A SYSTEMATIC LITERATURE REVIEW (SLR) ON THE UTILIZATION OF ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED CONCRETE (UHPFRC) FOR REPAIR AND STRENGTHENING APPLICATION

RAUL HAKIM BIN ROSELI

SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2022

Appendix A8

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2021/2022

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: A Systematic Literature Review (SLR) on The Utilization of Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) for Repair and Strengthening Application

Name of Student: Raul Hakim Bin Roseli

I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

Signature:

Date: 11th August 2022

Approved by:

PROF. DR. MEGAT AZMI MEGAT JOHARI
LECTURER
SCHOOL OF CIVIL ENGINEERING
ENGINEERING CAMPUS
UNIVERSITI SAINS MALAYSIA

(Signature of Supervisor)

Name of Supervisor: Professor Dr. Megat Azmi Megat Johari

Date : 11th August 2022

Approved by:

(Signature of Examiner)

Name of Examiner: Professor Ir. Dr. Badorul Hisham Abu Bakar

Date : 11th August 2022

A SYSTEMATIC LITERATURE REVIEW (SLR) ON THE UTILIZATION OF ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED CONCRETE (UHPFRC) FOR REPAIR AND STRENGTHENING APPLICATION

By

RAUL HAKIM BIN ROSELI

This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)

(CIVIL ENGINEERING)

School of Civil Engineering,
Universiti Sains Malaysia

JULY 2022

ACKNOWLEDGEMENT

To begin, I would like to offer my deepest gratitude to Universiti Sains Malaysia, and more specifically to the School of Civil Engineering, for giving me the opportunity to carry out my final year project at this institution. If I did not have this option, it would be impossible for me to complete this review in the allotted amount of time.

Next, I would like to express my gratitude to my supervisor, Professor Dr. Megat Azmi Megat Johari, for assisting me throughout the process of completing the dissertation by giving me a great deal of useful advice, encouragement, and motivation. In addition, I would like to take this time to express my gratitude to each and every lecturer who has taught me thus far.

Last but not least, I want to express my gratitude to my family and friends who are directly and indirectly involved in this project. They have offered me both mental and physical support, which has made it possible for me to successfully complete this project. Thank you.

TABLE OF CONTENTS

LISTS OF TABLES

LISTS OF FIGURES

LISTS OF ABBREVIATIONS

ASR	Alkali-Silica Reaction
UHPC	Ultra-High-Performance Concrete
UHPFRC	Ultra-High-Performance Fiber-Reinforced Concrete

ABSTRAK

Disertasi ini membentangkan tinjauan literatur sistematik tentang penggunaan konkrit bertetulang gentian berprestasi ultra tinggi (UHPFRC) untuk membaiki dan mengukuhkan konkrit yang rosak. Terdapat dua objektif bagi kajian ini. Pertama ialah mengenal pasti kes-kes kemerosotan konkrit yang berbeza dan penggunaan UHPFRC yang sepadan dalam aplikasi pembaikan dan pengukuhan. Objektif seterusnya adalah untuk membandingkan dan menilai keberkesanan penggunaan UHPFRC dalam aplikasi pembaikan dan pengukuhan yang berbeza berdasarkan literatur yang ada. UHPFRC ialah komposit bersimen yang mempunyai kekuatan mampatan lebih tinggi daripada 150 MPa. Kekuatan konkrit yang tinggi adalah disebabkan oleh kandungan simennya yang tinggi, menjadikannya sesuai untuk digunakan sebagai bahan pembaikan. Daripada pangkalan data Scopus, terdapat 12 artikel yang telah dikenal pasti untuk semakan ini. Strategi carian sistematik digunakan untuk menapis artikel yang tidak berkaitan dan artikel itu ditapis semula melalui penilaian kualiti untuk terus membuang artikel berkualiti rendah. Dalam kajian ini, penggunaan UHPFRC yang digunakan untuk membaiki kes kemerosotan konkrit yang berbeza telah dibincangkan. Daripada artikel yang disemak, ia menunjukkan bahawa UHPFRC sudah digunakan secara meluas untuk merawat konkrit yang rosak akibat kakisan, retak dan ASR. Juga, pelbagai jenis kaedah telah digunakan untuk menggunakan UHPFRC pada konkrit yang rosak. Berdasarkan kajian yang disemak, keberkesanan konkrit yang dibaiki didapati boleh diterima. Walaupun UHPFRC mempunyai kekuatan mampatan yang tinggi, pemilihan bahan pembaikan harus berdasarkan mekanisme kemerosotan konkrit, keadaan tapak, dan keperluan pelanggan kerana bahan pembaikan yang berbeza datang dengan kelebihan dan kekurangan yang berbeza. Mengetahui sifat-sifat ini seharusnya membantu untuk menentukan bahan yang paling sesuai yang diperlukan untuk kerja-kerja pembaikan.

