is obtained, the compressive strength of the cementitious material can also be conveniently predicted from the

resonance frequency with the aid of a calibration chart as shown in Figure 3.19, which was generated using the analytical model.

Figure 3.18 Relationship between dynamic modulus and square root of concrete strength.

Figure 3.19 Strength prediction from resonance frequency of Smart Probe based on analytical model.

It should also be noted that the mechanical properties of concrete containing coarse aggregates could be different from those of cementitious materials. Therefore, it is also recommended that further studies be carried out to investigate the performance of the proposed technique on concrete with coarse aggregates. Correction factors can be determined and calibration charts can be established to account for the effect of various types and sizes of aggregates by conducting experimental calibrations. Calibrations for various mix proportions might also be required in future study so that the test results reach a certain level of confidence.

3.6.6 Empirical approach for strength assessment

A pure empirical relation can also be directly established between the resonance frequency and the compressive strength provided a sufficient number of experiments have been carried out. In this study, a second degree polynomial function was fitted to the experimental data to establish the relation between the resonance frequency and the compressive strength, as illustrated in Figure 3.20. Such charts can also be conveniently applied in engineering practice, proving the robustness of the proposed EMI technique employing Smart Probe.

Figure 3.20 Empirical relationship between compressive strength and experimental resonance frequency.

While a quadratic polynomial function seems to show good performance in fitting to the data, a large number of reliable experimental tests have to be conducted before a suitable function can be concluded for the relation. Therefore, the proposed model can be a good alternative to experiment, which can also be conveniently applied in actual strength monitoring.

3.6.7 Comparison with conventional EMI technique

For the sake of comparison, the conventional EMI technique using direct surface-bonded PZT transducers was also applied to monitor the strength gain of the mortar slab specimen. A PZT patch with dimensions of $20\text{ mm} \times 20\text{ mm} \times 0.5\text{ mm}$ was surface-bonded on the top of the specimen after the mortar paste set. The first resonance peak of the PZT transducer (occurring at approximately 100 kHz at the curing age of 1 day) was selected for monitoring purpose. Figure 3.21 shows the conductance spectrum of the surface-bonded PZT in the frequency range of 50 and 170 kHz. As shown in the figure, the resonance peak shifts to the right progressively as the stiffness and strength of the mortar increase during the process of curing, which shows the same trend as the movement of the peaks obtained from Smart Probes. These results are consistent with the works reported by previous researchers (Soh and Bhalla 2005, Tawie and Lee 2010).

The main drawback of this approach is the elastic modulus of the mortar could not be identified from the data as no parametric model is available to predict the response of the PZT. In other words, the approach is qualitative in nature. Furthermore, the PZT resonance peaks are highly sensitive to the thickness and the type of adhesive used (Yang et al. 2008a). Repeatability is therefore a major concern. Usually one could only perform statistical analysis, such as RMSD, to depict the change in the strength. The proposed technique using Smart Probe, is capable of overcoming the abovementioned shortcoming as it not only shows high repeatability, but also, when complemented with theoretical model, enables parametric estimation of physical

properties. Significant improvement to the capability of EMI technique in the monitoring of concrete curing is therefore achieved.

Figure 3.21 Conductance signatures versus frequency obtained from surface-bonded PZT.

3.7 Concluding remarks

In this chapter, a novel EMI-based technique is proposed for strength development monitoring of cementitious materials. In this technique, the concept of Smart Probe is employed and the cementitious material is considered to be an equivalent elastic foundation, the modulus of which is related to the dynamic modulus of elasticity of the cementitious material. An analytical model is developed to predict the electromechanical response of the coupled system composed of the Smart Probe and the cementitious material. Experimental results from the mortar slab specimen show that the structural resonance peaks (ranges from 5 to 30 kHz) of the Smart Probe are effective in monitoring the strength gain of the mortar. The analytical model is successfully employed to identify the dynamic modulus of the mortar using the

experimental data obtained from the Smart Probes. The identified dynamic modulus shows good correlation with the compressive strength of the mortar.

The proposed Smart Probe showed significant improvement over the conventional EMI technique. In addition to being highly repeatable, the proposed theoretical model enables parametric estimation of the dynamic modulus of the host cementitious material. Also, the technique has better potential to be standardized for commercialization, compared with the conventional monitoring technique.

Chapter 4

Numerical modelling and distributed-embedment analytical modelling for “Smart Probe” based indirect EMI technique

4.1 Introduction

In Chapter 3, strength development monitoring of cementitious materials using the novel Smart Probe technique is presented. As a simplified analytical model is used with the Smart Probe technique in the previous chapter, more work is conducted to improve the modelling technique. The influence of various physical parameters of the Smart Probe on its performance in curing monitoring of cementitious material is investigated.

Finite element method is a versatile numerical approach that can adapt to structures with various shapes and boundaries in simulation. Studies showed that FEM is effective in modelling of the EMI technique using its multi-physics feature (Madhav and Soh 2007, Yang et al. 2008b). However, no FEM based studies have been carried out on concrete curing monitoring using the EMI technique, in particular, the newly developed Smart Probe based technique. Existing studies show that the 3-D coupled field finite element method for EMI simulation yield the most accurate simulation results (Lim and Soh 2014b). In this study, attempt is thus made to conduct 3-D coupled field FE simulation of the strength development monitoring of cementitious materials using the Smart Probe-based technique.

In addition, a distributed-embedment analytical model of the Smart Probe is developed in this chapter to allow more realistic predictions of the dynamic features of the integrated system by explicitly formulating the distributed stiffness and mass of the embedded segment of the Smart Probe in the governing equations. Both FE

and analytical predictions are compared with the experimental results for verification. Then parametric study is performed with both the FE and analytical models to investigate the influence of different parameters on the performance of the technique.

4.2 Modelling of Smart Probe

4.2.1 Finite element model

In this study, commercially available FEM software ANSYS 14.0 was used for the 3-D coupled field FE analysis. The analysis was firstly attempted on a free-free Smart Probe, based on which the material properties were updated using experimental data. The updated material properties were used in the simulation of the integrated system including the Smart Probe and the cementitious materials.

4.2.1.1 Free-free Smart Probe

The 3-D FE model of the Smart Probe, which included an aluminium flat bar and a surface bonded PZT patch, is shown in Figure 4.1. As the flexural motion of the aluminium flat bar is dominant in this study, the flat bar is referred to as aluminium beam in the following text. The dimensions of the aluminium beam and the PZT patch were respectively 200 mm x 10 mm x 2 mm and 10 mm x 10 mm x 0.3 mm. Due to symmetry, only one quarter of the model was considered in the analysis. Solid 45 structural and solid 5 coupled field elements both with the dimensions of 0.5 mm were adopted for the aluminium beam and the PZT patch, respectively. The convergence of the solution has been investigated in previous studies (Yang et al. 2008b, Lim and Soh 2011). Since the bonding layer has little influence on the structural resonance frequencies of the Smart Probe (Yang et al. 2008a), the bonding layer is not considered in this FE model. Thus, the PZT patch was modelled as perfectly bonded onto the aluminium beam. The nodes of the PZT and the aluminium that shared the same spatial coordinates were merged, so that their displacement were coupled. The PZT patch was excited by a 1V sinusoidal voltage applied along the z-

direction of the patch. The resulting complex electric current in the PZT patch can be obtained using full solution method for harmonic analysis. The complex electric admittance equalled to the solved electric current as the applied voltage was 1 V.

4.2.1.2 Smart Probe embedded in cementitious material

Figure 4.2 shows the FE model of the cementitious material and the partially embedded Smart Probe. The sizes of the cementitious material block were 100 mm x 100 mm x 100 mm. Due to symmetry, one half of the integrated system was analysed. The convergence issue of this model is studied in section 4.3. Solid 45 structural element was used to model the cementitious material. Meshing size for the cementitious material block was 0.5 mm within the region in contact with the Smart Probe. The dimensions of this region were 35 mm x 20 mm x 10 mm (including the embedded portion of the Smart Probe), and this region was referred to as Region A. The mesh size varied from 0.5 mm to 8 mm progressively in the remaining region (Region B) of the cementitious material block (Figure 4.2). In Region B, the cementitious material was modelled with relatively high damping ratio ($\zeta = 0.25$) serving as transmitting boundary (Song et al. 2008a). The Smart Probe was in full contact with the cementitious material in the model and the nodes on the interface were merged. Similar coupled field harmonic analysis was then performed.

Figure 4.1 Isometric view of part of the Smart Probe model (quarter) in ANSYS.

Figure 4.2 Isometric view of the numerical model of the Smart Probe embedded in cementitious material (half) in ANSYS.

4.2.2 Analytical Modelling

4.2.2.1 EMI model for PZT patch with end-supports

As described in Section 3.4.1, the PZT patch surface-bonded on an aluminium beam can be modelled as a longitudinally vibrating PZT bar constrained by certain dynamic stiffness at both ends. Using this model, the general expression for the admittance of an end-constrained PZT patch can be written as per Equation (3-15). This model was based on the simplification approach used in the 1-D models developed by Liang et al. (1994a) and Giurgiutiu and Zagari (2000).

4.2.2.2 Distributed-embedment model for partially embedded Smart Probe

In this section, the simplified model of the embedded Smart Probe (presented in Chapter 3) is improved. The cementitious material is considered as an elastic foundation, on which a segment of the Smart Probe is resting. By treating the displacement of the embedded segment of the Smart Probe as an unknown variable to be solved in the governing equation, the distributed mass and flexural rigidity of the whole Smart Probe are considered in this model. Note that the axial motion of the aluminium bar can also be modelled and formulated. However, the amplitude of the resonance peaks in the conductance signatures corresponding to the axial motion is considerably smaller than that of the bending motion (Lim 2012). These ‘axial’ peaks would be largely damped out and unrecognisable when the Smart Probe is embedded to monitor the strength development of cementitious materials. Therefore, only flexural motion of the beam is considered in the following modelling.

To construct the governing equations, reference is made to the model of the Smart Probe in Figure 4.3. Two coordinates x_1 and x_2 are used to formulate the transverse displacements w_1 and w_2 in the governing equations. Here, the subscript 1 and 2 represent the physical parameters corresponding to the embedded segment and the cantilevered segment. For instance, w_1 denotes the transverse displacement of the embedded segment of the Smart Probe. In this manner, the governing equations can be written as

$$\begin{aligned}
& EI \frac{\partial^4 w_1(x_1, t)}{\partial x_1^4} + \rho_l \frac{\partial^2 w_1(x_1, t)}{\partial t^2} + k w_1 \\
& = - \frac{\partial m_1(x_1, t)}{\partial x_1} + f_1(x_1, t) \quad 0 \leq x_1 \leq L_1
\end{aligned} \tag{4-1}$$

$$\begin{aligned}
& EI \frac{\partial^4 w_2(x_2, t)}{\partial x_2^4} + \rho_l \frac{\partial^2 w_2(x_2, t)}{\partial t^2} \\
& = - \frac{\partial m_2(x_2, t)}{\partial x_2} + f_2(x_2, t) \quad 0 \leq x_2 \leq L_2
\end{aligned} \tag{4-2}$$

where m_1 and m_2 denote the distributed body couples, f_1 and f_2 are the distributed transverse forces, and ρ_l is the mass density per unit length of the beam. EI is the flexural rigidity of the beam. k is the Winkler foundation constant (Timoshenko 1955, Boresi et al. 1993), which can be related to the modulus and Poisson's ratio of the cementitious material. L_1 is the effective embedment length which is equal to αL_E , where α is the effective length modification factor and L_E is the measured embedment length. The elastic settlement w_0 on the surface of a semi-infinite body subjected to a uniform normal pressure f_0 in a rectangular area is expressed as (Holtz et al. 2011)

$$w_0 = \frac{f_0 B}{E} (1 - \nu^2) I_s \tag{4-3}$$

where B is the width of the loaded area, E is the elastic modulus of the body, ν is the Poisson's ratio and I_s is the shape and rigidity factor. Hence, dividing the normal pressure f_0 by the settlement w_0 and multiplying the result by the width B gives the Winkler foundation constant

$$k = \frac{f_0}{w_0} \cdot B = \frac{E}{(1 - \nu^2) I_s} \tag{4-4}$$

In the case of cementitious material, the elastic modulus is represented by E_c in Equation (4-4).

Figure 4.3 Model for a Smart Probe partially embedded in cementitious material.

Free vibration of the beam is considered first, and hence the distributed external loads on the right-hand side of Equations (4-1) and (4-2) vanished. The solutions for the free vibration problem are assumed to take the form (Bottega 2014)

$$w_1 = \phi_1(x_1)e^{i\omega t} \quad (4-5)$$

$$w_2 = \phi_2(x_2)e^{i\omega t} \quad (4-6)$$

Substitution of Equations (4-5) and (4-6) into Equations (4-1) and (4-2), respectively, yields the eigenvalue problem

$$\phi_1'''' + \beta_0^4 \phi_1 = 0 \quad (4-7)$$

$$\phi_2'''' - \beta^4 \phi_2 = 0 \quad (4-8)$$

where

$$\beta_0^4 = -\frac{\omega^2 \rho_l - k}{EI} \quad (4-9)$$

$$\beta^4 = \frac{\omega^2 \rho_l}{EI}. \quad (4-10)$$

Here, the notation prime is used to denote spatial derivatives. Assuming the modal functions $\phi_1(x_1) = e^{\lambda_1 x_1}$ and $\phi_2(x_2) = e^{\lambda_2 x_2}$, it follows from Equations (4-7) and (4-8) that

$$\lambda_1^4 + \beta_0 = 0 \quad (4-11)$$

$$\lambda_2^4 - \beta = 0 \quad (4-12)$$

Solving Equations (4-11) and (4-12) gives λ_1 and λ_2 . Subsequently, considering Euler's Formula, the general form of the modal functions can be written as

$$\begin{aligned} \phi_1(x_1) = & C_{11} \cosh(\beta'_0 x_1) \cos(\beta'_0 x_1) + C_{12} \cosh(\beta'_0 x_1) \sin(\beta'_0 x_1) \\ & + C_{13} \sinh(\beta'_0 x_1) \cos(\beta'_0 x_1) + C_{14} \sinh(\beta'_0 x_1) \sin(\beta'_0 x_1) \quad 0 \leq x_1 \leq L_1 \end{aligned} \quad (4-13)$$

$$\begin{aligned} \phi_2(x_2) = & C_{21} \cos \beta x + C_{22} \sin \beta x \\ & + C_{23} \cosh \beta x + C_{24} \sinh \beta x \quad 0 \leq x_2 \leq L_2 \end{aligned} \quad (4-14)$$

where $\beta'_0 = \frac{\sqrt{2}}{2} \beta_0$. The integration constants and the parameter β are determined using the following boundary conditions

$$\begin{aligned} w_1''(0, t) &= 0 \\ w_1'''(0, t) &= 0 \\ w_1(L_1, t) &= w_2(0, t) \\ w_1'(L_1, t) &= w_2(0, t) \\ w_1''(L_1, t) &= w_2''(0, t) \\ w_1'''(L_1, t) &= w_2'''(0, t) \\ w_2''(L_2, t) &= 0 \\ w_2'''(L_2, t) &= 0 \end{aligned} \quad (4-15)$$

Considering Equations (4-5) and (4-6), it can be seen that the boundary conditions given by (4-15) can be written as time-independent equations. Imposing these boundary conditions on the formal modal functions, Equations (4-13) and (4-14), yields a system of equations with eight algebraic equations for the constants to be determined. This system of equations can be written in matrix form. Letting the determinant of the coefficient matrix of the system of equations vanish gives the frequency equation, from which the natural frequencies ω are determined. For each value of the natural frequency, a corresponding set of constants and consequently the modal function are determined. Note that one of the constants is arbitrary for each mode, and it can be set equal to one.

