CRACKING EVALUATION OF MICRO STEEL FIBRE (MSF) CONCRETE BY UTILISING ACOUSTIC EMISSION SIGNAL METHOD

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For my beloved family.

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ABSTRACT

Concrete is one of the world's most widely used construction material. However, it is known that concrete is a brittle composite which is sensitive to cracking. Hence, this study was conducted to enhanced the mechanical properties of concrete and to monitor the cracking activities through acoustic emission (AE) technique. The main additional material used in this research was micro steel fibres (MSF) with a volume fraction of 0%, 0.5%, 0.75%, 1.00% and 1.25%. At the earliest stage, the mechanical properties (e.g. compressive strength test, splitting tensile test and modulus of elasticity) was determine. Next, a series of prisms were made to carry out acoustic emission (AE) signal analysis. From the data analysis, the highest compressive strength of 74.50 MPa was obtained by a concrete specimen containing 1.25% MSF at the age of 28 days. The very same specimen achieved the highest splitting tensile strength and modulus of elasticity at 5.96 MPa and 49.47 GPa, respectively. The presence of 0.5% MSF for both specimens aged for 7 and 28 days had a signal strength of 3.6×10^9 pVs and 4.0×10^9 pVs, respectively. Meanwhile, the maximum readings of absolute energy were obtained by specimens containing 0.5% and 1.00% of MSF at 8.0×10^9 aJ and 9.0×10^9 aJ, respectively. In addition, the highest amplitude value gained from this study is 99dB. From the RA value analysis, it can be concluded that the concrete specimen failed through tensile cracking. In a nutshell, the higher the presence of MSF in a concrete composite, the higher its strength. Meanwhile, the highest signal strength and absolute energy prove that the specimens have better resistance towards cracking. Moreover, the RA value analysis is appropriate for concrete crack classification. Therefore, the AE technique is found to be suitable for crack evaluation and monitoring methods.

ABSTRAK

Konkrit adalah salah satu bahan binaan yang paling banyak digunakan di dunia. Walau bagaimanapun, telah diketahui bahawa konkrit adalah komposit rapuh dan sensitif terhadap keretakan. Oleh itu, kajian ini dilakukan untuk meningkatkan sifat mekanikal konkrit dan untuk memantau aktiviti rekahan dengan menggunakan teknik pelepasan akustik (AE). Bahan tambahan utama yang digunakan dalam penyelidikan ini ialah gentian keluli mikro (MSF) dengan pecahan isipadu 0%, 0.5%, 0.75%, 1.00% dan 1.25%. Pada peringkat awal, sifat mekanik (misalnya. Ujian kekuatan mampatan, ujian tarik tegangan dan modulus keanjalan) akan ditentukan. Seterusnya, satu siri prisma dibuat untuk menjalankan analisis isyarat pelepasan akustik (AE). Dari analisis data kekuatan mampatan tertinggi sebanyak 74.50 MPa diperolehi pada spesimen konkrit yang mengandungi 1.25% MSF pada usia 28 hari. Manakala, konkrit mengandungi 1.25% MSF mempunyai kekuatan tegangan pemisahan dan modulus keanjalan tertinggi, iaitu 5.96 MPa dan 49.47 GPa. Akhir sekali, kehadiran 0.5% MSF untuk kedua-dua spesimen berusia 7 dan 28 hari mempunyai kekuatan isyarat, masing-masing 3.6×10^9 pV dan 4.0×10^9 pVs. Manakala, bacaan tertinggi tenaga mutlak, dapat pada konkrit yang mengandungi 0.5% dan 1.00% MSF. Bacaan maksimum yang diperolehi ialah 8.0×10^9 aJ dan 9.0×10^9 aJ. Selain daripada itu, nilai amplitud tertinggi yang diperoleh daripada kajian ini ialah 99dB. Dari analisis nilai RA, disimpulkan bahawa spesimen konkrit gagal melalui rekahan tegangan. Kesimpulannya, semakin tinggi kehadiran MSF dalam komposit konkrit meningkatkan prestasinya dari segi kekuatan. Sementara itu, kekuatan isyarat tertinggi dan tenaga mutlak membuktikan bahawa spesimen mempunyai rintangan yang lebih baik terhadap rekahan. Selain daripada itu, analysis nilai RA sesuai dipraktikkan untuk mengagihkan mode rekahan yang timbul di permukaan konkrit. Dengan ini, teknik AE sesuai digunakan dalam kaedah pemantauan rekahan.

