INFLUENCE OF MICROENCAPSULATED AS A CONCRETE SELF-HEALING AGENT CONTAINING SODIUM SILICATE

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By

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Date : 09/08/2022

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ABSTRAK

Konkrit adalah bahan binaan paling popular yang digunakan secara meluas di seluruh dunia. Walau bagaimanapun, kelemahan konkrit ialah terdedah kepada keretakan kerana tingkah laku kerapuhannya. Oleh itu, konkrit penyembuhan sendiri telah dicipta dan diperkenalkan untuk mencegah dan mengehadkan kesan rekahan pada konkrit. Matlamat penyiasatan ini adalah untuk menjalankan kajian literatur sistematik mengenai pengaruh mikroenkapsul sebagai agen penyembuhan diri konkrit yang mengandungi natrium silikat. Melalui semakan sistematik ini, penemuan terkini dan jurang pengetahuan akan dapat diketengahkan dan digariskan untuk siasatan lanjut. Objektif kajian sistematik ini adalah untuk menyiasat faktor penyumbang dalam mekanisme mikroenkapsul dan prestasi natrium silikat sebagai agen penyembuhan diri konkrit. Selain itu, jurang pengetahuan menggunakan mikroenkapsul yang mengandungi natrium silikat sebagai agen penyembuhan diri konkrit akan dikenal pasti dan dikelaskan. Terdapat 27 artikel telah diterokai dan ditinjau daripada Science Direct, Scopus dan Google Scholar untuk disemak. Semakan sistematik harus mengikut protokol dengan langkah yang digariskan dengan jelas untuk memberikan pemahaman yang jelas tentang persoalan penyelidikan, dan memastikan ketelusan dan kebolehulangan. Dalam ulasan ini, keberkesanan menyampaikan agen penyembuhan cecair melalui mikrokapsul dibincangkan. Saiz, bentuk dan dos kapsul mikrokapsul mempengaruhi kuantiti agen penyembuhan cecair yang dilepaskan ke dalam rekahan. Selain itu, sifat mekanikal mikrokapsul juga dijelaskan dalam perbincangan kerana ia akan mempengaruhi mekanisme mikrokapsul. Tambahan pula, pemilihan natrium silikat sebagai agen penyembuhan memberi banyak kelebihan terhadap konkrit penyembuhan sendiri. Oleh itu, mikrokapsul dengan bantuan natrium silikat sebagai teras boleh meningkatkan

kekuatan mampatan dan lenturan konkrit yang retak. Mikrokapsul untuk bahan bersimen penyembuhan sendiri boleh mendapat manfaat daripada penemuan kajian ini.

ABSTRACT

Concrete is the most popular building material that is widely used around the world. However, the weakness of concrete is prone to cracking due to its brittleness behavior. Therefore, self-healing concrete was invented and introduced to prevent and limit the impact of cracks on the concrete. The aim of this investigation is to carry out a systematic literature review on the influence of microencapsulated as a concrete self-healing agent containing sodium silicate. Through this systematic review, the recent findings and gap of knowledge would be able highlighted and underlined for further investigation. The objectives of this systematic review is to investigate the contributing factors in the mechanism of microencapsulated and the performance of sodium silicate as a concrete self-healing agent. In addition, the gap of knowledge using microencapsulated containing sodium silicate as a concrete self-healing agent will be identified and classified. There were 27 articles have been explored and surveyed from Science Direct, Scopus and Google Scholar to be reviewed. The systematic review should follow the protocol with distinctly delineated steps to provide a clear understanding of research questions, and ensures transparency and reproducibility. In this review, the effectiveness of delivering liquid healing agents via microcapsules is discussed. Size, shape and dosage of capsules of microcapsules affecting quantity of liquid healing agent released into cracks. Moreover, the mechanical properties of microcapsules also explained in the discussion because it will affect the mechanism of microcapsules. Furthermore, the election of sodium silicate as healing agent give many advantages towards self-healing concrete. Thus, microcapsules with help of sodium silicate as a core can enhance the compressive and flexural strength of the crack concrete. Microcapsules for self-healing cementitious materials could benefit from this review's findings.

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LIST OF ABBREVIATIONS

CSH	Calcium Silica Hydrate
SLR	Systematic Literature Review
RO	Research Objectives
RQ	Research Questions
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
QAC	Quality Assesment Criteria
PF	Phenol-formaldehyde
DCPD	Dicyclopentadiene
LWA	Lightweight Aggregates
SS	Sodium Silicate
SEM	Scanning Electron Microscope
EDS	Energy Dispersive X-ray Spectroscopy
LAM	Lambson Ltd. Microcapsules
THI	Thies Technology Inc. Microcapsules
TDI	Toluene Diisocyanate
TAM	Temperature Adaptive Microcaspules
OM	Optical Microscope
TGA	Thermogravimetric Analysis
XCT	X-ray Computed Tornography
XRD	X-Ray Diffraction Analysis
EDX	Energy Dispersive X-ray Spectroscopy
FTS	Fourier Transform Spectrometer
FTIR	Fourier Transform Infrared Spectroscopy
TPB	Three Point Bending
CMOD	Crack Mouth Opening Displacement
UPV	Ultrasonic Pulse Velocity
LVDT	Linear Variable Differential Transformer
DTG	Derivative Thermogravimetry