The orthogonality of the modal functions can be established as

$$\int_0^{L_1} \phi_{1(j)}(x_1) \rho_l \phi_{1(i)}(x_1) dx_1 + \int_0^{L_2} \phi_{2(j)}(x_2) \rho_l \phi_{2(i)}(x_2) dx_2 = \delta_{ij} (M_{1(i)} + M_{2(i)}) \quad i, j = 1, 2, \dots \quad (4-16)$$

$$\begin{aligned} & \int_0^{L_1} \phi_{1(j)}(x_1) EI \phi_{1(i)}''''(x_1) dx_1 + \int_0^{L_2} \phi_{2(j)}(x_2) EI \phi_{2(i)}''''(x_2) dx_2 \\ & + \int_0^{L_1} \phi_{1(j)}(x_1) k \phi_{1(i)}(x_1) dx_1 = \delta_{ij} \omega_{(i)}^2 (M_{1(i)} + M_{2(i)}) \quad i, j = 1, 2, \dots \end{aligned} \quad (4-17)$$

where δ_{ij} is the Kronecker delta. Note that the subscripts i and j in parentheses denote the order of the modes. The modal mass $M_{1(i)}$ and $M_{2(i)}$ are given by

$$M_{1(i)} = \int_0^{L_1} \phi_{1(i)}(x_1) \rho_l \phi_{1(i)}(x_1) dx_1 \quad i = 1, 2, \dots \quad (4-18)$$

$$M_{2(i)} = \int_0^{L_2} \phi_{2(i)}(x_2) \rho_l \phi_{2(i)}(x_2) dx_2 \quad i = 1, 2, \dots \quad (4-19)$$

Since the eigenvalue problem has been solved and the mutual orthogonality of the modal functions has been established, the dynamic response of the Smart Probe subjected to harmonic excitations can be readily obtained. Using mode superposition

method, the transverse displacement response is expressed as the combination of all the modal functions

$$w_1(x_1, t) = \sum_{i=1}^{\infty} \phi_{1(i)}(x_1) q_{(i)}(t) \quad (4-20)$$

$$w_2(x_2, t) = \sum_{i=1}^{\infty} \phi_{2(i)}(x_2) q_{(i)}(t) \quad (4-21)$$

Substitution of Equations (3-19) and (4-21), respectively, into Equations (4-1) and (4-2) and considering the orthogonality as per Equations (4-16) and (4-17) gives

$$\ddot{q}_{(i)}(t) + \omega_{(i)}^2 q_{(i)}(t) = \frac{f_{1p(i)}(t) + f_{2p(i)}(t)}{M_{1p(i)} + M_{2p(i)}} \quad i = 1, 2, 3 \dots, \quad (4-22)$$

where

$$f_{1p(i)}(t) = \int_0^{L_1} \phi_{1(i)}(x_1) \left(-\frac{\partial m_1(x_1, t)}{\partial x_1} + f_1(x_1, t) \right) dx_1, \quad (4-23)$$

$$f_{2p(i)}(t) = \int_0^{L_2} \phi_{2(i)}(x_2) \left(-\frac{\partial m_2(x_2, t)}{\partial x_2} + f_2(x_2, t) \right) dx_2 \quad (4-24)$$

The resultant forces acting on the top of the beam can be equivalent to a pair of couples and a pair of axial forces. Figure 4.4 shows the amplified profile of the Smart Probe and the equivalent forces from the PZT. As the contribution of the flexural motion is predominant in the application of EMI technique (Lim 2012), only the couples are considered. As can be seen in Figure 4.4, the terms $m_1(x_1, t)$, $f_1(x_1, t)$ and $f_2(x_2, t)$ vanish. Since only harmonic excitation is considered, the external force is given by

$$-\frac{\partial m_2(x_2, t)}{\partial x_2} = -\frac{\partial}{\partial x_2} \{ \hat{M}_{PZT} [\delta(x_2 - x_{a1}) - \delta(x_2 - x_{a2})] \} e^{i\omega t}, \quad (4-25)$$

where $\delta(x)$ is the Dirac Delta function, and x_{a1} and x_{a2} are the positions of the two sides of the PZT patch. Referring to Figure 4.4, the magnitude of the couple can be calculated as

$$\hat{M}_{PZT} = \hat{T}_{PZT} \frac{h}{2}, \quad (4-26)$$

where $\hat{T}_{PZT}$ is the amplitude of the force transferred from the PZT patch.

Figure 4.4 Equivalent driving forces acting on the beam.

Then, the modal force in Equation (3-20) can be expressed as

$$\begin{aligned} f_{2p(i)} &= \int_0^{L_2} \phi_{2(i)}(x_2) \left(-\frac{\partial m_2}{\partial x_2} \right) dx_2 \\ &= \hat{M}_{PZT} [\phi'_{2(i)}(x_{a1}) - \phi'_{2(i)}(x_{a2})] e^{i\omega t} = \hat{f}_{2p(i)} e^{i\omega t} \end{aligned} \quad (4-27)$$

The steady state solution to Equation (3-20) takes the form

$$q_{(i)}(t) = \bar{q}_{(i)} e^{i\omega t} \quad (4-28)$$

Substituting Equation (4-28) into Equation (4-22) and considering Equation (4-27), the amplitude of the modal displacement can be found as

$$\bar{q}_{(i)} = \frac{\hat{f}_{2p(i)}}{M_{1p(i)} + M_{2p(i)}} \cdot \frac{1}{\omega_{(i)}^2 - \omega^2} \quad (4-29)$$

The transverse displacement of the beam can then be obtained by substituting Equation (4-28) into Equations (4-20) and (4-21), and using Equations (4-27) and (4-29).

In order to obtain the equivalent structural stiffness of the beam constraining the PZT patch, the displacement on the surface of the beam along the horizontal direction needs to be determined. The general kinematic relation for the horizontal displacement can be expressed as

$$u_2(x_2, z, t) = -z \frac{\partial w_2(x_2, t)}{\partial x_2}. \quad (4-30)$$

Taking $z = \frac{h}{2}$ in Equation (4-30) gives the surface displacement. The equivalent dynamic structural stiffness is then obtained by dividing the PZT force $\hat{T}_{PZT}$ by the surface displacement. The final expressions for the dynamic structural stiffness are given by

$$K_{str1} = \left\{ \left(\frac{h}{2} \right)^2 \sum_{i=1}^{\infty} \frac{[\phi'_{2(i)}(x_{a1}) - \phi'_{2(i)}(x_{a2})]}{[M_{1p(i)} + M_{2p(i)}](\omega_{2(i)}^2 - \omega^2)} \phi'_{2(i)}(x_{a1}) \right\}^{-1}, \quad (4-31)$$

$$K_{str2} = \left\{ - \left(\frac{h}{2} \right)^2 \sum_{i=1}^{\infty} \frac{[\phi'_{2(i)}(x_{a1}) - \phi'_{2(i)}(x_{a2})]}{[M_{1p(i)} + M_{2p(i)}](\omega_{2(i)}^2 - \omega^2)} \phi'_{2(i)}(x_{a2}) \right\}^{-1}. \quad (4-32)$$

The above obtained dynamic structural stiffness is then employed in the general formulae for admittance of an end-constrained PZT patch, as mentioned in Section 4.2.2.1, to predict the admittance signatures. In comparison to Equations (3-30) and (3-31), which are derived for the simplified analytical model, the modal features incorporated in Equations (4-31) and (4-32) are closer to the actual physical behaviour of the system. In fact, in this model, the distributed coupling between the Smart Probe and the cementitious material is taken into account by explicitly formulating the distributed stiffness and mass of the embedded segment of the Smart Probe.

4.3 Results and Discussions

The experimental results presented in this section are obtained from the experiment presented in Section 3.5, in which the experimental setup and data acquisition procedures can be found.

4.3.1 Free-ended Smart Probe

The material properties of the FE model are given in Table 4.1 and Table 4.2. Figure 4.5 compares the conductance signatures measured from a free-ended Smart Probe with those predicted using FE model with updated material properties. As illustrated in the figure, excellent agreement between FE simulation and experiment results can be observed in terms of resonance frequency and magnitude of peak. This establishes the basis for simulating the Smart Probe based monitoring of cementitious materials with FEM.

Table 4.1 Materials properties of PZT PIC 151 in FE simulation

Physical variables	Symbols	Values	Unit
Density	ρ_a	7760	kg/m ³
Compliance (constant electric field)	$s_{11} = s_{22}$	16.5	10 ⁻¹² m ² /N
	s_{33}	19	
	$s_{44} = s_{55}$	45	
	s_{66}	44.97	
	s_{12}	-5.66	
	$s_{13} = s_{23}$	-7.11	
Relative electric permittivity	$\epsilon_{11}^S = \epsilon_{22}^S$	1110	
	ϵ_{33}^S	852	
Piezoelectric strain coefficients	$d_{31} = d_{32}$	-3.08	10 ⁻¹⁰ m/V
	d_{33}	18.3	

Physical variables	Symbols	Values	Unit
Damping ratio	d_{15}	6.1	
	ζ_a	0.018	

Table 4.2 Materials properties of aluminium beam and cementitious material in FE model

Physical variables	Aluminium	Cementitious material	Unit
Density	2715	2220	kg/m ³
Young’s modulus	70.6	33	10 ⁹ N/m ²
Poisson’s ratio	0.35	0.25	
Damping ratio	0.0005	0.01	

Figure 4.5 Comparison of conductance signatures versus frequency obtained from a free suspended Smart Probe between FEM and experiment (5 kHz - 30 kHz).

4.3.2 Smart Probe embedded in cementitious material

To investigate the convergence of the FE model with embedded Smart Probe, analyses were first performed for two models of the cementitious materials with different sizes. The material properties of the cementitious material used for the FE simulations are given in Table 4.2. The results of the analyses are presented in Figure 4.6, in which overlapping can be observed between the conductance spectra given by the two FE models. This showed that the model with size of 100 mm side length was adequate to achieve convergence (the model is shown in Figure 4.2). This can be attributed to the introduction of the transmitting boundary in the FE model, which renders the model sufficient to represent the slab specimen in the experiment. The conductance signatures from a Smart Probe embedded in cementitious material computed with FE simulation were compared with the experiment results in the frequency range 6 - 22 kHz, as shown in Figure 4.7. The experimental data shown in Figure 4.7 were measured at the curing age of 28 days. As shown in the figure, the conductance spectrum produced by FE modelling was in excellent agreement with the experimental results in terms of resonant frequencies and the number of peaks in the frequency range studied. There are a couple of peaks showing good agreement between FE modelling and experiment in the zoom-in view with higher resolutions (Figure 4.8), which shows the validity of the established FE model. The mechanical properties, such as dynamic modulus, of the cementitious material can thus be identified once the FEM-predicted peaks coincide with experiment.

Figure 4.6 Comparison of computed conductance signatures between FE models of cementitious material blocks with different sizes.

Figure 4.7 Comparison of conductance signatures versus frequency obtained from a monitoring Smart Probe embedded in cementitious material between FEM and experiment (6 kHz - 22 kHz).

(a)

(b)

(c)

Figure 4.8 Zoom-in view of the comparison of the resonance peaks in the conductance signatures between FEM and experiment: (a) 11.1 kHz -12.0 kHz, (b) 13.6 kHz - 15.2 kHz and (c) 20 kHz - 22 kHz.

4.3.3 Strength development indication

The conductance signatures were obtained using the distributed-embedment analytical model and the FE model (shown in Figure 4.9 and Figure 4.10, respectively) for various values of dynamic modulus of the cementitious material. As shown by the modelling results in both figures, with the increase of the dynamic modulus, the peak shifts to the right gradually in the conductance spectrum. Figure 4.11 shows the conductance signatures obtained from a Smart Probe for various curing ages of the cementitious material in the experiment. Apparently, the experimental resonance peak moves rightwards as curing age increases. This is due to the growth of the strength and the stiffening of the cementitious material resulting from its hydration. Both analytical and FE modelling results show the same pattern of movement of the resonance peak as the experiment. This consistency shows the effectiveness of the proposed numerical and analytical modelling methods in describing the electromechanical behaviour of the Smart Probe during curing. As can be seen from

the results, the analytical model is representative of the numerical simulation and experimental study, which are much more time and effort-consuming in nature.

Figure 4.9 Conductance signatures (14 kHz - 14.6 kHz) predicted with FE simulation for various elastic modulus of the cementitious material being monitored.

Figure 4.10 Conductance signatures (13.5 kHz - 14.9 kHz) calculated using the distributed-embedment analytical model for various elastic modulus of the cementitious material.