.

TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURE

LIST OF SYMBOLS

AE – Acoustic Emission

aJ – atto Joules

ASTM – American society for testing and materials

BS – British Standard

dB – Decibels

DOE - Department of Environment

EAMC - Early Age Micro Cracking

GPa - GigaPascal

HPC – High performance concrete

Kg/m^3 – kilogram per meter cube

MOE – Modulus of Elasticity

MPa – MegaPascal

MSF – Micro Steel Fibre

Mm – millimeter

N/mm^2 – Newton per meter square

OPC – Ordinary Portland cement

pVs – pico Volt second

SPs - Superplasticizers

w/c – water / cement

% - Percentage

μ - micron

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Concrete has been widely used as a construction material since the Roman age. In general, concrete is made of Portland cement, coarse and fine aggregates and water. When these four components are mixed together, cement reacts with water to form a binder that holds the aggregates together. The end product it produces is a composite which is strong in compression but relatively weak in tension (Ranaivomanana *et al*., 2012). The control mixtures are proportioned to achieve a compression strength between 40 MPa and 60 MPa with slump values between 75 mm and 125 mm (Butler *et al*., 2013). The tensile strength test obtained from a concrete mixture with a compressive strength of 150 MPa is in the range of 14 – 34 MPa (Cornelia *et al*., 2012).

In the early stage, concrete undergoes drying shrinkage due to the loss of free water through evaporation (Ghourchian *et al*., 2017). This may cause the concrete to become brittle and sensitive to cracking. Premature cracking is a prime cause for deterioration of concrete structures. Cracks contribute a path for water and other intrusive agents such as chloride, sulphates or carbon dioxide to enter building structure and cause reinforcement to corrode, as well as concrete spalling (Pal *et al*., 2019). Various non-destructive techniques, including the impact-echo method, ground probing radar, infrared thermography and acoustic emission have been proposed for assessing the conditions of concrete structures (Giri & Kharkovsky, 2016).

In order to detect the crack form in concrete structures, acoustic emission (AE) technique can be used to identify both tensile cracks and shear movements at critical zones within a structure (Ong, 2016). An advantage in the application of this technique for concrete structures is that AE detects irreversible and real cracking processes in a material. Moreover, the elastic waves released during crack propagation incidences are recorded by transducers placed on the surface of the material (Shahidan *et al*., 2013). The information of these waveforms includes the location of the source crack (by comparing the arrival time to different sensors), the density of the cracks, as well as the severity of the material condition *(Alam et al*., 2015).

To overcome cracking in concrete, fibres are added to concrete to increase the toughness of cementitious matrices. The application of fibre in cementitious matrices has a history of 4500 years. For example, the ancient people in Egypt and China have the knowledge of using straw fibres in sun-dried mud bricks primarily made out of clay (adobe), horse hair with mud clay, and adding asbestos fibres to ceramic pottery, thus creating a composite with better performance. However, organic fibres such as straw cannot lead to an increase in tensile strength. Therefore, advanced artificial fibres such as steel fibre, glass fibre, carbon fibre and polypropylene fibre are manufactured and sold in the market.

Fibre reinforced concrete is able to resist cracking generated in a concrete structure (Bagherzadeh *et al*., 2012). Fibre reinforcement converts brittle, unreinforced concrete into a ductile material and improves its mechanical properties such as its tensile strength and resistance to crack formation (Won *et al*., 2013). Tensile tests show that the tensile strength and flexural strength of steel fibre reinforced concrete improves with increasing fibre volume fraction (Won *et al*., 2012). Moreover, the application of fibres in concrete structures such as bridge decks may reduce early age micro cracking (EAMC) (Khan & Ali, 2016).

To conclude, the presence of steel fibres in a concrete matrix can mitigate crack occurrence. Meanwhile, the AE technique can be used to detect the initiation of cracks in a specimen.