ABSRACT

This dissertation presents a systematic literature review about the utilisation of ultra-high-performance fiber-reinforced concrete (UHPFRC) to repair and strengthen damaged concrete . There are two objectives of this review. First is to identify the different cases of concrete deterioration and the corresponding utilization of UHPFRC in the repair and strengthening applications. The next objective is to compare and assess the effectiveness of the use of UHPFRC in different repair and strengthening applications based on the available literatures. UHPFRC is a cementitious composite that has compressive strength higher than 150 MPa. The high strength of the concrete is thanks to its high cement content, making it suitable to be used as repair material. From the Scopus database, there were 12 articles that had been identified for this review. Systematic searching strategies was used to filter out irrelevant articles and the articles are filtered again through quality assessment to further remove low quality articles. In this review, the usage of UHPFRC that is used to repair different cases of concrete deterioration were discussed. From the articles reviewed, it showed that UHPFRC is already widely used for treating concrete damaged by corrosion, cracking and ASR. Also, various kind of methods were used to apply the UHPFRC onto the damaged concrete. Based on the studies reviewed, the effectiveness of the repaired concrete was found to be acceptable. Although UHPFRC have high compressive strength, the selection of repair material should be based on the deformation mechanism, site condition, and client requirement because different repair materials come with different advantages and disadvantages. Knowing these properties should be helpful to decide the most suitable material needed for repair works.

CHAPTER 1

INTRODUCTION

1.1 Background

According to Buttignol et al., (2017), Ultra-High-Performance Concrete (UHPC) is a cementitious composite comprising of high cement content that is more than 600 kg, small aggregates size that is smaller than 6 mm, supplementary binder (silica fume, pozzolana) and low water/cement ratio that is lesser than 0.2. By utilising these properties in the concrete mix design, concrete characteristics such as dense, interconnected microstructure with high homogeneity, capillary porosity of lesser than 1.5 % and compressive strength higher than 150 MPa can be achieved. Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) incorporates steel fibres that significantly increases the tensile capacity of concrete. Hence, the concrete produced will have better performance, durability, bearing capacity and toughness as compared to normal concrete.

There are various applications of UHPFRC including the fabrication of precast elements for civil and structural engineering, archi-structural features, durable components exposed to marine or aggressive environments, blast or impact protective structures, strengthening material for repair/rehabilitation work for deteriorated reinforced concrete structures, portal frame building construction and others (Nematollahi & Voo, 2012). In this study, the major focus of the research is the utilization of UHPFRC for repair and strengthening application. Throughout the lifespan of any structure, its materials may be exposed to physical (fire damage, frost action), mechanical (erosion, abrasion, blast), or chemical (sulphate attack, carbonation, reinforcement corrosion) attacks if the materials are not protected and maintained correctly. This will result in early or quick deterioration and decay of concrete where the

concrete strength will be weakened, have unpleasant appearance and may also cause danger to person and property if left untreated.

When repairing concrete, the main concerns are to reduce water and air permeability, control the rate of corrosion, improve the aesthetic view, extend the life of a structure, etc (Megat Johari, 2021a). To achieve these objectives, it is important to select the most suitable repair material based on the cause of deterioration, owner requirements and service conditions. As mentioned earlier, since the properties of UHPFRC are superior to those of normal concrete, UHPFRC is a promising material that can be utilized to significantly increase the durability and structural resistance of deteriorated concrete structures.

While using UHPFRC may come with difficulties in terms of high initial cost and limited codes and guidelines, there are several studies that had utilised UHPFRC in their repair works with positive outcomes. A study had mentioned that when an existing concrete beam is repaired with UHPFRC as cross-sectional restorative material, it had resulted in higher stiffness and increased bending capacity as compared to the previously repaired thickness (Safdar et al., 2016). In a research work by Zmetra et al. (2017), UHPC has been used to repair a corroded bridge girder where the bearing capacity is increased to over five times the capacity of the damaged girder.