DTA	Differential Thermal Analysis
TG	Thermogravimetric
DLS	Dynamic Light Scattering
NMRM	Nuclear Magnetic Resonance
ECC	Engineered Cementitious Composite

CHAPTER 1

INTRODUCTION

1.1 Background

Concrete is recognized as the material that is used for construction the most frequently all over the world. It is easy to produce since it is a low-cost material and also recyclable. Due to its affordability, locally available, and durability, it become the most-consumed material for any construction. It possesses desirable engineering qualities, allowing it to be molded into any shape (Pelletier *et al.*, 2010). However, throughout the world, many concrete structures, especially infrastructure, are cracked and deteriorating significantly. This has led to an increase in the focus on concrete structure inspection and conservation methods. However, implementing continuous inspection and conservation is challenging due to the significant amount of manpower and money required, particularly in the case of huge concrete structures such as infrastructures. Alternatively, repair may be difficult or impossible due to existing surroundings, such as the location of the damage sustained by the structure's interior. Additionally, a significant number of infrastructures, including tunnels and highways are continual use, which makes repair work extremely challenging (Wu, Johannesson, and Geiker, 2012).

A new technique called self-healing concrete is introduced to prevent and limit the effect of cracks on concrete in order to solve the problems caused by concrete. Self-healing is the capacity of concrete to automatically repair cracks. Self-healing material development is a relatively new area of study, and there are a great number of approaches and procedures for self-healing cracks in damaged concrete while maintaining the specifications' integrity (Gandhimathi *et al.*, 2012). The self-healing concrete is a workable method for reducing deterioration and improving durability. In the use of

concrete components, it is difficult to obtain sufficient human and material resources for damage diagnosis and quick repair. As a potential answer to this problem, self-healing concrete materials with bionic properties have been proposed (Jiang *et al.*, 2021).

There are two classifications for self-healing concrete: autogenous and autonomous. Crack healing known as "autogenous healing" is dependent on the occurrence of chemical reactions and the presence of water in order to take place. Autogenous healing is also referred to as crack-width reduction because it encourages autogenous healing. Autonomous self-healing entails the use of specially formulated additives that mixed with a cementitious matrix for healing purposes, as well as the employment of specific procedures to transport such additives (Sidiq, Gravina and Giustozzi, 2019). Autonomous healing concrete designs primarily emphasize the concrete's self-healing potential, i.e., additional hydration of cement-based components via carbonation and pozzolanic reaction. In terms of cement-based materials, microencapsulated self-healing composites have received a lot of study attention (Jiang *et al.*, 2021).

White et al. demonstrated the application of a microencapsulation technique containing a healing agent for self-healing materials. Microencapsulation is defined as the technique of enclosing micron-sized solid particles or droplets of fluids or gases in an unactive shell, which separates and protects them from unpleasant or unwanted interactions in the exterior environment (Wu, Johannesson and Geiker, 2012). In an epoxy matrix, encapsulation healing agent and a spontaneous chemical trigger are combined to create an autonomic healing process. When a fracture occurs, embedded microcapsules rupture and release a healing chemical into the fracture plane via capillary action. As can be seen in Figure 1.2, the fracture surface is healed as a result of the healing agents having a chemical reaction with the matrix material (Indhumathi, Dinesh

and Pichumani, 2022). Figure 1.3 shows the typical ruptured microcapsule when the crack happens (Wu, Johannesson and Geiker, 2012).

There were over 100 trials attempted that involved the stabilization for the two different microencapsulation methods that were utilized for DCDP, as well as sodium silicate. The first microencapsulation procedure that was attempted was that of the autonomic. This was one of the first attempts to the microencapsulation procedure utilizing the urea-formaldehyde method. This method focused on developing a procedure that would control the properties of the microcapsule geometry, and its mechanical triggering system (Tseng, 2005). The term "microcapsule" is define as a spherical particle with the size varying between 50 nm to 2 mm containing a core substance. When evaluating the wall thickness parameters, it was understood that microcapsule walls that were too thin would fail during the manufacturing process. In retrospect, capsule shells that are too thick will not allow wanted breaking or fracturing of the shell as the crack penetrates through the microcapsules plane. This method also achieved a specific robustness, virtual toughness, and a strong interface with the matrix and the microcapsule itself (Tseng, 2005).