1.2 Problem Statements

Cracking in concrete is a concern, because a lot of research has proven that cracks can cause steel to corrode and concrete to deteriorate, resulting in a decrease in a structure's service life (Ju *et al*., 2017 ;Zhang *et al*., 2019 ;Liew & Akbar, 2020). Cracking can arise from internal factors or external factors such as over-stressing (premature loading), restraint or improper construction practice, thermal expansion, chemical reactions (aggressive environment exposure) and shrinkage of concrete (Li *et al*., 2020; Jongvivatsakul *et al*., 2019).

The existence of cracking can significantly increase the penetration of moisture and salts into concrete (Akhavan *et al*., 2012). The carbonation process causes a decrease in concrete pH and leads to the instability of the passive layer. Additionally, the presence of oxygen and humidity makes steel corrode uniformly. Localised corrosion will also take place when the steel surface is in contact with chlorides (Angst *et al*., 2012). A study carried out by Zhang *et al.*, (2019) revealed the presence of defects in the middle of a concrete cover. However, it will reduce the durability of concrete and adversely affect the long term serviceability of concrete structure

In order to mitigate cracking in concrete elements, fibres such as steel fibres, micro steel fibres (MSF), polypropylene fibres and etc. were included in concrete mixtures. Steel fibres have higher strength and greater Young's modulus of elasticity compared to other fibres. The addition of fibre to concrete improves the performance of concrete at the meantime it may resist cracking generation (Bagherzadeh *et al.*, 2012).

However, the previous studies mostly combined micro and macro fibres in a concrete matrix to gained a positive outcome. Also, there were studies where the researcher includes cementitious materials and micro steel fibres (MSF) in a concrete composite to observe both crack resistance and its strength. In addition, the inclusion of straight short MSF fills up the void that occurs between the particles inside the concrete matrix resulting the concrete specimen to become more rigid. Therefore, there is a need to conduct a study by using MSF in a concrete matrix to determine its ability to mitigate cracking and enhancing the strength of a concrete composite.

Through the acoustic emission (AE) technique, AE events are monitored to detect damage development before a crack becomes visible on the surface (Xu *et al.*, 2018). It is possible because of the fact that the number of AE events is more or less proportional to the number of growing cracks, and the AE amplitudes (or energy) are proportional to the length of the crack growth increments in materials such as concrete and rock. Meanwhile, it is possible to determine classified the type of cracks occurs on the concrete specimens by applying RA value analysis (Wang *et al.*, 2018). Therefore, compared to real time monitoring methods, it is recommended that the AE technique is more useful in detecting and monitoring the formation of micro-cracks and their growth during the entire fracturing process in quasi-brittle materials. Yet, the limited analysis on the AE parameters such as amplitude, absolute energy and signal strength by previous researchers had proven that there is a need to conduct a study to explore more on these parameters to gained more accurate findings.

In a nutshell, this study is dedicated to determining the relationship between the application of micro steel fibres (MSF) and crack propagation in concrete. Besides that, this research also examined the application of the AE technique in crack classification and shear movements in critical zones within concrete specimens.

1.3 Research Objectives

The objectives of this research are as shown in below:

i. To determine the workability, compressive and splitting tensile strength, and modulus of elasticity for the concrete consists of 0% to 1.25% micro steel fibres (MSF).

ii. To evaluate the crack initiation of the micro steel fibres concrete using acoustic emission (AE) method.

iii. To analyze the type of crack classification of micro steel fibres concrete through RA value analysis.

1.4 Scope of Research

This study is divided into three stages, namely preliminary stage, secondary stage and tertiary stage. At the preliminary stage, normal concrete with a targeted compressive strength of 40 MPa at the age of 28 days was designed. During this stage, a batch of concrete specimens was produced using different volume fractions of MSF such as 0%, 0.50%, 0.75%, 1.00% and 1.25%. The water-to-cement (w/c) ratio used was 0.47. On the other hand, the mix design was determined through the Department of Environment (DOE) method. These specimens were stored for curing for 7 and 28 days.