Figure 4.11 Experimental conductance spectra obtained from Smart Probe at various curing ages.

It is worth mentioning that multiple resonance peaks of the conductance spectra in the frequency range studied (5 kHz - 25 kHz) are capable of monitoring the strength development process. Also, both theoretical and FE analyses show that these resonance peaks are well separated from each other for the particular experimental setup in this study. In particular, the resonance peak appears between 13 kHz and 15 kHz, showed sufficient sensitivity to the modulus and strength development. This peak has a relatively small bandwidth, which does not require a large number of frequency points to be covered during data acquisition. Therefore, tracking the movement of this peak is sufficient to monitor the strength development throughout the process of curing.

4.4 Parametric study of Smart Probe based monitoring technique

This section presents the parametric study of the Smart Probe based curing monitoring technique, which was conducted by performing both the FEM and the analytical analyses. The performance of the analytical model is first investigated by studying the effect of dynamic modulus and Poisson's ratio of the cementitious material using both the FE and analytical models. Then, the influence of geometric parameters of the Smart Probe on the conductance signatures is investigated.

4.4.1 Effect of dynamic modulus and Poisson's ratio

The peak with resonance frequency of 14.38 kHz at the age of 28 days (as the peak shown in Figure 4.11) in the experiment was investigated in the parametric study. This peak in such frequency range has certain advantages over other peaks for monitoring purpose, such as moderate sensitivity and well separation from other resonance peak. Figure 4.12 shows the resonance frequency versus the cementitious material's dynamic modulus E_c and Poisson's ratio ν calculated using the distributed-embedment analytical model. Apparently, the resonance frequency increases as either the dynamic modulus or Poisson's ratio increases. However, it can be observed that the effect of Poisson's ratio on the resonance frequency is limited when compared with that of dynamic modulus.

Figure 4.12 Resonance frequency (14-15kHz peak) versus dynamic modulus and Poisson's ratio obtained using the distributed-embedment analytical model.

As shown in Figure 4.13, the above-mentioned relation between the resonance frequency, E_c and ν is further corroborated by the results obtained from the FE simulation. The effectiveness of the proposed analytical model is thus verified since both the FE and the analytical models predict the same relation. It's worth mentioning that computation time of the FE simulation for a single frequency point took minutes, in spite of the fact that the FE model for the integrated Smart Probe-cementitious material system considered only half of the actual structure. The proposed analytical model, on the other hand, swept over a few thousand frequency points in seconds. Although the 3-D coupled field FE analysis yielded more accurate results, the computational efficiency of the analytical model is enormously higher than the FE model. Thus, the analytical model was used for the following parametric studies.

Figure 4.13 Resonance frequency (14-15kHz peak) versus dynamic modulus and Poisson's ratio obtained from FE analysis.

4.4.2 Effect of size of PZT patch

To study the effect of the length (along the axis of the Smart Probe) of the PZT patch on the conductance signatures, all other parameters were kept unchanged as those in the experimental study. The properties of the cementitious material used for the parametric study hereafter are as per Table 4.2. Figure 4.14 (a) shows the variation of the resonance peak in the conductance spectrum when the length (denoted as “L” in the legend) of the PZT patch changed from 0.004 m to 0.022 m. As shown in the figure, when the PZT length is less than 0.014 m, the resonance peak magnitude increases considerably as the PZT length increases. The peak also shifts to the right gradually within this range of length. When the PZT length is greater than 0.02 m, the resonance peak magnitude starts to decline and frequency reduces as well. The relation between the resonance peak magnitude and the length of the PZT patch is illustrated in Figure 4.14 (b). To characterize the sharpness of the resonance peak, the electromechanical quality factor is defined as (Bottega 2014)

$$Q_e = \frac{\omega_0}{\omega_H - \omega_L} \quad (4-33)$$

where ω_0 is the resonance frequency, at which the conductance reaches the peak value. ω_H and ω_L are the higher and lower frequency corresponding to the half-power points (Chopra 2012) of the resonance peak. The relation between the quality factor and the PZT length is shown in Figure 4.14 (c). As shown in Figure 4.14 (b) and Figure 4.14 (c), the peak magnitude and the quality factor are not monotonically increasing functions of the PZT length. This indicates that with the aid of parametric study an optimum value for the length of the PZT patch can be found to achieve the largest peak magnitude or highest peak sharpness of the signal, which could potentially reduce disturbance induced by ambient noise.

(a)

(b)

(c)

Figure 4.14 (a) Conductance signatures (12.5 kHz -16 kHz) for various length of the PZT patch, (b) Peak value of the conductance spectrum versus PZT length and (c) Quality factor of the resonance peak versus PZT length.

Figure 4.15 (a) shows the variation of the resonance peak in the conductance spectrum when the width (denoted as “W” in the legend) of the PZT patch changed from 0.005 m to 0.02 m. The peak magnitude increases rapidly as the width of the

PZT patch increases within this range. The results show that the peak magnitude and the sharpness of the resonance peak are monotonically increasing functions of the width of the PZT (see Figure 4.15 (b) and Figure 4.15 (c)). Figure 4.16 shows the effect of the thickness of the PZT patch on the conductance signatures. The horizontal movement of the resonance peak (Figure 4.16) indicates that increasing the thickness of the PZT patch mainly raises the resonance frequency.

(a)

(b)

(c)

Figure 4.15 (a) Conductance signatures (12.5 kHz -16 kHz) for various width of the PZT patch, (b) Peak value of the conductance spectrum versus PZT width and (c) Quality factor of the resonance peak versus PZT width.

Figure 4.16 Conductance signatures (12.5 kHz -16 kHz) for various thickness of the PZT patch.

4.4.3 Effect of width of Smart Probe

The influence of the width of the aluminium beam on the conductance signatures is shown in Figure 4.17 (a). It can be seen that the resonance peak depresses and shifts leftwards as the width of the aluminium beam increases. Increasing the width of the aluminium beam has a similar effect as decreasing the width of the PZT (Figure 4.15). This can be further illustrated by plotting the peak magnitude and the quality factor against the beam width (Figure 4.17 (b) and Figure 4.17 (c)).

(a)

(b)

(c)

Figure 4.17 (a) Conductance signatures (13 kHz -15.5 kHz) for various width of the Smart Probe, (b) Peak value of the conductance spectrum versus width of Smart Probe and (c) Quality factor of the resonance peak versus width of Smart Probe.

4.4.4 Effect of bonding position of PZT patch

For optimized application of Smart Probe with given sizes, it is worthwhile to study the effect of the PZT's bonding position on the conductance signatures. To investigate the effect of the PZT position, other parameters were kept the same as those in the experiment. Figure 4.18 shows the variation of the resonance peak as the PZT's bonding position changed. The PZT's position shown in the figure is defined as the relative distance from the cementitious material to the centre of the PZT patch. For instance, 10% denotes that the distance from the cementitious material is 10% of the cantilevered length of the Smart Probe (L_2 in Figure 4.3). As shown in Figure 4.18, as the bonding position moves away from the cementitious material, the peak gets sharper and its magnitude gets higher. The peak magnitude reaches a maximum value when the position is around 70%. However, the peak magnitude declines when the bonding position moves further away.

Figure 4.18 Conductance signatures (13 kHz -15.5 kHz) for various bonding positions of the PZT patch.

4.5 Concluding remarks

This chapter presents a distributed-embedment analytical model for the Smart Probe-based EMI technique. With the distributed stiffness and mass of the embedded segment of the Smart Probe explicitly formulated in the governing equations of motion, this model enables more realistic representation of the dynamic behaviours of the Smart Probe-cementitious material system. A 3D coupled field finite element model is also proposed to predict the conductance signatures of the Smart Probe in cementitious material-curing monitoring process.

The results of the experimental study presented in Chapter 3, which was conducted on a mortar slab specimen monitored for 28 days after casting, are utilized for verification. Both analytical and FE results showed the same trend of movement of the resonance peak as the experiment. With multiple resonance peaks in excellent agreement with the experiment, the FE model yielded more accurate results than the analytical model, as it considered the 3D coupling of the PZT patch and the host structure. On the other hand, the distributed-embedment analytical model has much higher computational efficiency than FEM and is representative of FEM analysis and

experiments. This renders the analytical model a useful tool for speedy parametric study and provides guidelines for optimizing the dimensions of the Smart Probe for application purpose. Effect of various parameters, such as the dynamic modulus and Poisson's ratio of the cementitious material, the sizes and bonding position of the PZT patch and the size of the aluminium beam, on the conductance signatures was studied using the FE and the distributed-embedment analytical modelling.

Chapter 5

Strength development monitoring and dynamic modulus assessment of cementitious materials using EMI-Miniature Prism technique

5.1 Introduction

The traditional resonant frequency test method can be used to non-destructively determine the dynamic modulus of elasticity of concrete. The standard testing procedure of this method is covered in a number of structural design codes or test standards, such as BS 1881-209:1990 (British Standards Institution 1990). The EMI technique also possesses the capability to serve as an alternative approach to evaluating dynamic modulus of elasticity with its distinctive advantage. Previous study showed that the PZT resonance peak is effective in monitoring early age hydration, but not as effective in the later stage. On the other hand, structural peaks have been found to be effective in monitoring the hydration of fresh concrete after 1 day (Lim 2014).

In this chapter, a new EMI technique for determining the dynamic modulus of cementitious materials is proposed. In this technique, a PZT patch is surfaced-bonded on a specially designed specimen of cementitious material, which is termed “Miniature Prism”. This technique ensures consistency of the resonance peaks in the conductance spectrum between specimens, which is very difficult to achieve by the conventional EMI technique. This advantage renders the proposed technique superior to the conventional EMI technique. In addition, combining the EMI technique with FEM analysis, the dynamic modulus of the cementitious materials used to cast the Miniature Prism can be non-destructively determined.

In application, the Miniature Prism specimens will be cast from the same batch of cementitious material as the structural members and together cured on site, so that they all will be under identical curing condition. The strength and modulus of elasticity of the cementitious material in the structure can then be non-destructively assessed. While the Smart Probe is embedded in the structural cementitious material, the Miniature Prism serves as a field-cured specimen. It provides another alternative to the conventional testing methods. Also, compared with the Smart Probe technique, the Miniature Prism is more sensitive to the mechanical property change in the cementitious material as the PZT patch is in direct contact with the cementitious material.

This chapter presents a series of experimental studies and FE numerical simulations to investigate the performance of the proposed technique. A FE model is established to predict the EM conductance signatures. With this model, the dynamic modulus of the cementitious material being monitored is determined from the measured conductance signatures. To verify the effectiveness of the Miniature Prism technique, conventional EMI technique, surface hardness method (rebound hammer test) and Smart Probe technique were also applied in the experiment.

5.2 Experimental study

A batch of mortar mix was prepared with the proportions of water, cement and sand being 0.37:1:2. Specimens were cast using the prepared mortar in the forms of normal prisms, Miniature Prisms, and standard test cylinders. The dimensions of these specimens are listed in

Table 5.1. All specimens were cured under the same curing condition. The temperature was closely monitored and controlled during the electromechanical impedance measurement process.

Table 5.1 Dimensions of different mortar specimens

Specimen type	Dimensions (mm)
Miniature Prism	$250 \times 15 \times 10$
Prism	$500 \times 100 \times 100$
Cylinders	$100(\varnothing) \times 200$

5.2.1 Miniature Prisms

The Miniature Prisms were demoulded after curing for 20 hours. Two PZT patches dimensioned $10 \text{ mm} \times 10 \text{ mm} \times 0.3 \text{ mm}$ were then surface-bonded at the centre of each Miniature Prism (Figure 5.1) using two-part quick set epoxy adhesive. The epoxy was allowed to cure for 2 hours before data acquisition was conducted. The PZT patches surface-bonded on to the two Miniature Prisms were labelled as MP_10-1 and MP_10-2, respectively. While the dimensions of specimen MP_10-1 were precise, the length of MP_10-2 was measured as 251 mm after demoulding, which was probably due to slight manufacturing error of the moulds.

Figure 5.1 Miniature Prism.

5.2.2 Normal-sized prisms and rebound test

A PZT patch dimensioned 30 mm × 30 mm × 1 mm was surface-bonded onto the centre of one of the prisms approximately 6 hours after casting when the mortar started to harden, with no excessive water remained on its surface (Figure 5.2). This PZT patch was labelled as P_30. The prism was demoulded 20 hours after casting. Another PZT patch with dimensions of 10 mm × 10 mm × 0.3 mm was then bonded onto the centre of another surface of the prism (Figure 5.3) and was labelled P_10. The rebound test was conducted on two adjacent faces of this specimen using an Original SCHMIDT hammer (Proceq N – 34), as shown in Figure 5.4. A total of eight different locations were chosen as the impact points which were spaced at least 50 mm apart from each other (Figure 5.5). The test surface at the impact points were smoothed prior to test using the manufacturer-provided grindstone.

Figure 5.2 Prism specimen with surface-bonded PZT patch before demoulding.

Figure 5.3 Prism specimen instrumented with two PZT patches after demoulding.

Figure 5.4 Original SCHMIDT hammer.

Figure 5.5 Schematic representation of impact locations for rebound hammer tests: (a) face bonded with P_30 and (b) face bonded with P_10.

5.2.3 Smart Probe technique

A Smart Probe (as shown in Chapter 3, Figure 3.6) was prefabricated with an aluminium flat bar and a PZT patch, with dimensions of $200 \text{ mm} \times 10 \text{ mm} \times 2 \text{ mm}$ and $10 \text{ mm} \times 10 \text{ mm} \times 0.3 \text{ mm}$, respectively. This Smart Probe was instrumented on another prism specimen and was labelled as PSP-1. During the casting process of the prism specimen, the Smart Probe was partially embedded in the prism from the centre of the top surface (Figure 5.6) with a nominal embedment length of 30 mm. The experimental procedure is essentially the same as that described in Chapter 3 Section 3.5. After the specimen was transported to the temperature controlled laboratory, the mortar was further compacted by tapping its surface so that the Smart Probe was in full contact with the mortar. As to the data acquisition in both the Smart Probe and Miniature Prism techniques, a precision impedance analyser (as shown in Figure 5.7) was utilized to measure the electrical admittance of the PZT transducers with a 2V sinusoidal actuating signal.