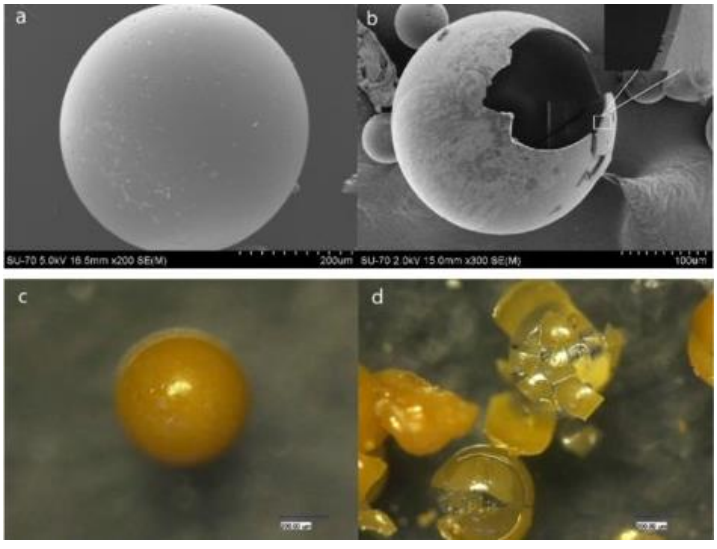

Figure 1.1: Surface morphology of microcapsules

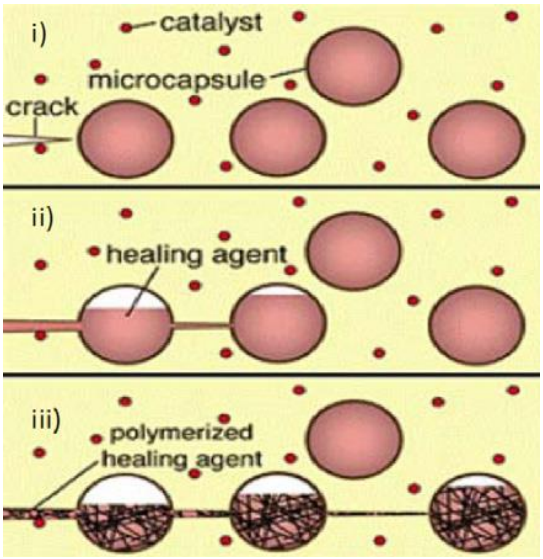

Figure 1.2: Microencapsulated healing agent embedded in the matrix (Wu, Johannesson and Geiker, 2012)

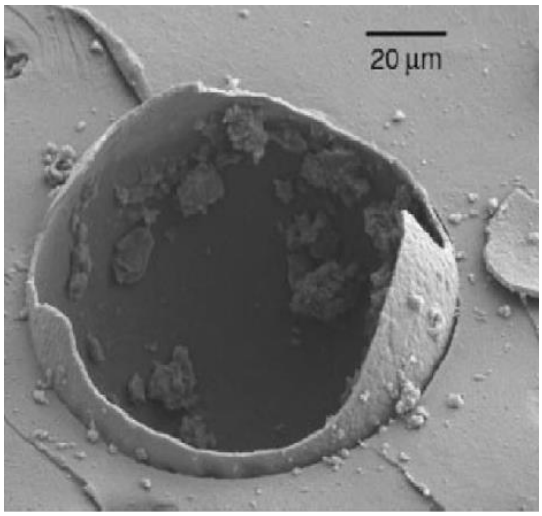

Figure 1.3: Condition of microcapsule when crack happen (Wu, Johannesson and Geiker, 2012)

To ensure that the microcapsules are utilised in the most effective manner possible, the microcapsules should have the following properties: an appropriate shell thickness and size, a healing agent, mixing viability, good compatibility with the concrete matrix, interfacial adhesion, and good fracture sensitivity. (Indhumathi, Dinesh and Pichumani,

2022). This review will further discuss the contributing factors in mechanism involved and how material properties will result in continued self-healing.

In this review, sodium silicate, Na_2O_3Si is the healing agent used as a active ingredient and main material in the microcapsules. CSH gel, also known as calcium-silica-hydrate gel, is produced when sodium silicate combines with calcium hydroxide, a waste product generated during the hydration of cement. The resulting CSH gel will act as a binding material and healer in cracks and pores. The CSH gel will serve as a lubricant and a healer in the crevices and pores of the material. A healing agent, sodium silicate, is encapsulated and embedded in the concrete. When a crack spreads to the microcapsule, the shell of the capsule rupture, releasing sodium silicate, which is present as main material in the microcapsule and reacting with calcium hydroxide to form CSH gel. (Litina and Al-Tabbaa, 2020). It is important to review the material properties of the microcapsules and the amount of sodium silicate that needs to be build on to the concrete matrix to make sure the efficiency of self-healing concrete. This goal of this study is purposely to perform a systematic literature review to identify gaps in the current knowledge of the mechanism of microencapsulated and the performance of sodium silicate in self-healing concrete.

1.2 Research questions

i. What is the effective mechanism of microencapsulated to heal the crack of concrete?
ii. How does sodium silicate help improve the performance of self-healing concrete?
iii. What is the next journey or direction of research in this field?

1.3 Objectives of the systematic review

i. To investigate the contributing factors in the mechanism of microencapsulated as a concrete self-healing agent.

ii. To review the performance of sodium silicate as an agent for self-healing concrete.

iii. To identify the gap of knowledge of using microencapsulated containing sodium silicate as a concrete self-healing agent.

1.4 Scope of the systematic review

Self-healing concrete is a special, innovative concrete that can self-heal small cracks. The usage of concrete healing has been widely investigated over the last decade and many methods are involved in the crack self-healing (Figure 1.3) (Sidiq, Gravina and Giustozzi, 2019). Although there are many methods used in self-healing concrete, in this review, only autonomous self-healing methods will be discussed further. Microencapsulated is one of the most common techniques categorized under the autonomous method to deliver the healing agent to recover the concrete crack and sodium silicate is the act as an agent that dispersed into the concrete matrix. This method is examined using a systematic literature review.