Next, the properties of concrete specimens containing different percentages of MSF were determined using slump values, compression, splitting tensile strength and modulus of elasticity (MoE) tests. The data obtained in this stage was recorded and analysed to acquire the highest strength of the concrete specimen consists of MSF. Moreover, the secondary and tertiary stages were conducted together. A series of prisms containing 0%, 0.50%, 0.75%, 1.00%, and 1.25% of MSF were produced to determine crack propagation and damage level of the specimens. The acoustic emission (AE) monitoring system consists of two sensors and a PC-based multi-channel monitoring system as well as a sensor-based acoustic multi-channel operating system were used to determine crack initiation in the concrete specimens. Later on, the data obtained was analysed to classify the cracks as tensile cracks or shear movement.

The data collected from the test above was analysed to obtain the optimum percentage of MSF that is suitable to be used in a concrete structure to mitigate the occurrence of cracking. Meanwhile, the data obtained through AE tests is useful for detecting microcracks and the cracks initiation in concrete structures. Lastly, a conclusion was made after all the data was verified. Detailed procedures of each test mentioned above are discussed in chapter 3. All these tests were conducted according to British Standard (BS).

1.5 Significance of Research

Concrete is widely used in construction industries. It plays an important role in built environment. As mentioned, concrete has relatively good compression strength but has poor tensile strength. In order to improve tensile strength, steel reinforcement was embedded within the concrete structures. However, due to the exposure of concrete structures to harsh climate and the presence of extra loading, cracking may occur. Therefore, fibres such as synthetic polymer fibres, glass fibres and micro steel fibres were introduced to the construction material industry.

These fibres play an important role in the mitigation of cracking and enhance the service life of concrete structures. At the same time, the concept of sustainability that is significant in the life cycle of construction was applied in terms of economic, environmental and social aspects. Several studies were conducted on the addition of fibre in concrete in terms of economic and environmental impact. For example, (Banthia *et al.*, 2014) have demonstrated that the addition of steel fibre can greatly influence the environment by lowering the emission of poisonous gas and energy consumption.

Simultaneously, these steel fibres can be partially included in the main elements of concrete reinforcement such as slabs and bridge decks because they have higher toughness and ductility. Hence, cracking can be reduced and it also may enhance performance in terms of dynamic effects or impact. Furthermore, the inclusion of steel fibres enhances abrasion resistance and provides extended life for bridge decks and industrial floors. Nevertheless, it also increases corrosion resistance and provides protection to areas with bad or harsh climate conditions.

On the other hand, to prolong the service life of concrete structure, scheduled monitoring in terms of cracking detection, corrosion detection and structural integrity evaluation is required. Consequently, the acoustic emission (AE) technique was chosen because sensors can be used to locate the source and defect areas. Compared to conventional monitoring methods, the AE technique has plenty of advantages. The sensors used are highly sensitive. An early and rapid detection of defects, flaws, cracks etc. can be located through wavelength. As a result, the maintenance cost of a concrete structure can be reduced.

In conclusion, this study is essential as the findings may contribute to the construction industry through the development of a bridge deck and slabs with high resistance towards cracking and corrosion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a broad review on micro steel fibre (MSF) concrete. There are three main highlights in this chapter, specifically MSF, cracking, and acoustic emission (AE). Apart from the highlights mentioned above, a brief review on concrete, steel fibres, superplasticizers (SPs), analysis of AE technique and previous studies on MSF and AE in concrete are included.

2.2 Concrete material

Concrete is widely used as an engineering material to build modern civil structures and infrastructures. The materials required for concrete are easily available in most places and the production cost is economical. Other than that, it can be manufactured to the desired strength based on the requirements of the structures. Fresh concrete can be cast on site in any complex shape with the assistance of formwork. Furthermore, concrete is highly resistant towards water and temperature. Although chemicals such as sulphate and chloride in water prompt corrosion in reinforced concrete, concrete remains the best choice for dams, pipelines and waterfront structures dependent on its high durability in water without critical deterioration.

In addition, concrete can withstand high temperatures compared to wood and steel. This is because the presence of calcium silicate hydrate (C-S-H) in the main binder of concrete allows it to withstand temperatures up to 910^{O}C. Hence, higher fire resistance contributes to lower thermal conductivity, higher thermal capacity and stiffness degradation in concrete (Kodur & Alogla, 2017). However, a concrete matrix is strong in compression but is relatively weak in tension (Grzymski *et al*., 2019). Therefore, steel reinforcements are usually embedded in concrete composites to withstand tensile stresses. Over the decades, several studies have experimented on the addition of supplementary cementitious materials, micro steel fibres, macro steel fibres, natural fibres (obtained from plantations), and etc. to improve the mechanical properties of concrete.