Figure 5.6 Prism specimen with a partially embedded Smart Probe.

Figure 5.7 Precision impedance analyser.

5.2.4 Compression test of cylinders

Compression tests of the mortar cylinders were conducted to determine the compressive strength and static elastic modulus of the mortar at various curing ages, using the compression test machine (Figure 5.8). To determine the static modulus of elasticity of the mortar, three linear variable displacement transducers (LVDT) were used as displacement gauges to measure the axial deformation of the cylinder during the process of compression test. The LVDTs were fixed on two metal rings which were rigidly attached to the mortar specimen (See Figure 5.9). The three LVDTs, two of which can be seen in Figure 5.9, were evenly distributed along the circumference of the cylinder with a uniform gauge length of 100 mm. Both the displacement readings from the LVDTs and the applied load output from the compression test machine were recorded continuously using an automatic multi-channel data logger (Figure 5.10). The axial deformation of the cylinder specimen was derived from the average readings of the three LVDTs.

Figure 5.8 Compression test machine with test cylinder in position.

Figure 5.9 Test cylinder instrumented with LVDTs to measure its axial deformation.

Figure 5.10 Automatic multi-channel data logger.

5.3 Numerical simulation

5.3.1 Finite element modelling of the Miniature Prism

FE simulation of the electromechanical behaviour of the mortar Miniature Prism was performed using ANSYS, a general-purpose finite element software. The 3-D FE model of the Miniature Prism is shown in Figure 5.11. Solid5 3-D coupled-field solid element was used to model the PZT patch, and solid45 3-D structural solid element was adopted for the mortar prism. A mesh size of 1 mm was used for both the PZT patch and the mortar prism. Due to symmetry of the geometry and excitation of the Miniature Prism, only one quarter of the system needs to be modelled in the FE simulation. Thus, constraints were applied to the out-of-plane degrees of freedom (DOF) of the nodes on the symmetrical interfaces. Previous studies have shown that the influence of the bonding condition on the resonance frequencies is not significant (Yang et al. 2008a, Lim and Soh 2011). As the resonance frequency is used as the indicator for strength development in this study, the bonding layer was not considered in the FE modelling in this study. Hence, the nodes on the interface between PZT and mortar prism was merged directly, which simulates perfect bonding condition.

The voltage DOF of the top and bottom surfaces of the PZT were coupled, respectively (Figure 5.12). As shown in Figure 5.12, the green lines converge on a

node at the corner, indicating the coupling of the voltage DOF. A 1V sinusoidal voltage was applied to the coupling node on the upper surface of the PZT. Also, the voltage of the coupling node on the bottom surface of the PZT was fixed at 0V. In this manner, simulation of a 1V actuating voltage along the thickness direction of the PZT patch was achieved. The electromechanical harmonic response can be calculated by performing harmonic analysis with full solution method. The value of the electric admittance of the PZT transducer was equal to the complex electric current through the PZT.

Figure 5.11 FE model of the Miniature Prism.

Figure 5.12 Coupling of Voltage DOF of the PZT patch on the Miniature Prism.

5.3.2 Convergence of FEM solutions

The convergence of FE solutions has been discussed by (Yang et al. 2008b). In this section, the convergence issue is investigated with two approaches.

First, the minimum number of elements per wave length needs to be satisfied. Figure 5.13 shows the 10th flexural mode shape of the FE model in ANSYS, the natural frequency of which is about 72.6 kHz, higher than all the frequencies considered in the proposed technique. The wavelength of this mode is about 0.0263 m. The element size of the mesh is 1 mm, corresponding to around 26 elements per wavelength at this frequency. Therefore, this mesh density is considerably higher than the requirement for accurate modelling (Fan and Lowe 2012), which is approximately eight elements per wavelength as recommended by Alleyne et al. (1998).

Second, the accuracy was assessed by performing an analysis on a mesh of smaller elements. The conductance signatures predicted using two meshes with different

element sizes (1 mm and 0.5 mm) for the Miniature Prism MP_10-2 are compared in Figure 5.14. As shown in the figure, the peak positions in the conductance spectra computed by the two meshes with different element sizes are in good agreement, indicating the consistency in the predicted resonance frequencies between the two meshes. Note that the computation time for the 1 mm mesh is between 2 to 3 seconds for each frequency point, for simulations conducted on a personal computer with i7 CPU and 8 GB RAM.

As shown in Figure 5.14, inconsistency in the overall amplitudes of the conductance signatures between the two meshes can also be observed. This can be largely attributed to the fact that a mesh with 1 mm element size may not be fine enough to accurately predict the PZT resonance peaks (Yang et al. 2008b), which occur above 100 kHz. Since resonance frequencies (shown in Figure 5.14), will be used as the index for monitoring, such overall vertical shift of the conductance signatures, however, is not likely to compromise the performance of the proposed technique, as will be demonstrated later. Therefore, a 1 mm mesh would meet the accuracy requirement for predicting the conductance spectra in the frequency range considered in this technique.

Figure 5.13 Flexural mode shape of FE model for the Miniature Prism (isometric view)

Figure 5.14 Conductance signatures versus frequency predicted by FE models with different mesh sizes.

5.4 Characterization of hydration and strength development process

5.4.1 Consistency in conductance signatures between Miniature Prisms

As the two Miniature Prism specimens were cast with the same batch of mortar mix, their electromechanical behaviours should be virtually the same. In particular, the resonance peaks in the conductance spectra acquired from the two specimens should be consistent. The conductance signatures measured from two identical Miniature Prisms, i.e. MP_10-1 and MP_10-2, at the curing age of 1 day are shown in Figure 5.15. It can be seen that the conductance acquired from these two specimens were in fairly good agreement, especially the resonance frequencies, which were indicated by the positions of the peaks. Slight differences can be observed in the amplitudes of the resonance peaks between the two curves. This can be attributed to the variance between the bonding conditions of the two PZT transducers (Yang et al. 2008a). However, this variance has negligible effect on the performance of the proposed technique.

In previous research of curing monitoring using EMI technique, resonance peaks are hardly consistent among identical specimens in terms of both resonance frequency and amplitude. In the proposed technique, this drawback is overcome as the resonance frequencies reflected in the conductance spectra are consistent among specimens. In other words, the resonance frequencies reflect only the electromechanical properties of the specimens, and the influence of the bonding condition on the signatures can be ignored in the proposed technique. This enables determination of the elastic modulus of the cementitious materials from the conductance signatures, with the use of physical model.

Figure 5.15 Consistency in the conductance signatures of MP_10-1 and MP_10-2 (measured at the curing age of 1 day).

5.4.2 Miniature Prism resonance frequency as strength indicator

As proven in previous studies (Lim 2012), the real part of the admittance (conductance) is more sensitive to changes in the structure's mechanical properties than the imaginary part (susceptance). Also, the consistency of the conductance has been shown in the previous section. Thus, conductance signatures of the PZT are used for monitoring the development of the strength and stiffness of the cementitious material in this study.

Figure 5.16 shows the experimental conductance signatures measured from the transducers MP_10-1 and MP_10-2, respectively, throughout the curing process in the frequency range from 3 to 50 kHz. Multiple peaks, which are well separated from each other, in the conductance spectrum can be clearly identified in this frequency range (Figure 5.16). These peaks correspond to the structural vibration modes of the specific Miniature Prism in the experiment. These peaks are therefore referred to as structural peaks. Movement of these peaks can be observed as hydration of the cementitious materials progressed. This pattern generally applies to all the structural

peaks throughout the conductance spectrum. However, the peaks are usually densely spaced when the frequency is higher than 80 kHz, and clearly identifying the peaks may become difficult when comparing different curing states of the specimen. Hence, the structural peaks occurring below 50 kHz are favourable.

The movement of the structural resonance peaks can be seen more clearly in Figure 5.17 and Figure 5.18, which show the shift of the structural peaks of MP_10-1 and MP_10-2, respectively, in the frequency ranges of 9 – 14 kHz and 16 – 22 kHz. As shown in the figures, the resonance peaks shift to the right progressively, which indicates an increase in the resonance frequencies. This is attributed to the gradual stiffening of the cementitious materials throughout the curing process. In other words, the stiffness increase of the cementitious material can be effectively reflected in the movement of the structural resonance peaks, which can be quantified by resonance frequency.

The strength of hardened cementitious materials is closely related to the stiffness (American Concrete Institute 2014). Therefore, the structural resonance frequencies extracted from the conductance peaks can serve as an effective indicator for strength development. Also note that the peaks in Figure 5.17 (a) and (b) correspond to two different structural resonances of MP_10-1. Both these two peaks are effective in monitoring the strength development, showing that multiple peaks of the Miniature Prism can be used for strength monitoring.

(a)

(b)

Figure 5.16 Conductance spectra in the frequency range from 3 to 50 kHz at various curing ages: (a) MP_10-1 and (b) MP_10-2.

(a)

(b)

Figure 5.17 Zoom-in view of the structural resonance peaks of MP_10-1 at various curing ages: (a) 9 – 14 kHz and (b) 16 – 22 kHz.

(a)

(b)

Figure 5.18 Zoom-in view of the structural resonance peaks of MP_10-2 at various curing ages: (a) 9 – 14 kHz and (c) 16 – 22 kHz.

5.5 Determination of dynamic modulus using Miniature Prism

5.5.1 General process of determination of dynamic modulus

The dynamic modulus of elasticity of the mortar is determined through an iteratively updating process. First, an initial value of the dynamic modulus E_{CP} is estimated within a reasonable range. Next, using the initial value in the first step, the conductance signatures of the Miniature Prism in selected frequency ranges are calculated using the established FE model. The resonance frequency (RF) of the Miniature Prism can then be extracted from the peaks in the calculated conductance signatures. The calculated resonance frequency is then compared with the resonance frequency obtained from the experimental conductance signatures. After that, if the calculated frequency is different from the experimental resonance frequency (RF_e), the dynamic modulus is then updated and a new resonance frequency calculated using the updated dynamic modulus can be determined. Finally, the dynamic modulus of the Miniature Prism is determined once the difference between the calculated and experimental frequencies approaches zero. This process is illustrated by the flow chart shown in Figure 5.19.

Figure 5.19 Flow chart for the iteratively updating process of elastic modulus determination using Miniature Prism.

Take curing age of 1 day as an example of modulus determination, in which the dynamic modulus of specimen MP_10-1 was identified as 29.8 GPa. Figure 5.20 compares the conductance signatures computed using FEM with the experimental measurement from specimen MP_10-1 at the curing age of 1 day. In the FE simulation, the Poisson's ratio of the cementitious materials was taken as 0.25 (Swamy 1971, Lim et al. 2016). The density of the cementitious material was measured as 2200 kg/m³.

The FE-predicted conductance and the experimental results are in very good agreement in terms of resonance frequency and peak amplitude. In the frequency range (3 – 40 kHz) shown in Figure 5.20, all the resonance peaks predicted by FE simulation occurred at the same frequencies as the experimental counterpart. The

results of MP_10-2 at the curing age of 28 days are also presented in Figure 5.21, in which good agreement between experimental and numerical results can again be observed. Therefore, one can conclude that the FE model with the updated material properties accurately predicted the electromechanical behaviours of the specimen and its dynamic modulus was thus determined. Note that the discrepancy in the magnitude can be caused by the inaccuracy of the damping ratio, which is difficult to be determined (Yang et al. 2008b).

5.5.2 Selection of resonance peaks

As described in section 5.4.2, structural peaks in the frequency range of 3 – 50 kHz could serve as strength indicator. These peaks could therefore be used for determination of dynamic modulus. In general, peaks in higher frequency range would have higher sensitivity to the change in structural properties. However, more resonances would be excited, and peaks tend to overlap each other in the higher frequency range above 80 kHz, which makes it difficult to identify the corresponding peak in various monitoring stages. One particular peak in moderate frequency range (25 – 35 kHz) was selected for strength development monitoring and dynamic modulus determination in this study. In this frequency range, the peak is sufficiently sensitive to change in structural stiffness and the adjacent resonance peaks are well separated from each other allowing ease of peak identification.

5.5.3 Identified dynamic modulus

Figure 5.22 (a) shows the conductance signatures computed from the FE model of MP_10-1 with increasing dynamic modulus for the selected resonance peak. As shown in the figure, the resonance peak shift to the right as the dynamic modulus is elevated, indicating an increase in resonance frequency, which is in accordance with the experimental results (Figure 5.22 (b)). As the resonance frequencies (reflected as peak positions) in Figure 5.22 (a) match with those in Figure 5.22 (b) one by one, the values of the modulus shown in the legend of Figure 5.22 (a) correspond to the curing ages shown in Figure 5.22 (b). In other words, the dynamic modulus of the cementitious material at various ages were determined in this manner. For example,

the dynamic modulus of MP_10-1 at the curing age of 1 day was predicted as 29.8 GPa (denoted by solid line in Figure 5.22 (a)).

The above-mentioned procedure for determining the dynamic modulus was applied to specimen MP_10-2 as well. Table 5.2 lists the experimental resonant frequencies for the selected peak, the FE simulated resonant frequencies and the predicted dynamic modulus of the cementitious materials at various curing ages. The dynamic modulus takes the average of the two specimens.

Table 5.2 Resonance Frequency of Miniature Prism and identified dynamic modulus

Day	Experimental Resonance Frequency (kHz)		Numerical Resonance Frequency (kHz)		Dynamic Modulus (GPa)
	MP_10-1	MP_10-2	MP_10-1	MP_10-2	
1	26.04	25.92	26.04	25.92	29.85
2	27.42	27.22	27.44	27.22	33.05
3	28.08	27.88	28.04	27.86	34.6
7	28.92	28.6	28.92	28.58	36.6
14	29.56	29.2	29.54	29.2	38.2
28	30.08	29.72	30.1	29.74	39.65

Figure 5.20 Comparison of conductance signatures versus frequency (3 – 40 kHz) between FE simulation and experimental measurement for specimen MP_10-1 at the curing age of 1 day.

Figure 5.21 Comparison of conductance signatures versus frequency (3 – 40 kHz) between FE simulation and experimental measurement for specimen MP_10-2 at the curing age of 28 days.