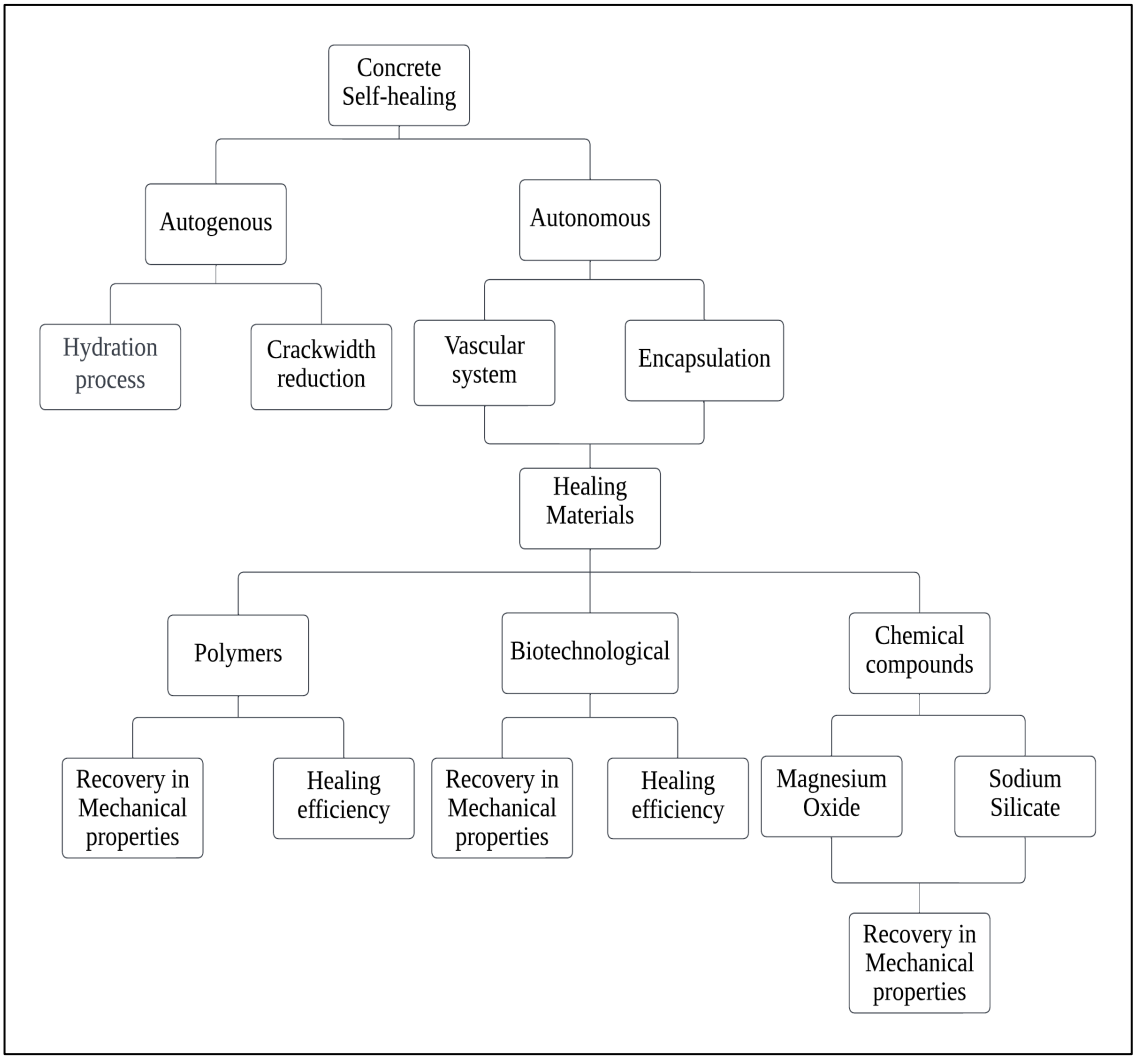

Figure 1.4: Classification of self-healing concrete (Sidiq, Gravina and Giustozzi, 2019)

1.5 Significance of the systematic review

The anticipated outcome of this project will be a systematic review of the contributing factors in the mechanism of microcapsules and the performance of sodium silicate as an agent in self-healing concrete. This review can help to determine the effect of microcapsules usage and the accomplishment of sodium silicate utilized in the concrete mix to achieve successful self-healing. Furthermore, it may be challenging to determine the fundamental of microcapsules' material properties and their preparation; nonetheless, this review gives guidance in presenting the specific process parameters and basic properties of microcapsules. Lastly, the reader can obtain information from the literature review about microencapsulated containing sodium silicate in self-healing concrete which can result in up to an 80% recovery of toughness after a fracture.