A concrete matrix known as high performance concrete (HPC) with a compressive strength within the range of 50 MPa – 150 MPa has been produced (Chithra *et al*., 2016). Later on, the HPC matrix evolved to become ultra-high performance concrete (UHPC) where its compressive strength was improved to a range of 150 MPa – 810 MPa (Wang *et al*., 2015).

2.3 Steel Fibres

Concrete is a quasi-brittle material that experiences low tensile strength and contains micro-cracks. In recent years, many researchers discovered methods to increase tensile strength and minimise cracking in concrete. One of the prevalent methods is through the use of steel fibres. For example, Park *et al*., (2012) has conducted an experiment on tensile behavior of ultra-high performance hybrid fiber reinforced concrete by using macro steel fibres (smooth, hooked end, and twisted) and micro steel fibres.

Another idea proposed by Cao *et al*., (2017) on the application of steel fibre and other types of fibre in self-compacting concrete and the determination of its strength and crack width. Both experiments conclude that the application of steel fibre in concrete can assist in improving tensile strength and also in controlling concrete cracking.

2.3.1 Types of steel fibres

Steel fibres have various dimensions as shown in Figure 2.1. Generally, the steel fibres can be categorised into two groups, namely macro steel fibres (Figure 2.2) and micro steel fibres (Figure 2.3). Macro steel fibre can be in many shapes, but micro steel fibres are only produced in straight strands since they are very fine in thickness. Normally, macro steel fibres have a length of 30 mm with a diameter of 0.3 mm – 0.4 mm. Thus, macro steel fibre provides resistance to plastic shrinkage and at the same time enhances durability, toughness and the ability to assist limited structural capacity during the design phase.

In contrast to the macro steel fibres, micro steel fibres have a length of 13 mm and a diameter of 0.2 mm. Taking its fine dimension as an advantage, micro steel fibres allow superior resistance to the formation of plastic shrinkage cracks. Therefore, it is suitable to include micro steel fibres in steel reinforced concrete so that it could aid structural elements to resist cracks that occur due to extra load and stress (Usman *et al*., 2020).

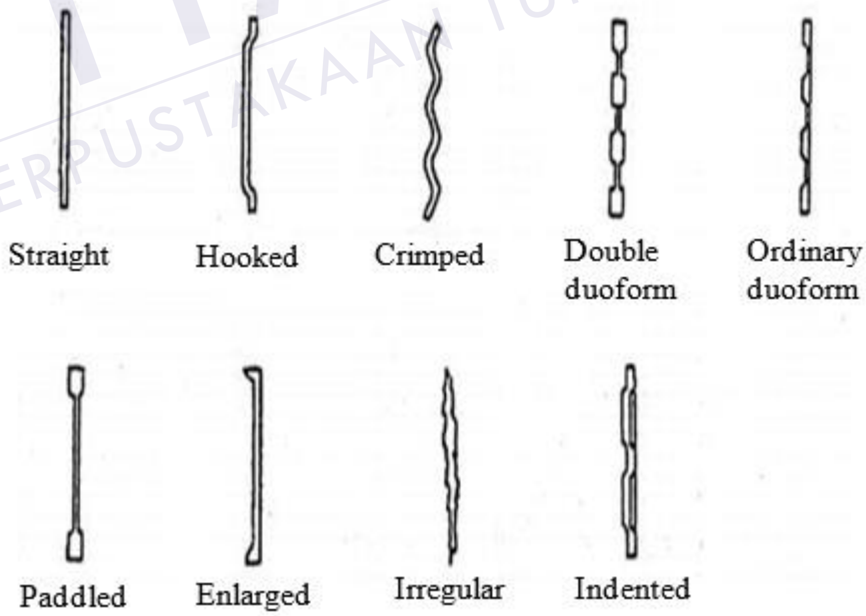

Figure 2. 1: Steel fibre shapes (Labib, 2018)

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