(a)

(b)

Figure 5.22 Conductance signatures versus frequency (25 – 31 kHz) plot of MP_10-1 for the selected resonance peak: (a) computed from the FE model with increasing dynamic modulus and (b) measured at different ages throughout the curing process in the experiment.

The relation between FE-computed resonance frequency and dynamic modulus, and the relation between experimental resonance frequency and curing time, are presented in Figure 5.23 and Figure 5.24, respectively. For a certain frequency in both charts, there would be a corresponding value of the dynamic modulus and a corresponding curing time, respectively. The dynamic modulus at various curing ages were predicted using this relationship.

From Figure 5.23 and Figure 5.24, it can be observed that the frequencies of the two specimens were slightly different. This could be attributed to the fact that the length of MP_10-2 is greater than MP_10-1 by 1 mm, as mentioned in the section of experimental setup. According to vibration theory, greater length would lead to lower resonance frequency, which is consistent with our experimental observation.

Figure 5.25 presents the relation between curing time and the dynamic modulus of the cementitious material predicted by the Miniature Prism technique. Apparently, the dynamic modulus of elasticity of the cementitious material increased rapidly during the first 7 days. Results show that the cementitious material gained approximately 92% of its modulus (as compared with the age of 28 days) after curing for 7 days, which complies with the results of previous studies (Lim et al. 2016). The increase in the dynamic modulus of elasticity was particularly fast in the first day (reached 75% of the 28-day modulus), suggesting a high hydration rate.

Figure 5.23 FE-simulated resonance frequency for different dynamic modulus.

Figure 5.24 Resonance frequency extracted from experiment at different curing time.

Figure 5.25 Dynamic modulus on different curing days predicted by Miniature Prism.

5.5.4 Determination of dynamic modulus through linear extrapolation

Generally, the resonance frequency of a structure is not expected to be linearly related to the modulus. However, the results shown in Figure 5.23 shows that the resonance frequency of the selected peak and the dynamic modulus exhibit a linear relationship in the range of modulus (approximately 29 – 40 GPa) studied.

This feature could be particularly advantageous as it adds convenience to the application of the EMI monitoring technique. That is, once a resonance frequency is obtained from the acquired conductance at any time during the monitoring process, the dynamic modulus of the cementitious material can be determined by conducting linear extrapolation. For example, suppose two set of data have been recorded at the curing ages of 20 hours and 30 hours, and the corresponding dynamic modulus have been determined using the numerical EMI model, respectively. Then, once another set of data is measured at the age of 3 days, the dynamic modulus at the age of 3 days can be determined expediently by performing linear extrapolation using the data acquired at 20 hours and 30 hours.

Note that although a linear relation between the resonance frequency and the modulus was observed in this study, this relation could be influenced by the mix proportion and the shape and size of the Miniature Prism. Therefore, a large number of experimentally calibrated data must be obtained before real-life application becomes practical.

5.6 Strength estimation

5.6.1 Miniature Prism based semi-empirical model for strength estimation of cementitious materials

The compressive strength of cementitious material is closely correlated to the modulus of elasticity, although no analytical relationship has been proposed. ACI 318-14 (American Concrete Institute 2014) suggests an empirical relationship in which the modulus of elasticity is linearly related to the square root of the compressive strength. Adopting this relation, the dynamic modulus of elasticity determined by the Miniature Prism can be correlated to the compressive strength using the following equation:

$$E_d = \eta_M \sqrt{f_{cu}}, \quad (5-1)$$

where E_d is the dynamic modulus of elasticity, f_{cu} is the compressive strength and η_M is the proportional coefficient.

The dynamic modulus determined by the Miniature Prisms were plotted against the square root of compressive strength obtained through compression test at various curing ages, as shown in Figure 5.26. The coefficient η_M was determined by performing linear least square curve fitting to the data. The proportional coefficient η_M was found to be 4.67 in this study when f_{cu} is in MPa and E_d is in GPa. Note that η_M may be influence by types of cement and types of aggregates (Lim et al. 2016).

As the coefficient η_M is determined, a calibration chart can be generated using the FE model, which can be used to conveniently estimate the compressive strength of the cementitious material from resonance frequency (Figure 5.27).

Figure 5.26 Correlation between square root of compressive strength and the dynamic modulus predicted by Miniature Prism.

Figure 5.27 Compressive strength estimation from resonance frequency of Miniature Prism based on FE numerical model.

5.6.2 Pure empirical approach

It is also possible to establish a pure empirical relation between the resonance frequency of the selected peak and the compressive strength with a good number of experimental results. In this study, the development of such a relation was attempted with a second degree polynomial function which was fitted to the experimental data, as presented in Figure 5.28. From the experimental results, the empirical relation between compressive strength and the resonance frequency can be expressed as

$$f_{cu} = 0.1321f_r^2 - 0.5839f_r - 32.238 \quad (5-2)$$

where f_{cu} is the compressive strength and f_r denotes the resonance frequency.

As can be seen in Figure 5.28, more data points are required to cover different ranges of the compressive strength, so that higher level of confidence on the empirical model can be achieved. In other words, a large number of experiments are required even for one particular mix proportion. Thus, the semi-empirical model (section 5.6.1), which

is easy to be applied in application, could be a good alternative to pure empirical relations established from experiments.

Figure 5.28 Compressive strength versus resonance frequency extracted from a selected experimental conductance peak of Miniature Prism.

5.7 Comparative study

5.7.1 Static modulus measured from compression test

LVDTs were used to measure and record the axial displacement of the cylinder specimens during the compression tests, based on which the longitudinal strain of the specimens was calculated. Figure 5.29 shows a typical stress-strain curve of the mortar specimen in the experiments. As shown in the figure, a straight line can be observed during the initial loading stage, indicating an approximate linear relationship between the stress and strain of the cementitious material when subjected to low stress. The point on the stress-strain curve corresponding to 30% of the

ultimate stress (at that curing age) was used to calculate the static modulus of the specimen.

To verify the performance of modulus prediction of the Miniature Prism, the static moduli obtained from compression test were plot against the dynamic moduli predicted by the Miniature Prism based EMI technique at various curing age (solid square in Figure 5.30). As shown in the figure, the static modulus increases as the dynamic modulus increases, showing strong positive correlation between the two variables.

Though no definite relation between the dynamic modulus of elasticity and the static modulus has been established to date, a number of empirical relations, which are valid over a certain range, have been proposed. An expression recommended by BS 8110-2:1985 (British Standards Institution 1985) is

$$E_c = 1.25E_d - 19 \quad (5-3)$$

where E_c is the static modulus (secant modulus) of elasticity and E_d is the dynamic modulus. This expression, however, is not valid for light weight concrete and concrete in which cement content is above 500 kg/m³. For light weight concrete, Swamy and Bandyopadhyay (1975) proposed an expression as

$$E_c = 1.04E_d - 4.1 \quad (5-4)$$

Popovics (1975) suggested that the relationship between the static modulus and dynamic modulus should be dependent on the density of the concrete and the relationship can be written as

$$E_c = \frac{k_p E_d^{1.4}}{\rho_c} \quad (5-5)$$

Given a particular dynamic modulus value, the corresponding static modulus can be estimated using Equations (5-3) to (5-5). The relation between the Miniature Prism-predicted dynamic modulus and the static modulus measured through compression

tests is compared with those relations recommended by previous studies (Equations (5-3) to (5-5)), as shown in Figure 5.30. It can be observed in the figure that the experimental results agreed well with the estimations based on the relations proposed by Swamy (Equation (5-4)) and Popovics (Equation (5-5)). This shows the effectiveness and validity of the proposed Miniature Prism technique in determining the dynamic modulus and subsequently estimating the static modulus of cementitious materials.

Note that the experimental results deviated from the estimations by BS 8110-2:1985. This can be attributed to the fact that the cementitious material used in the experimental study contained a cement content of more than 700 kg/m^3 , which Equation (5-3) does not apply to. Since various empirical models have been suggested for the relation between dynamic and static modulus, it can be conceivable that the relation should depend on the mix proportion, types of cement and types of aggregates used. Therefore, it is recommended that extensive experimental investigation on the relation between the static modulus and the dynamic modulus predicted by Miniature Prism be carefully conducted before real-life application becomes possible. Calibration of the technique in relating the static and dynamic modulus may be required for different mix proportions, and even for the concrete in each construction project.

Figure 5.29 Stress-strain curve of a mortar cylinder specimen in compression at the curing age of 1 day.

Figure 5.30 Comparison of static versus dynamic modulus of elasticity plot between experimental results and prediction by empirical models.

5.7.2 Dynamic modulus prediction using Smart Probe

Figure 5.31 (a) presents the conductance signatures acquired from the Smart Probe PSP-1 throughout the curing process of the cementitious material. The resonance peak (occurring at 16.07 kHz after 1 day) shifted to the right in the conductance spectrum, indicating a progressive increase in the resonance frequency of the embedded Smart Probe which resulted from the growth of the stiffness of the cementitious material. It can be seen that the movement trend of the conductance signatures acquired from Smart Probe is the same as the Miniature Prisms, demonstrating that both techniques are effective in curing monitoring of cementitious materials.

To predict the dynamic modulus, the analytical model for Smart Probe (Chapter 3) was used to calculate the conductance spectra for various values of the dynamic modulus. The conductance peaks calculated for increasing dynamic modulus are shown in Figure 5.31 (b), which correspond to different curing ages of the cementitious material.

(a)

(b)

Figure 5.31 Conductance signatures versus frequency (15.7 – 16.5 kHz) plot of PSP-1: (a) measured at different ages throughout the curing process in the experiment and (b) computed using analytical model with increasing dynamic modulus.

5.7.3 Strength estimation using rebound hammer test

In rebound test, the rebound value R was measured using an Original SCHMIDT rebound hammer. The impact direction of the device was vertically downwards, meaning the specimen was subjected to the impact from its top surface. Making use of the conversion curves provided by the manufacturer (Figure 5.32), the rebound value R can be converted to an estimated strength. Table 5.3 summarises the rebound value R and the estimated strength at different curing ages in the experiment.

Table 5.3 Compressive strength of cementitious material estimated by rebound test

Day	Rebound value R	Estimated strength (N/mm ²)
1	30.5	24.4
2	46	36.8
3	50.3	40.24
4	53	42.4
7	54.7	43.76
14	51.6	41.28
28	54.3	43.44

Figure 5.32 Strength conversion curves for SCHMIDT hammer.

5.7.4 Comparison of strength prediction

Figure 5.33 presents the comparison between the strength predicted by Miniature Prism technique, Smart Probe technique and rebound test, and the compressive strength determined from compression test of cylinder specimens. As shown in the figure, the results of all three strength estimation techniques show the same trend as

those of the compression test. Particularly, results from the Miniature Prism technique are in good agreement with the compression test results.

The strength predicted by rebound hammer test is essentially lower than that of the compression test. This could be attributed to the fact that the strength value of the conversion curve for the rebound hammer is close to the lower bound of the test results used to derive the conversion curve. This generally ensures conservative estimation of the actual strength by adding safety margin to the evaluation. Another fact to be considered is that micro damage may be accumulated near the surface of the prism specimen with multiple impacts from the hammer during the curing monitoring process in the experiment.

Figure 5.33 Comparison between compressive strength obtained via various techniques at different curing time.

5.7.5 Conventional EMI technique with surface-bonded PZT

For comparison purpose, conventional EMI technique, which makes use of the resonance peak of the PZT patch itself, was also employed to monitor the curing process of the cementitious material in the experiment. Conventional EMI analysis was performed on both the Miniature Prism and normal-sized prism specimens.

Figure 5.34 shows the conductance spectrum in the frequency range 50 – 75 kHz (first resonance of the PZT patch) measured from P_30 (Figure 5.3) at different curing ages. With careful examination of the conductance signatures, it can be observed that the resonance peak generally shifted to the right as hydration progressed. However, as a number of small peaks (structural peaks) exist on top of the PZT resonance peak, the movement of the PZT resonance peak becomes vague. Results from the other PZT patch (P_10) bonded on the same mortar specimen, on the other hand, shows more consistent rightward movement of the PZT resonance peak, as shown in Figure 5.35. This rightward shift of the first resonance peak indicates the cementitious material was undergoing a stiffening process (Soh and Bhalla 2005, Bhalla et al. 2012, Lim 2014).

Figure 5.34 Conductance versus frequency (50 – 75 kHz) acquired from PZT patch P_30 at different curing ages.

Figure 5.35 Conductance versus frequency (100 – 350 kHz) acquired from PZT patch P_10 at different curing ages.

One can observe that the first resonance of P_10, occurring approximately at 220 kHz on day 1 (Figure 5.35), is considerably higher than that of P_30 (at approximately 62 kHz on day 1, shown in Figure 5.34). This is consistent with the inherent vibrational properties of the PZT transducers, i.e. the larger transducer has a lower first resonance frequency.

Comparison between results shown in Figure 5.34 and Figure 5.35 also suggests that the smaller PZT transducer P_10 (10 mm sized) is more sensitive to the change in the stiffness of the host structure (i.e. the mortar prism in this experiment) than the larger transducer P_30. The insensitivity of P_30 could be attributed to the fact that the dynamic properties of the transducer itself can be dominant in the conductance spectrum, as the size of P_30 is significantly larger than P_10. The dominance of the PZT transducer could inhibit the stiffening of the cementitious material from being reflected in the conductance spectrum acquired from the transducer.

The most critical drawback of the technique is that, in most cases, consistency of the PZT resonance peak could not be achieved between transducers. This is due to the fact that PZT resonance peaks are more susceptible to bonding conditions. Additionally, in some cases (such as the one shown in Figure 5.34), overlapping of structural peaks, and superposition of structural peaks and the PZT resonance peak makes it challenging to extract the PZT resonance frequency. This, in turn, renders obtaining consistency between transducers more difficult.

To further illustrate the above-mentioned inconsistency, the traditional EMI technique was also applied to the two identical Miniature Prism specimens utilizing the same PZT patches. Figure 5.36 presents the conductance spectrum (50 – 350 kHz) acquired from different PZTs bonded on Miniature Prism specimens on the same curing days. As shown in the figures, on both day 7 and day 28, the conductance signatures are inconsistent between the two transducers (MP_10-1 and MP_10-2), in terms of both resonance frequency and amplitude.