CHAPTER 2

SYSTEMATIC LITERATURE REVIEW (SLR) PROTOCOL

2.1 Introduction

A literature review is a collection of current knowledge that includes substantive results as well as methodological contributions to a specific area of interest (Sani, 2017). It provides a summary of current knowledge, enabling the identification of pertinent theories, methods, and research gaps. Literature reviews are classified as secondary sources, and it is strongly recommended that they include academic-oriented literature found in recommended books and scholarly journal articles (in form of pdf format).

Traditional or narrative literature reviews and systematic literature reviews are the predominant types of literature reviews. Systematic literature review concentrates on promoting research knowledge (Bruette and Fitzig, 1993). A traditional literature review is a thorough, critical, and unbiased examination of the most recent research on a subject. They are an important aspects of the research method because they aid in the development of a theoretical framework as well as the focus or context for the investigation.

There should be a clear protocol or strategy for the systematic review to follow before it is conducted, including a list of the review's criteria. It is a transparent, exhaustive search of numerous databases and grey literature that other researchers can replicate. It requires formulating a well-considered search strategy with a specific focus or to answer particular questions. The evaluation specifies the categories of data to be retrieved, analysed, and reported by the due dates. The evaluation must include search terms, search strategies including database names, search platforms, and search dates and limits. (Literature review: Systematic Literature Reviews, 2022).

The phases of the protocol for conducting a systematic literature review are including the planning phase, conducting phase, and reporting phase. The components of the protocol are in sequence and illustrated in (Figure 2.1). Moreover, each of these components will be discussed in detail in each of the subchapters as follows:

- Planning of SLR (Chapter 2, section 2.2)
- Conducting the SLR (Chapter 2, section 2.3)
- Reporting SLR (Chapter 2, section 2.4)

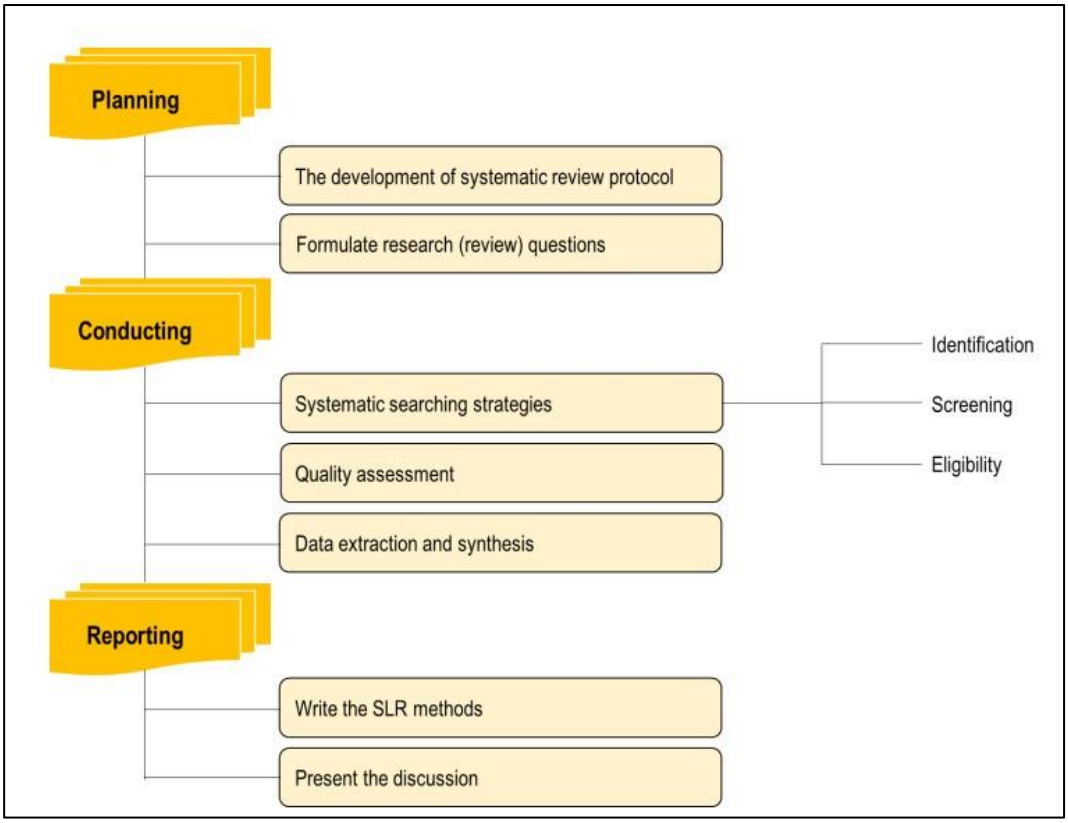

Figure 2.1: Flow chart of SLR protocol

2.2 Planning of SLR

The systematic review must strictly follow pre-defined and transparent steps before collecting the evidence. A successful review consists of three main phases: review planning, review execution, and review reporting. In the planning phase, researchers evaluate the necessity of a review, define research questions, and develop a review

procedure. (Kitchenham and Charters, 2007). Before executing the review methodology, it is critical to thoroughly validate it and understand the title background to give an overview of the topics. This will help the researcher to define and refine the review questions of the topics and set the inclusion and exclusion criteria. In the below subsection, the researcher will discuss the detailed process of a systematic literature review related to the topic “Influence Of Microencapsulated As A Concrete Self Healing Agent Containing Sodium Silicate”.

2.2.1 Review of protocol

The need for a systematic review comes from the need for researchers to summarise all current knowledge regarding a phenomenon in a complete and unbiased manner. It is prudent to conduct a preliminary area scan in order to account for previous literature reviews, determine the number of research studies that must be evaluated, and formulate and clearly define the review's purpose, scope, and specific research question. (Snyder, 2019).

The systematic review was performed by the Preferred Reporting Items for Systematic Reviews and Meta-analyses guideline (PRISMA). As a tool for systematic reviewers, the transparent reporting of the review's motivation, the authors' actions, and their findings was a goal of PRISMA 2009's design. The PRISMA 2020 statement replaces the 2009 statement and includes fresh reporting guidelines that account for advancements in techniques for finding, choosing, assessing, and synthesising studies. There are 27 items on the PRISMA 2020 checklist, a diversify checklist that includes the specific reporting recommendations for each item, an abstract checklist and the revised flow diagram of a robust protocol for a systematic review. However, just a subset of the items listed in PRISMA-P is used in this review. (Table 2.1)

Table 2.1: Selected PRISMA-P item checklist

Item no.	Item in PRISMA-P	Detail
3	Rationale	Describe the rationale for the review in the context of existing knowledge.
4	Objectives	Provide an explicit statement of the objective(s) or question(s) the review addresses.
5	Eligibility criteria	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.
6	Information sources	Specify all databases, registers, websites, organizations, reference lists, and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.
7	Search strategy	Present the full search strategies for all databases, registers, and websites, including any filters and limits used
8	Selection process	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.
9	Data collection process	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the Process

10b	Data items	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.
11	Study risk of bias assessment	Specify the methods used to assess the risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.
13c	Synthesis methods	Describe any methods used to tabulate or visually display the results of individual studies and syntheses.
14	Reporting bias assessment	Describe any methods used to assess the risk of bias due to missing results in a synthesis (arising from reporting biases).
16a	Study selection	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram
17	Study characteristics	Cite each included study and present its characteristics.
20a	Results of syntheses	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.
20d		Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.
22	Certainty of evidence	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.

23b	Discussion	Discuss any limitations of the evidence included in the review.
23c		Discuss any limitations of the review processes used.

2.2.2 Formulation of the research question

The most crucial aspect of any systematic review is the formulation of research questions. The research questions are required since they determine the possibility of the review being published as well as its impact on the research community (Snyder, 2019). From the research questions, it will determine the objective as the answer for the questions and become an outcome of this review paper.

Table 2.2: Relationship between research questions and research objectives

Research question 1 (RQ1)	What is the effective mechanism of microencapsulated to heal the crack of concrete?
Research objective 1 (RO1)	To investigate the contributing factors in the mechanism of microencapsulated as a concrete self-healing agent
Research question 2 (RQ2)	How does sodium silicate help to improve the performance of self-healing concrete?
Research objective 2 (RO2)	To review the performance of sodium silicate as an agent for self-healing concrete
Research question 3 (RQ3)	What is the next journey or direction of research in this field?
Research objective 3 (RO3)	To identify the gap of knowledge of using microencapsulated containing sodium silicate as a concrete self-healing agent.

2.3 Conducting the SLR

After determining the precise research question and the review's purpose, it is time to conduct the actual review. In conducting phase, there are three sub-processes are performed in a particular phase which are systematic searching strategy, quality assessment, data extraction, and data synthesis. This sub-process will be explained further in the subsequent subtopic.

- Systematic searching strategy (Chapter 2, section 2.3.1)
- Quality assessment (Chapter 2, section 2.3.2)
- Data extraction and data synthesis (Chapter 2, section 2.3.3)

2.3.1 Systematic searching strategy

This phase includes a method for searching and disseminating the relevant articles from scholarly sources and electronic databases. The search strategy assists in determining the required search string to make the findings easier. Identification, screening, and eligibility are the three subprocesses of systematic searching strategies.

2.3.1(a) Identification

The first sub-process in a systematic search strategy process is to identify synonyms, comparable phrases, and variations of the keyword. The keywords can be derived from the topic, review questions, and the review objectives (see Table 2.3). The initial searches for primary studies can be undertaken using electronic databases. Scopus, ScienceDirect, and Google Scholar served as the search engines for this review. These various, globally renowned databases were searched in order to gather pertinent information from publications. Science Direct is an online websites which provide access to large bibliographic database operated by the Elsevier while Scopus is a platform that combines an expertly curated abstract and citation database with enriched information

and widely-read scholarly literature. When it comes to covering citations that aren't covered by other databases, Google Scholar is a useful tool. The search delivery step involves using the search string to gain access to the chosen database in order to collect multiple pieces of literature that are related to one another.

When searching in the databases, combining or excluding keywords with the Boolean operator yields a search string with more targeted and actionable results. To save time and effort, unnecessary hits will be filtered out before being discarded. Boolean "OR" aims to connect two or more similar synonyms word while Boolean "AND" is used to link the main terms to create searching strings. Thus, the search string was listed in Table 2.4.