(a)

(b)

Figure 5.36 Conductance versus frequency (50 – 350 kHz) acquired from PZT patches MP_10-1 and MP_10-2 at curing ages of: (a) 7 days and (b) 28 days.

The traditional EMI technique employing the PZT resonance is able to monitor strength development of cementitious materials. It is also able to quantify the strength gain by introducing statistical metrics such as root mean square deviation (RMSD). However, on account of the drawback of the traditional approach, it would be difficult to define an index that could be associated with a valid physical model containing mechanical parameters of the cementitious material. This hinders the technique from being generalized.

Therefore, the proposed Miniature Prism technique is a superior approach in terms of providing parametric estimation of the mechanical properties of cementitious materials. Nevertheless, the conventional EMI technique can also serve as complement, since it is still effective in monitoring early age hydration before structural peaks become sufficiently identifiable.

5.8 Concluding remarks

This chapter presents the development of Miniature Prism based EMI technique for strength development monitoring of cementitious materials. Experimental results showed that, using the developed FE numerical model, this technique is capable of determining the dynamic modulus of elasticity of the cementitious material. The compressive strength of the cementitious material can be estimated by employing the empirical relation between the compressive strength and the modulus of elasticity, which is recommended in ACI 318. Comparative study showed that the technique is comparable to the traditional rebound test in estimating the compressive strength.

The proposed technique significantly improves the traditional EMI technique, as consistency of measured signals between transducers is achieved. This enables parametric estimation of the mechanical properties of cementitious materials.

In addition, the proposed Miniature Prism based EMI technique has remarkable advantage over the traditional methods for dynamic modulus determination, such as resonant frequency method, in terms of operability during testing. The technique can

be applied in an autonomous and real-time monitoring system with minimal human involvement. The technique is also expected to exhibit higher repeatability of measurement than the traditional resonant frequency method, as the PZT transducer is permanently mounted at the same location.

Chapter 6

Conclusions and future work

Real-time monitoring of the curing process and consequent strength development of concrete is highly desirable as it could improve the safety and efficiency of construction process by assessing the capacity of the newly constructed members. Additionally, it can potentially reduce the cost of construction by suggesting suitable time for formwork removal.

As the main originality of this thesis, a novel approach, “Smart Probe”, employing the principle of EMI is proposed for parametric evaluation of the mechanical properties of cementitious materials, in particular the dynamic modulus and compressive strength, which has not been achieved in existing studies using the EMI technique. By my proposed novel approaches to overcome the key limitations of the traditional approaches, and by my developed parametric physical models (analytical and numerical) to predict the electromechanical response of the PZT transducers, this study opens a new path for development of more effective strength monitoring techniques for concrete structures.

6.1 Conclusions

The conclusions of this study are:

- a. The structural resonance peaks in the conductance spectra measured in the frequency range of 5 – 40 kHz were well consistent among identical Smart Probes embedded in the same early age mortar specimen. This overcomes one of the key limitations of the conventional EMI based concrete strength monitoring technique with direct surface bonded PZT transducer, in which

the measured conductance signatures are highly sensitive to the bonding condition which is nearly intractable in practice.

- b. Results of the experiment conducted on a mortar slab specimen showed that multiple structural resonance peaks in the conductance spectrum (5 – 30 kHz) of the embedded Smart Probe can be effective in monitoring the strength development of the mortar. It was found that the structural resonance frequencies (positions of the structural resonance peaks) extracted from the measured conductance spectrum can serve as a good indicator of the modulus and strength of the cementitious material. Typically, as the strength and hardness of the cementitious material increased in the curing process, the structural resonance peak of the Smart Probe shifted to the right, implying an increase in the resonance frequency.
- c. One distinct feature of the Smart Probe is that it is embedded at the final stage of casting, hence does not require to wait for the cementitious material to set before mounting transducers. This enables very-early-age (refers to a curing age less than 12 hours) monitoring of cementitious materials and characterization of the corresponding hydration process. In the experimental study, it was found that no apparent resonance peaks could be observed between the curing ages of 1 hour and 5 hours, implying that the initial setting occurred at approximately 1 hour, and 5 hours might correspond to the final setting time of the cementitious material.
- d. A simplified analytical model for the embedded Smart Probe was developed for dynamic modulus identification and strength development monitoring of cementitious materials during the curing process. In this model, the cementitious material was modelled as an equivalent Winkler foundation where the foundation constant was dependent on the modulus of the cementitious material. Analytical expression of the conductance signatures of the smart probe was derived. The dynamic modulus of the cementitious material was predicted by matching the model-calculated resonance frequency with the experimental resonance frequency (occurring between 14

- 15 kHz in this study). Strength estimation was achieved by establishing the empirical relation, which is adopted by prevailing structural design codes, between the predicted dynamic modulus and the cylinder-tested compressive strength. With the availability of the parametric model, the proposed technique need not rely on statistical tools for quantification of the mechanical properties of cementitious material, which is the common approach in the traditional impedance based technique.
- e. A 3-D coupled field FE model was established for the simulation of the Smart Probe-cementitious material interaction. The FE-computed conductance signatures agreed very well with the experimental results in terms of number of structural resonance peaks that appeared and the structural resonance frequencies, showing that the simulation was successful. A distributed-embedment analytical model for the Smart Probe-based EMI technique was developed, which explicitly formulate the distributed stiffness and mass of the embedded segment of the Smart Probe in the equations of motion. Both models demonstrated their effectiveness in characterizing the strength development of cementitious materials using the structural resonance peaks in the conductance spectra. Parametric study of the Smart Probe using both models indicated that the effect of Poisson's ratio on the structural resonance frequency (in the range of 14 – 15 kHz) could be limited when compared with that of dynamic modulus.
- f. An EMI based technique using surface-bonded PZT transducers for strength development monitoring of cementitious materials was developed by introducing the concept of Miniature Prism. This EMI based technique, unlike its conventional counterpart, employs the structural resonance peaks of the Miniature Prism for monitoring. The structural resonance peaks in the conductance signatures experimentally measured from the Miniature Prism were in good agreement with the predictions by the 3-D coupled field FE simulation. In the FEM analysis, a uniform mesh size of 1 mm is adequate to simulate the structural resonances (frequency range 19 – 33 kHz) for the particular Miniature Prism used in this study.

- g. It was found that the Miniature Prism technique was capable of determining the dynamic modulus of the cementitious material by matching the FE predicted structural resonance frequency with the experimental measurement. The predicted dynamic modulus was well-correlated with the compressive strength. Strength estimation of the cementitious material could be made based on this correlation.
- h. The relationship between the dynamic modulus, predicted by the Miniature Prism technique, and the static modulus, measured from standard test cylinders in compression test, was in reasonably good agreement with the relations proposed by other researchers. This shows the effectiveness of the technique in determining the dynamic modulus of cementitious materials.
- i. Consistency of experimentally measured conductance signatures between identical specimens was achieved in the Miniature Prism based technique, implying its superiority over the traditional EMI technique in terms of parametric modelling. Comparative experiments conducted on Miniature Prism specimens and the normal-sized prism specimen further demonstrated the inconsistency of the conductance signatures obtained by the traditional EMI technique.
- j. Although the Miniature Prism technique uses similar principle as the standard resonant frequency method to determine the dynamic modulus, it is expected to yield more reliable results and possesses higher repeatability as the PZT transducer is permanently bonded on the specimen. In addition, taking into consideration the simplicity of operation (transducer installation and data acquisition) of the technique, it has better capability to provide real-time and autonomous monitoring of modulus development of fresh cementitious materials.

6.2 Future work

Future studies can be carried out in the following aspects.

- a) In general, concrete contains a large proportion of coarse aggregates that make the material non-homogeneous. To extend the application of the proposed Smart Probe, the performance of the technique should be tested on concrete specimens with coarse aggregates in future investigations. Also, the analytical model may need to be further modified to account for the effect of coarse aggregates.
- b) It is known that the quality and mechanical properties of concrete is significantly influenced by the mix proportions. In particular, the compressive strength is mainly controlled by the water-cement ratio. Hence, it is recommended that the performance of the Smart Probe technique be tested on concrete specimens of different mix proportions, varying water-cement ratio and with different types and sizes of coarse and fine aggregates. Particularly, the effect of concrete with various compressive strength on the frequency shift of identical Smart Probes should be investigated. Correction factors and calibration charts ought to be generated by conducting sufficient numbers of experimental calibrations, such that the results predicted by the technique can lie within certain levels of confidence.
- c) Due to the weak tensile strength of concrete, reinforcing steel bars (or rebar) are widely used with plain concrete to form a composite material, reinforced concrete. When a sinusoidal voltage is applied on the PZT transducer of the Smart Probe, ultrasonic standing waves will be excited in the concrete specimen. The existence of reinforcing bars could alter the elastic properties of the specimen or structure, and subsequently the propagation of the ultrasonic waves. The signals measured from the Smart Probe would hence be “contaminated” by the reinforcing bars. Nonetheless, it would be reasonable to expect that the Smart Probe will still be able to detect the development of the strength of reinforced concrete. Investigating the effect of

reinforcing bars on the conductance signatures of Smart Probe for concrete strength monitoring brings the technique closer to real-life application.

- d) Continued strength development of concrete relies on proper curing. The curing process requires sufficient amount of moisture content in the fresh concrete for a specified period of time (Mamlouk and Zaniewski 2011). If the relative humidity inside the concrete falls below 80%, hydration is very limited and strength gain stops (Neville 2011). Furthermore, shrinkage of concrete occurs when moisture content is not sufficient. Shrinkage of concrete could potentially have influence on the performance of the Smart Probe by changing the mechanical behaviour of the coupled system. Since ideal curing condition may not be always guaranteed in most practical situations, it's important to investigate the effect of concrete shrinkage. Compensation method for this factor is worth studying as well.
- e) As mentioned earlier in the Conclusions, the Smart Probe is able to perform monitoring of fresh concrete immediately after casting. Since the EMI based technique possesses high sensitivity to the structural conditions, the fluidity and plasticity of the cement paste can be characterized using the Smart Probe technique. More works can be conducted to explore this special capability of the Smart Probe. The author believes that it has promising potentials for practical applications, such as cold joint prevention.
- f) The sensitivity of the particular Smart Probe used in the experimental study is generally lower than that of surface bonded PZT transducers. Therefore, the effects of various geometries and material properties, and the embedment length of the Smart Probe is worth exploring in future studies. This can potentially improve the monitoring results, in particular, the amount of frequency shift induced by strength development. In addition, the effects of different dimensions of Smart Probe and PZT patch, and the position of the PZT patch etc. should also be investigated with more comprehensive experiments to optimize the Smart Probes for real-life application.

- g) As the resonance peaks in the conductance signatures correspond to the vibration modes of the Smart Probe, the motion of the PZT patch at resonance frequencies is largely governed by the mode shapes. Hence a particular mode shape of the Smart Probe significantly influences the EM response of the PZT at the corresponding structural resonance frequency. Attempting to establish the relation between the mode shapes and the EM response of the PZT is a noteworthy issue for future research. This can provide better understanding of the influence of the different parameters of the smart probe (geometry, PZT dimensions and position) on the conductance signatures.
- h) Cementitious material paste is alkaline with pH of up to 13. When the aluminium-based Smart Probe is embedded in the fresh cementitious material, the high-pH alkalinity may attack the aluminium surface during the initial stage of contact, but a protective film may also develop during this process to prevent further corrosion (Walton et al. 1957). This layer of corrosion protective film is limited to the surface of the aluminium, thus its influence on the electromechanical behaviour of the coupled system is neglected in this study. However, in certain situations, the corrosion of aluminium in contact with cementitious materials may be prolonged and serious. Therefore, it would be useful to determine other suitable material for the fabrication of Smart Probe.
- i) In this study, it was found that the 3-D FE simulation yielded more accurate results than the analytical model. However, the computational efficiency of the FE simulation was extremely low, which is impractical for online monitoring purpose. Thus, further research to investigate the possibility of incorporating more factors in the analytical model, such as considering the shear and rotation effect of the Smart Probe by adopting the Timoshenko beam model and taking the thickness mode into account is recommended.
- j) Note that the investigation on the Miniature Prism in Chapter 5 should be regarded as a feasibility and proof-of-concept study, in which the dimensions of the Miniature Prism specimens were only large enough for aggregates with

a maximum size of 2 mm ($1/5$ of the smallest dimension). Future study should investigate the application of the technique to larger specimens to accommodate coarse aggregates.

- k) No analytical model has been developed for the Miniature Prism in this study. This could be attributed to the fact that Euler beam theory, which is adopted for Smart Probe, applies only to thin beams and it is not practical to cast a thin miniature prism of cementitious material. The current study made use of 3-D coupled field FE simulation to predict the electromechanical response of the Miniature Prism. However, the computational cost of this modelling approach could be too high for practical online monitoring purpose, especially for large size specimens. In future studies, several possible approaches to more computationally efficient modelling should be attempted, which include analytical modelling of the Miniature Prism with Timoshenko beam theory, modelling with semi-analytical methods and with other approximate solution methods.
- l) It is known that the behaviours of piezoelectric materials are influenced by temperature variations to a certain extent. Behaviours of cementitious materials and aluminium might be affected by the ambient humidity. In this study, all the experiments were carried out in a temperature controlled laboratory and the humidity can be considered negligible. The effects of temperature and humidity on the results of concrete strength development monitoring using both the Smart Probe and the Miniature Prism are thus worth investigating. Temperature and humidity compensation coefficients can be determined from experimental studies.
- m) The frequency equations of the analytical models, in Chapter 3 and 4, for example Equation (3-39), are transcendental equations. So these equations were solved numerically to obtain the natural frequencies. It is known that numerical errors might accumulate in subsequent calculations and affect the ultimate results. Further research may investigate the effect of the accuracy of the numerical solutions of these equations on the conductance signatures.

References

Abe M., Park G. and Inman D. J. (2000). Impedance-based monitoring of stress in thin structural members. ELEVENTH INTERNATIONAL CONFERENCE ON ADAPTIVE STRUCTURES AND TECHNOLOGY. Nagoya, Japan: 285.