Table 2.3: Identification of main and enriched keywords

Section	Main keywords	Enriched keywords
Title Influence Of Microencapsulated As A Concrete Self Healing Agent Containing Sodium Silicate	1. influence 2. microencapsulated 3. concrete self-healing 4. agent 5. sodium silicate	1. Consequence, effect, significance 2. embedded 3. concrete self-repairing, crack concrete 4. material, admixture
RO1 To investigate the contributing factors in the mechanism of microencapsulated as a concrete self-healing agent	1. mechanism 2. microencapsulated 3. concrete self-healing 4. agent	1. process, technique, procedure, performance 2. embedded 3. concrete self-repairing, crack concrete 4. material, admixture

RQ1 What is the effective mechanism of microencapsulated to heal the crack of concrete?	1. effective 2. mechanism 3. microencapsulated 4. heal 5. crack	1. adequate, successful, competent, efficient 2. process, technique, procedure, performance 3. embedded 4. repair, improve, rebuild, fix
RO2 To review the performance of sodium silicate as an agent for self-healing concrete	1. performance 2. sodium silicate 3. agent 4. self-healing concrete	1. achievement 2. concrete self-repairing, crack concrete 3. material, admixture
RQ2 How does sodium silicate help to improve the performance of self-healing concrete?	1. sodium silicate 2. improve 3. performance 4. self-healing concrete	1. develop, enhance, help 2. achievement 3. concrete self-repairing, crack concrete
RO3 To identify the gap of knowledge of using microencapsulated containing sodium silicate as a concrete self-healing agent.	1. microencapsulated 2. sodium silicate 3. concrete self-healing 4. agent	1. embedded 2. concrete self-repairing, crack concrete 3. material, admixture
RQ3 What is the next journey or direction of research in this field?	Refer RO3	

Table 2.4: Searching Strings Developed for Title

Database	Search String
Scopus	TITLE-ABS-KEY ((“influence” OR “consequence” OR “effect” OR “significance”) AND (“microencapsulated” OR “embedded”) AND (“concrete self-healing” OR “concrete self-repairing” OR “crack concrete”) AND (“agent” OR “material” OR “admixture”) AND (“sodium silicate” OR “Na2SiO3”))
Science Direct	("influence" OR "consequence) AND ("encapsulated" OR "embedded") AND ("concrete self healing") AND ("agent" OR "material" OR "admixture") AND ("sodium silicate")

Table 2.5: Searching Strings Developed for RO1

Database	Search String
Scopus	TITLE-ABS-KEY ((“mechanism” OR “process” OR “technique” OR “procedure” OR “performance”) AND (“microencapsulated” OR “embedded”) AND (“concrete self-healing” OR “concrete self-repairing” OR “crack concrete”) AND (“agent” OR “material” OR “admixture”))
Science Direct	(“mechanism” OR “process” OR “performance”) AND (“microencapsulated” OR “embedded”) AND (“concrete self-healing” OR “crack concrete”) AND (“agent” OR “material”)

Table 2.6: Searching Strings Developed for RQ1

Database	Search string
Scopus	TITLE-ABS-KEY ((“effective” OR “adequate” OR “successful” OR “competent” OR “efficient”) AND (“process” OR “technique” OR “procedure” OR “performance”) AND (“microencapsulated” OR “embedded”) AND (“heal” OR “repair” OR “improve” OR “rebuild”) AND (“crack”)
Science Direct	(effective” OR “successful”) AND (“process” OR “technique) AND (“microencapsulated” OR “embedded”) AND (“heal” OR “repair”) AND (“crack”)

Table 2.7: Searching Strings Developed for RO2

Database	Search string
Scopus	TITLE-ABS-KEY ((“performance” OR “achievement”) AND (“sodium silicate”) AND (“agent” OR “material” OR “admixture”) AND (“self-healing concrete” OR “concrete self-repairing” OR “crack concrete”))
Science Direct	(“performance” OR “achievement”) AND (“sodium silicate”) AND (“agent” OR “material”) AND (“self-healing concrete” OR “concrete self-repairing”)

Table 2.8: Searching Strings Developed for RQ2

Database	Search String
Scopus	TITLE-ABS-KEY ((“sodium silicate”) AND (“improve” OR “develop” OR “enhance” OR “help”) AND (“performance” OR “achievement”) AND (“self-healing concrete” OR “concrete self-repairing” OR “crack concrete”))
Science Direct	(“sodium silicate”) AND (“improve” OR “enhance”) AND (“performance” OR “achievement”) AND (“self-healing concrete” OR “concrete self-repairing”)

2.3.1(b) Screening

Screening is the second sub-process in the systematic searching strategy process, in which the inclusion and exclusion criteria for the articles to be reviewed are established. Timeliness, publication types, and language are the standard criteria considered in the inclusion and exclusion setup. The search was conducted in March 2022 on three databases (ScienceDirect, Scopus, and Google Scholar) utilising the search term and Boolean operators listed in Table 1, followed by a search of the references of the downloaded manuscripts. The search was limited to English-language manuscripts published between 2015 and 2022, as the author wished to evaluate all relevant guidelines reported in the scientific literature. Thus, precise inclusion and exclusion criteria were necessary to narrow the results to the most pertinent studies in order to meet the objectives of the review. (See Table 2.11)

Table 2.9: Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Timeline	2015-2022	Before 2015
Publication type	Research articles and review articles	Journal, book, note, newspaper, book chapter, conference proceeding, report, and short survey
Language	English	Other than English

2.3.1(c) Eligibility

The authors manually review the retrieved articles as part of the third sub-process of the systematic searching strategy to make sure that all of the articles that are still present after the screening process adhere to the criteria. This can be done by simply reading the papers' titles and abstracts. If there is still a lack of clarity about the relevance of the discovered articles to the study, the substance of the articles must be assessed.

2.3.2 Quality assessment

Each publication included in the final collection will be judged on its own quality. Primary studies must be evaluated in addition to the standard inclusion and exclusion criteria. The strength of the evidence and the awarding of grades to the systematic review recommendations are both determined by the study quality evaluation method. Each selected paper was subjected to a questionnaire with specific questions based on the research questions, research objectives, and the type of study in order to address bias and external validity. (Major, Kyriacou and Brereton, 2011)

The eligibility questions for the overall quality assessment criteria (QAC) were established by referring to the SLR conducted by (Caldwell et al., 2011), the article covers the establishment of a framework for critiquing health research. The framework

is designed to the framework proposed in this article addresses both quantitative and qualitative research within a single set of questions. However, not all questions are being used from the framework since some questions are not relevant to the current review topic. Furthermore, this review is a qualitative systematic review, therefore the quantitative question in the formwork will be ignored.

A value of 1 (‘Yes’) or 0 (meaning ‘No’, ‘Not applicable’, ‘cannot answer’) is entered into a table for each question regarding each piece of literature in the SLR. In the phase of confirming the eligibility, only 27 papers will be used for qualitative synthesis. To determine the quality of the articles, they are categorized into three rate of quality which are low quality (0-4 score), moderate quality (5-7) and high quality (8-10). From the assessment, all articles listed in Table 2.13 are categorized as high quality where the scores of each articles are within 8 to 10. As a result, those articles are appropriate for review.

Table 2.10: Description of the questions of QAC

Number	Question	Description
Q1	Does the title reflect the content?	The title should be related with content of study. The title must be precise and easy to understand.
Q2	Are the authors credible?	Researchers must have sufficient academic credentials and be affiliated with a professional discipline relevant to the research.
Q3	Does the abstract summarize the key components?	The abstract should be describe in simple way where it include the overall of study content. This include aim of study, methodology and main findings.

Q4	Is the rationale for the research clearly outlined?	The researcher should present clear rationale and knowledge for the research
Q5	Is the literature review comprehensive and up-to-date?	The literature review should reflect the current state of knowledge relevant to the study and identify any gaps for conflicts.
Q6	Is the aim of the research clearly stated?	The aim of study must clearly defined and that the settimg out to be accomplished by researchers is discussed.
Q7	Is the methodology identified and justified?	The researcher should state the methodology used to make the reade more understand what have been conducted.
Q8	Are the results presented in a way that is appropriate and clear?	The results of the study must be precise and easy to understand
Q9	Is the discussion comprehensive?	Detail discussions about the study must include the important keywords related to research questions and research objectives.
Q10	Is the conclusion comprehensive?	Conclusion should determine the outcome of the study. There may also consist of gap between study and recommendation for further research.

Table 2.11: The article assessment scoring mark

Answer	Score
Yes	1
No, can’t answer, not applicable	0

Table 2.12: The rate of quality of the articles

Categories	Total score
Low quality	0-4
Moderate quality	5-7
High quality	8-10

Table 2.13: The articles included in review

No	Title	Year
1	Numerical Studies of the Effects of Water Capsules on Self-Healing Efficiency and Mechanical Properties in Cementitious Materials	2015
2	Self healing concrete with a microencapsulated healing agent	2015
3	Self healing in cementitious materials: Materials, methods and service condition	2016
4	Synthesis and characterization of a new polymeric microcapsule and feasibility investigation in self-healing cementitious materials	2016
5	Sealing of cracks in cement using microencapsulated sodium silicate	2016
6	Impregnation and encapsulation of lightweight aggregates for self-healing concrete	2016
7	The effect of varying volume fraction of microcapsules on fresh, mechanical and self-healing properties of mortars	2016
8	Performance of modified self-healing concrete with calcium nitrate microencapsulation	2017
9	New self-healing techniques for cement-based materials	2017
10	Experimental Study on Self Healing Concrete using Micro Encapsulation	2017
11	Sodium silicate/polyurethane microcapsules used for self-healing in cementitious materials: Monomer optimization, characterization, and fracture behavior	2017
12	Ultrasonic Monitoring of the Interaction between Cement Matrix and Alkaline Silicate Solution in Self-Healing Systems	2017
13	Microencapsulated sodium silicate for self-healing cement-based in-ground barriers	2019
14	First UK field application and performance of microcapsule-based self-healing concrete	2019
15	Is concrete healing really efficient? A review	2019
16	Preparation and application of microcapsules containing toluene-di-isocyanate for self healing of concrete	2019