Alleyne D. N., Lowe M. J. S. and Cawley P. (1998) "The Reflection of Guided Waves From Circumferential Notches in Pipes." Journal of Applied Mechanics, Vol. 65, No. 3, pp. 635-641.

American Concrete Institute (2014). Building code requirements for structural concrete (ACI 318-14) and commentary. Farmington Hills, MI, American Concrete Institute.

Annamdas V. and Rizzo P. (2010) "Monitoring concrete by means of embedded electromechanical impedance sensors." Proceedings of SPIE, sensors and smart structures technologies for civil, mechanical, and aerospace systems, No., pp. 7647-7671.

Annamdas V. G. and Radhika M. A. (2013) "Electromechanical impedance of piezoelectric transducers for monitoring metallic and non-metallic structures: A review of wired, wireless and energy-harvesting methods." Journal of Intelligent Material Systems and Structures, Vol. 24, No. 9, pp. 1019 - 1040.

Annamdas V. G. M. (2007) "Characterization of smart PZT transducer and admittance signatures using PZT-structure interaction models for structural health monitoring". Ph.D Thesis, Nanyang Technological University.

Annamdas V. G. M., Bhalla S. and Soh C. K. (2017) "Applications of structural health monitoring technology in Asia." Structural Health Monitoring, Vol. 16, No. 3, pp. 324-346.

Annamdas V. G. M., Radhika M. A. and Soh C. K. (2009) Health monitoring of concrete structures using embedded PZT transducers based electromechanical impedance model. Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, pp. 729225-729229.

Annamdas V. G. M. and Soh C. K. (2007a) "Three-Dimensional Electromechanical Impedance Model. I: Formulation of Directional Sum Impedance." Journal of Aerospace Engineering, Vol. 20, No. 1, pp. 53-62.

Annamdas V. G. M. and Soh C. K. (2007b) "Three-Dimensional Electromechanical Impedance Model. II: Damage Analysis and PZT Characterization." Journal of Aerospace Engineering, Vol. 20, No. 1, pp. 63-71.

Annamdas V. G. M. and Soh C. K. (2008) "Three-Dimensional Electromechanical Impedance Model for Multiple Piezoceramic Transducers and Structure Interaction." Journal of Aerospace Engineering, Vol. 21, No. 1, pp. 35-44.

Annamdas V. G. M., Yang Y. and Soh C. K. (2007) "Influence of loading on the electromechanical admittance of piezoceramic transducers." Smart Materials and Structures, Vol. 16, No. 5, pp. 1888.

Annamdas V. G. M. and Yang Y. W. (2012) "Practical implementation of piezo-impedance sensors in monitoring of excavation support structures." Structural Control & Health Monitoring, Vol. 19, No. 2, pp. 231-245.

Ayres J. W., Lalande F., Chaudhry Z. and Rogers C. A. (1998) "Qualitative impedance-based health monitoring of civil infrastructures." Smart Materials and Structures, Vol. 7, No. 5, pp. 599.

Bhalla S., Annamdas V. G. M. and Soh C. K. (2012). Strength and Damage Assessment of Concrete. Smart Materials in Structural Health Monitoring, Control and Biomechanics. Berlin, Heidelberg, Springer Berlin Heidelberg: 187-221.

Bhalla S. and Soh C. K. (2003) "Structural impedance based damage diagnosis by piezo-transducers." Earthquake Engineering & Structural Dynamics, Vol. 32, No. 12, pp. 1897-1916.

Bhalla S. and Soh C. K. (2004a) "Electromechanical impedance modeling for adhesively bonded piezo-transducers." Journal of Intelligent Material Systems and Structures, Vol. 15, No. 12, pp. 955-972.

Bhalla S. and Soh C. K. (2004b) "Structural health monitoring by piezo-impedance transducers. I: Modeling." Journal of Aerospace Engineering, Vol. 17, No. 4, pp. 154-165.

Bhalla S. and Soh C. K. (2004c) "Structural Health Monitoring by Piezo-Impedance Transducers. II Applications." Journal of Aerospace Engineering, Vol. 17, No. 4, pp. 166-175.

Boresi A. P., Schmidt R. J. and Sidebottom O. M. (1993), Advanced mechanics of materials, Wiley New York.

Bottega W. J. (2014), Engineering vibrations, CRC Press.

British Standards Institution (1985). BS 8110-2:1985. Structural use of concrete. Code of practice for special circumstances. Chiswick High Road, London, British Standards Institution.

British Standards Institution (1990). BS 1881-209:1990. Testing concrete. Recommendations for the measurement of dynamic modulus of elasticity. Chiswick High Road, London, British Standards Institution.

Bungey J. H., Grantham M. G. and Millard S. (2006), Testing of concrete in structures, Crc Press.

Campeiro L. M., Silveira R. Z. d. and Baptista F. G. (2017) "Impedance-based damage detection under noise and vibration effects." Structural Health Monitoring, Vol. 0, No. 0, pp. 1475921717715240.

Chaudhry Z., Lalande F., Ganino A., Rogers C. and Chung J. (1995a). Monitoring the integrity of composite patch structural repair via piezoelectric actuators/sensors. 36th Structures, Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics.

Chaudhry Z. A., Joseph T., Sun F. P. and Rogers C. A. (1995b) Local-area health monitoring of aircraft via piezoelectric actuator/sensor patches. Smart Structures and Materials '95, San Diego, CA, United States, pp. 9.

Cheng C. C. and Lin C. C. (2005) "An impedance approach for vibration response synthesis using multiple PZT actuators." Sensors and Actuators A: Physical, Vol. 118, No. 1, pp. 116-126.

Chopra A. K. (2012), Dynamics of structures : theory and applications to earthquake engineering, Boston : Prentice Hall.

Crawley E. F. and De Luis J. (1987) "Use of piezoelectric actuators as elements of intelligent structures." AIAA journal, Vol. 25, No. 10, pp. 1373-1385.

Dineva P., Gross D., Müller R. and Rangelov T. (2014), Dynamic Fracture of Piezoelectric Materials. [electronic resource] : Solution of Time-Harmonic Problems via BIEM. Cham, Springer International Publishing.

Divsholi B. S. and Yang Y. (2009) Application of reusable PZT sensors for monitoring initial hydration of concrete. SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, pp. 729222-729222-729229.

Duan W. H., Wang Q. and Quek S. T. (2010) "Applications of piezoelectric materials in structural health monitoring and repair: Selected research examples." Materials, Vol. 3, No. 12, pp. 5169-5194.

Dumoulin C. and Deraemaeker A. (2017) "Real-time fast ultrasonic monitoring of concrete cracking using embedded piezoelectric transducers." Smart Materials and Structures, Vol. 26, No. 10, pp. 104006.

Fairweather J. A. (1998) "Designing with active materials: An impedance based approach". Ph.D Thesis, Rensselaer Polytechnic Institute.

Fan W. and Qiao P. (2011) "Vibration-based damage identification methods: a review and comparative study." Structural Health Monitoring, Vol. 10, No. 1, pp. 83-111.

Fan Z. and Lowe M. (2012) "Interaction of weld-guided waves with defects." NDT & E International, Vol. 47, No., pp. 124-133.

Giurgiutiu V. (2008), Structural health monitoring: with piezoelectric wafer active sensors. Amsterdam ; Boston, Elsevier/Academic Press.

Giurgiutiu V., Zagrai A. and Bao J. (2002a) "Embedded active sensors for in-situ structural health monitoring of thin-wall structures." Journal of pressure vessel technology, Vol. 124, No. 3, pp. 293-302.

Giurgiutiu V., Zagrai A. and Bao J. J. (2002b) "Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring." Structural Health Monitoring-an International Journal, Vol. 1, No. 1, pp. 41-61.

Giurgiutiu V., Zagrai A. and Bao J. J. (2004) "Damage identification in aging aircraft structures with piezoelectric wafer active sensors." Journal of Intelligent Material Systems and Structures, Vol. 15, No. 9-10, pp. 673-687.

Giurgiutiu V. and Zagrai A. N. (2000) "Characterization of piezoelectric wafer active sensors." Journal of Intelligent Material Systems and Structures, Vol. 11, No. 12, pp. 959-976.

Giurgiutiu V. and Zagrai A. N. (2002) "Embedded self-sensing piezoelectric active sensors for on-line structural identification." Journal of Vibration and Acoustics, Vol. 124, No. 1, pp. 116-125.

Gu H., Song G., Dhonde H., Mo Y. L. and Yan S. (2006) "Concrete early-age strength monitoring using embedded piezoelectric transducers." Smart Materials and Structures, Vol. 15, No. 6, pp. 1837.

Gururaja T. R. (1992) Piezoelectric transducers for medical ultrasonic imaging. Applications of Ferroelectrics, 1992. ISAF '92., Proceedings of the Eighth IEEE International Symposium on, Greenville, SC, USA, USA, pp. 259-265.

Hansford M. (2012). "No.11 Nicoll Highway collapse." Retrieved Dec 25, 2017, from <https://www.newcivilengineer.com/latest/no11-nicoll-highway-collapse/8629881.article>.

Helal J., Sofi M. and Mendis P. (2015) "Non-Destructive Testing of Concrete: A Review of Methods." Electronic Journal of Structural Engineering, Vol. 14, No. 1, pp. 97-105.

Hetényi M. (1974), Beams on elastic foundation: theory with applications in the fields of civil and mechanical engineering. Ann Arbor, Mich., The University of Michigan Press.

Holtz R. D., Kovacs W. D. and Sheahan T. C. (2011), An introduction to geotechnical engineering. Upper Saddle River, NJ Pearson.

Hong X.-b., Lin X., Yang B. and Li M. (2017) "Crack Detection in Plastic Pipe Using Piezoelectric Transducers based on Nonlinear Ultrasonic Modulation." Smart Materials and Structures, Vol. 26, No. 10.

Huynh T.-C. and Kim J.-T. (2014) "Impedance-based cable force monitoring in tendon-anchorage using portable PZT-interface technique." Mathematical Problems in Engineering, Vol. 2014, No.

Huynh T. C. and Kim J. T. (2017) "Quantification of temperature effect on impedance monitoring via PZT interface for prestressed tendon anchorage." Smart Materials and Structures, Vol. 26, No. 12.

Inman D. J., Ahmadian M. and Claus R. O. (2001) "Simultaneous Active Damping and Health Monitoring of Aircraft Panels." Journal of Intelligent Material Systems and Structures, Vol. 12, No. 11, pp. 775-783.

Kaplan M. (1959) "The effects of age and water/cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete." Magazine of Concrete Research, Vol. 11, No. 32, pp. 85-92.

Kim W. C., Jo H. J. and Park G. (2015) Concrete cure monitoring using piezoelectric admittance measurements. Proceedings of the 2015 World Congress on Advances in Structural Engineering and Mechanic.

Lalande F. (1995) "Modeling of the induced strain actuation of shell structures". Ph.D Thesis, Virginia Polytechnic Institute and State University.

Levey D. (2008). "IAP class probes Singapore highway collapse." Retrieved Dec 25, 2017, from <http://news.mit.edu/2008/collapse-highway-0201>.

Liang C., Sun F. and Rogers C. (1994a) "Coupled electro-mechanical analysis of adaptive material systems—determination of the actuator power consumption and

system energy transfer." Journal of Intelligent Material Systems and Structures, Vol. 5, No. 1, pp. 12-20.

Liang C., Sun F. and Rogers C. A. (1996) "Electro-mechanical impedance modeling of active material systems." Smart Materials and Structures, Vol. 5, No. 2, pp. 171.

Liang C., Sun F. P. and Rogers C. A. (1994b) "An Impedance Method for Dynamic Analysis of Active Material Systems." Journal of Vibration and Acoustics, Vol. 116, No. 1, pp. 120-128.

Lim Y. Y. (2012) "Fatigue life estimation of 1-D aluminum beam using electromechanical impedance technique". Ph.D Thesis Thesis, Nanyang Technological University.

Lim Y. Y. (2014). Monitoring of concrete hydration using electromechanical impedance technique. 23rd Australasian Conference on the Mechanics of Structures and Materials Byron Bay, NSW. **II**: 1155-1160.

Lim Y. Y., Bhalla S. and Soh C. K. (2006) "Structural identification and damage diagnosis using self-sensing piezo-impedance transducers." Smart Materials and Structures, Vol. 15, No. 4, pp. 987.

Lim Y. Y., Kwong K. Z., Liew W. Y. H. and Soh C. K. (2016) "Non-destructive concrete strength evaluation using smart piezoelectric transducer—a comparative study." Smart Materials and Structures, Vol. 25, No. 8, pp. 085021.

Lim Y. Y., Kwong K. Z., Liew W. Y. H. and Soh C. K. (2017) "Practical issues related to the application of piezoelectric based wave propagation technique in monitoring of concrete curing." Construction and Building Materials, Vol. 152, No., pp. 506-519.

Lim Y. Y. and Soh C. K. (2011) "Fatigue life estimation of a 1D aluminum beam under mode-I loading using the electromechanical impedance technique." Smart Materials and Structures, Vol. 20, No. 12, pp. 125001.

Lim Y. Y. and Soh C. K. (2012) "Effect of varying axial load under fixed boundary condition on admittance signatures of electromechanical impedance technique." Journal of Intelligent Material Systems and Structures, No., pp. 1045389X12437888.

Lim Y. Y. and Soh C. K. (2013) "Damage detection and characterization using EMI technique under varying axial load." Smart Struct Syst, Vol. 11, No., pp. 349-364.

Lim Y. Y. and Soh C. K. (2014a) "Electro-mechanical impedance (EMI)-based incipient crack monitoring and critical crack identification of beam structures." Research in Nondestructive Evaluation, Vol. 25, No. 2, pp. 82-98.

Lim Y. Y. and Soh C. K. (2014b) "Towards more accurate numerical modeling of impedance based high frequency harmonic vibration." Smart Materials and Structures, Vol. 23, No. 3, pp. 035017.

Lin B., Giurgiutiu V., Pollock P., Xu B. and Doane J. (2010) "Durability and survivability of piezoelectric wafer active sensors on metallic structure." AIAA journal, Vol. 48, No. 3, pp. 635.

Liu W. and Giurgiutiu V. (2007) Finite element simulation of piezoelectric wafer active sensors for structural health monitoring with coupled-filed elements. Proceedings of SPIE, the International Society for Optical Engineering, pp. 65293R.

Madhav A. V. G. and Soh C. K. (2007) "An electromechanical impedance model of a piezoceramic transducer-structure in the presence of thick adhesive bonding." Smart Materials and Structures, Vol. 16, No. 3, pp. 673.

Malhotra V. M. and Carino N. J. (2004), Handbook on Nondestructive Testing of Concrete. West Conshohocken, PA, CRC press.

Mamlouk M. S. and Zaniewski J. P. (2011), Materials for civil and construction engineers. Upper Saddle River, NJ, Prentice Hall.

Monkhouse R. S. C., Wilcox P. D. and Cawley P. (1997) "Flexible interdigital PVDF transducers for the generation of Lamb waves in structures." Ultrasonics, Vol. 35, No. 7, pp. 489-498.

Murata Manufacturing Co. L. (2017). "Piezoelectric Diaphragms." Retrieved Dec 3, 2017, from <https://www.murata.com/en-sg/products/sound/diaphragm>.

Na S. and Lee H. (2012) "A technique for improving the damage detection ability of the electro-mechanical impedance method on concrete structures." Smart Materials and Structures, Vol. 21, No. 8, pp. 085024.

Na S. and Lee H. (2013) "A multi-sensing electromechanical impedance method for non-destructive evaluation of metallic structures." Smart Materials and Structures, Vol. 22, No. 9, pp. 095011.

Narayanan A., Kocherla A. and Subramaniam K. V. L. (2017) "Embedded PZT Sensor for Monitoring Mechanical Impedance of Hydrating Cementitious Materials." Journal of Nondestructive Evaluation, Vol. 36, No. 4.

Neville A. (2001) "Core tests: Easy to perform, not easy to interpret." Concrete International, Vol. 23, No. 11, pp. 59-68.

Neville A. M. (2011), Properties of concrete. Edinburgh Gate, Harlow, Essex CM20 2JE, England, Pearson Education Limited.

Park G., Cudney H. H. and Inman D. J. (2000) "Impedance-based health monitoring of civil structural components." Journal of infrastructure systems, Vol. 6, No. 4, pp. 153-160.

Park G. and Inman D. J. (2007) "Structural health monitoring using piezoelectric impedance measurements." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Vol. 365, No. 1851, pp. 373-392.

Park G., Kabeya K., Cudney H. H. and Inman D. J. (1999) "Impedance-based structural health monitoring for temperature varying applications." Jsme International Journal Series a-Solid Mechanics and Material Engineering, Vol. 42, No. 2, pp. 249-258.

Park G., Sohn H., Farrar C. R. and Inman D. J. (2003) "Overview of piezoelectric impedance-based health monitoring and path forward." Shock and Vibration Digest, Vol. 35, No. 6, pp. 451-464.

Park S., Ahmad S., Yun C.-B. and Roh Y. (2006) "Multiple crack detection of concrete structures using impedance-based structural health monitoring techniques." Experimental Mechanics, Vol. 46, No. 5, pp. 609-618.

Park S., YUN C. B. and Inman D. (2008) "Structural health monitoring using electro - mechanical impedance sensors." Fatigue & Fracture of Engineering Materials & Structures, Vol. 31, No. 8, pp. 714-724.

Pauw A. (1960) "Static modulus of elasticity of concrete as affected by density." ACI Journal, Vol. 57, No. 12, pp. 679-687.

Peairs D. M., Grisso B. L., Margasahayam R. N., Page K. R. and Inman D. J. (2004a) Impedance-based health monitoring of space shuttle ground structures. Proceedings of SPIE, San Diego, CA, United States, pp. 99-107.

Peairs D. M., Park G. and Inman D. J. (2004b) "Improving accessibility of the impedance-based structural health monitoring method." Journal of Intelligent Material Systems and Structures, Vol. 15, No. 2, pp. 129-139.

Popovics S. (1975) "Verification of relationships between mechanical properties of concrete-like materials." Matériaux et Construction, Vol. 8, No. 3, pp. 183-191.

Popovics S. (1992), Concrete materials: Properties, specifications, and testing. Park Ridge, New Jersey, William Andrew.

Providakis C. and Liarakos E. (2011) "T-WiEYE: An early-age concrete strength development monitoring and miniaturized wireless impedance sensing system." Procedia Engineering, Vol. 10, No., pp. 484-489.

Providakis C. and Liarakos E. (2014) "Web - based concrete strengthening monitoring using an innovative electromechanical impedance telemetric system and extreme values statistics." Structural Control and Health Monitoring, Vol. 21, No. 9, pp. 1252-1268.

Quinn W., Angove P., Buckley J., Barrett J. and Kelly G. (2011) "Design and performance analysis of an embedded wireless sensor for monitoring concrete curing and structural health." Journal of Civil Structural Health Monitoring, Vol. 1, No. 1-2, pp. 47-59.

Quinn W., Kelly G. and Barrett J. (2012) "Development of an embedded wireless sensing system for the monitoring of concrete." Structural Health Monitoring, Vol. 11, No. 4, pp. 381-392.

Raghavan A. and Cesnik C. E. (2007) "Review of guided-wave structural health monitoring." Shock and Vibration Digest, Vol. 39, No. 2, pp. 91-116.

Saravanan T. J., Balamonica K., Priya C. B., Reddy A. L. and Gopalakrishnan N. (2015) "Comparative performance of various smart aggregates during strength gain and damage states of concrete." Smart Materials and Structures, Vol. 24, No. 8, pp. 085016.

Shin S. W. and Oh T. K. (2009) "Application of electro-mechanical impedance sensing technique for online monitoring of strength development in concrete using smart PZT patches." Construction and Building Materials, Vol. 23, No. 2, pp. 1185-1188.

Shin S. W., Qureshi A. R., Lee J.-Y. and Yun C. B. (2008) "Piezoelectric sensor based nondestructive active monitoring of strength gain in concrete." Smart Materials and Structures, Vol. 17, No. 5, pp. 055002.

Simpson Gumpertz & Heger. (1971). "2000 Commonwealth Avenue | Simpson Gumpertz & Heger." Retrieved Dec 24, 2017, from <http://www.sgh.com/projects/2000-commonwealth-avenue>.

SMART MATERIAL C. L. (2017). "MFC." Retrieved Dec 5, 2017, from <https://www.smart-material.com/MFC-product-main.html>.

Soh C., Tseng K. K., Bhalla S. and Gupta A. (2000) "Performance of smart piezoceramic patches in health monitoring of a RC bridge." Smart materials and Structures, Vol. 9, No. 4, pp. 533.

Soh C. K. and Bhalla S. (2005) "Calibration of piezo-impedance transducers for strength prediction and damage assessment of concrete." Smart materials and structures, Vol. 14, No. 4, pp. 671.

Song F., Huang G., Kim J. and Haran S. (2008a) "On the study of surface wave propagation in concrete structures using a piezoelectric actuator/sensor system." Smart materials and Structures, Vol. 17, No. 5, pp. 055024.

Song G., Gu H. and Mo Y.-L. (2008b) "Smart aggregates: multi-functional sensors for concrete structures—a tutorial and a review." Smart Materials and Structures, Vol. 17, No. 3, pp. 033001.

Song G., Gu H., Mo Y., Hsu T. and Dhonde H. (2007) "Concrete structural health monitoring using embedded piezoceramic transducers." Smart Materials and Structures, Vol. 16, No. 4, pp. 959.

Song H., Lim H. J. and Sohn H. (2013) "Electromechanical impedance measurement from large structures using a dual piezoelectric transducer." Journal of Sound and Vibration, Vol. 332, No. 25, pp. 6580-6595.

Su Z. and Ye L. (2009), Identification of damage using Lamb waves: from fundamentals to applications. London, Springer, London.

Su Z., Ye L. and Lu Y. (2006) "Guided Lamb waves for identification of damage in composite structures: A review." Journal of sound and vibration, Vol. 295, No. 3, pp. 753-780.

Sun F. P., Chaudhry Z., Liang C. and Rogers C. A. (1995a) "Truss Structure Integrity Identification Using PZT Sensor-Actuator." Journal of Intelligent Material Systems and Structures, Vol. 6, No. 1, pp. 134-139.

Sun F. P., Chaudhry Z. A., Rogers C. A., Majmundar M. and Liang C. (1995b) Automated real-time structure health monitoring via signature pattern recognition. Smart Structures & Materials' 95, pp. 12.

Swamy R. and Bandyopadhyay A. (1975) "The elastic properties of structural lightweight concrete." Proceedings of the Institution of Civil Engineers, Vol. 59, No. 2.

Swamy R. N. (1971) "Dynamic Poisson's ratio of portland cement paste, mortar and concrete." Cement and Concrete Research, Vol. 1, No. 5, pp. 559-583.

Talakokula V. and Bhalla S. (2014) "Reinforcement corrosion assessment capability of surface bonded and embedded piezo sensors for reinforced concrete structures."

Journal of Intelligent Material Systems and Structures, Vol. 26, No. 17, pp. 2304-2313.

Talakokula V. and Bhalla S. (2016) "Non-destructive Strength Evaluation of Fly Ash Based Geopolymer Concrete Using Piezo Sensors." Procedia Engineering, Vol. 145, No., pp. 1029-1035.

Talakokula V., Bhalla S. and Gupta A. (2018) "Monitoring early hydration of reinforced concrete structures using structural parameters identified by piezo sensors via electromechanical impedance technique." Mechanical Systems and Signal Processing, Vol. 99, No., pp. 129-141.

Tawie R. and Lee H. (2010) "Monitoring the strength development in concrete by EMI sensing technique." Construction and Building Materials, Vol. 24, No. 9, pp. 1746-1753.

Tawie R. and Lee H. (2011) "Characterization of cement-based materials using a reusable piezoelectric impedance-based sensor." Smart Materials and Structures, Vol. 20, No. 8, pp. 085023.

Timoshenko S. (1955), Vibration problems in engineering, New York : Van Nostrand.

Tomosawa F. and Noguchi T. (1993) Relationship between compressive strength and modulus of elasticity of high-strength concrete. Proceedings of the Third International Symposium on Utilization of High-Strength Concrete, Lillehammer, Norway, pp. 1247-1254.

Walton C., McGearry F. and Englehart E. (1957) "Compatibility of Aluminum With Alkaline Building Products." Corrosion, Vol. 13, No. 12, pp. 41-50.

Wang D., Song H. and Zhu H. (2014) "Embedded 3D electromechanical impedance model for strength monitoring of concrete using a PZT transducer." Smart Materials and Structures, Vol. 23, No. 11, pp. 115019.

Wang D. and Zhu H. (2011) "Monitoring of the strength gain of concrete using embedded PZT impedance transducer." Construction and Building Materials, Vol. 25, No. 9, pp. 3703-3708.

Webster J. G. and Eren H. (2014), Measurement, instrumentation, and sensors handbook: spatial, mechanical, thermal, and radiation measurement. Boca Raton, FL, CRC press.

Wight J. K., Richart F. E. and MacGregor J. G. (2012), Reinforced concrete : mechanics and design. Upper Saddle River, NJ, Pearson Prentice Hall.

Wigton K. T. (2009). "Failures - 2000 Commonwealth Avenue - Boston." Retrieved Dec 25, 2017, from <https://failures.wikispaces.com/2000+Commonwealth+Avenue+-+Boston>.

Xu K., Kong Q., Chen S. and Song G. (2017) "Early Determination of the Presence of Low Strength Concrete in Reinforced Concrete Beam-Column Joints Using Piezoceramic-Based Transducers." IEEE Sensors Journal, Vol. 17, No. 11, pp. 3244-3250.

Yang Y., Divsholi B. S. and Soh C. K. (2010) "A reusable PZT transducer for monitoring initial hydration and structural health of concrete." Sensors, Vol. 10, No. 5, pp. 5193-5208.

Yang Y., Lim Y. Y. and Soh C. K. (2008a) "Practical issues related to the application of the electromechanical impedance technique in the structural health monitoring of civil structures: I. Experiment." Smart Materials and Structures, Vol. 17, No. 3, pp. 035008.

Yang Y., Lim Y. Y. and Soh C. K. (2008b) "Practical issues related to the application of the electromechanical impedance technique in the structural health monitoring of civil structures: II. Numerical verification." Smart Materials and Structures, Vol. 17, No. 3, pp. 035009.

Yang Y. and Miao A. (2008) "Effect of external vibration on PZT impedance signature." Sensors, Vol. 8, No. 11, pp. 6846-6859.

Yun C.-B. and Min J. (2011) "Smart sensing, monitoring, and damage detection for civil infrastructures." KSCE Journal of Civil Engineering, Vol. 15, No. 1, pp. 1-14.

Zhou S.-W., Liang C. and Rogers C. A. (1996) "An impedance-based system modeling approach for induced strain actuator-driven structures." Journal of Vibration and Acoustics, Vol. 118, No. 3, pp. 323-331.

Zhou S., Liang C. and Rogers C. (1995) "Integration and design of piezoceramic elements in intelligent structures." Journal of Intelligent Material Systems and Structures, Vol. 6, No. 6, pp. 733-743.

Zhu J., Ho M., Patil D., Wang N., Hirsch R. and Song G. (2017) "Underwater Pipeline Impact Localization Using Piezoceramic Transducers." Smart Materials and Structures, No. in press.

Zhuang Y., Kopsaftopoulos F., Dugnani R. and Chang F.-K. (2017) "Integrity monitoring of adhesively bonded joints via an electromechanical impedance-based approach." Structural Health Monitoring, No.

Zhuang Y., Lia Y.-h., Kopsaftopoulos F. and Chang F.-K. (2016) A self-diagnostic adhesive for monitoring bonded joints in aerospace structures. SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, pp. 98030I-98030I-98010.

Zuo C., Feng X., Zhang Y., Lu L. and Zhou J. (2017) "Crack detection in pipelines using multiple electromechanical impedance sensors." Smart Materials and Structures, Vol. 26, No. 10, pp. 104004.