1.2 Problem Statement

Although the previously mentioned studies and other past studies had utilised UHPFRC in their repair works, there is only a few collective information regarding its effectiveness for different repair and strengthening applications. Hence, this study aims to undertake a comprehensive review by referring to relevant literatures so that the efficiency of UHPFRC for different repair and strengthening purposes could be evaluated.

1.3 Objectives of the Systematic Review

The objectives of the study are:

1. To identify the different cases of concrete deterioration and the corresponding utilization of UHPFRC in the repair and strengthening applications.
2. To compare and assess the effectiveness of the use of UHPFRC in different repair and strengthening applications based on the available literatures.

1.4 Review Questions

1. In which type of defect or deterioration scenarios of concrete structures is UHPFRC used for repair and strengthening?

2. How effective is UHPFRC when it is used to repair and strengthen the corresponding concrete structures undergoing deterioration or defect?

1.5 Significance of Study

The proposed project is beneficial to expose the application of UHPFRC in the repair and strengthening works of deteriorated concrete to Civil Engineers and the public. This allows the people to have more options to consider when repairing damaged

structures. By considering the relevant conditions, effective, durable, sustainable and economical repair works may be achieved.

1.6 Scope of Study

Due to its high compressive strength, UHPFRC has been utilised in various kinds of work including the construction of tall buildings, rehabilitation works, structural elements, non-structural elements, machine parts, dams and also military structures. The scope of this study is limited to the utilization of UHPFRC in repair and strengthening application. The study focuses on usage or potential usage of UHPFRC that is available from the literature within the past five years.

1.7 Overall Structure of Dissertation

This dissertation is presented in five chapters and appendices which attempt to discuss different subtopics related to the title. The chapters are organised to aid the readers to understand the topic better. The chapters in this dissertation are summarised as follows from chapter 1 to chapter 5.

Chapter 1: Introduction. The first chapter briefly introduces the overall structure of the dissertation comprising background of the study, problem statement, objectives and the review questions so that the readers will have the general idea of the topic reviewed.

In the second chapter, **Chapter 2: Systematic Literature Review: A Methodology,** the processes involved to produce the systematic literature review is explained. The phases of planning, conducting and reporting of the topic are described in detail such that consistent results can be reproduced if the topic is reviewed using the same methods.

Chapter 3: Data Extraction and Synthesis. In the third chapter, the overview of the method used for data extraction and synthesis is provided. The processes explained in this topic are the final process before making the conclusions for the review.

In the fourth chapter, **Chapter 4: Results and Discussions,** the information obtained from the research articles studied is discussed and analysed to answer the review questions in Chapter 2. Also, the divergence and gap of knowledge between the articles reviewed are discussed in this chapter.

Chapter 5: Conclusions and Recommendations. In the fifth chapter, the overall work and the results are summarised. The conclusions derived from the extracted and reviewed information as well as appropriate future research recommendations are provided.

CHAPTER 2

SYSTEMATIC LITERATURE REVIEW: A METHODOLOGY

2.1 Introduction

A systematic literature review (SLR) is a literature review designed to locate, appraise, and synthesize the best available primary scholarly sources relating to specific review questions in order to provide informative and evidence-based answers (Boland et al., 2017). Through SLR, it is possible to give different perspective towards previous research works. A literature review should summarise and synthesise its sources at the same time. By summarising, important information is extracted from the sources whereas by synthesising, the information is reorganized to answer the review questions. Through the synthesis of the information, a new opinion or argument can be inspired by old materials or combined new with old materials. For researchers with expertise on the reviewed topic, they can determine the contradiction and knowledge gap from the reviewed sources. This could help to filter out unreliable sources of information and also to maintain the credibility of the paper.

SLR requires the scholar to review numerous information to determine the answer to their review questions. The relevant information from the research article will be identified, selected and synthesized to answer the review questions. In the systematic review, there is a strict and well-defined method for conducting the review, unlike the traditional review. It has a clearly stated aim, review questions, searching method, stating inclusion and exclusion criteria, etc. to produce a qualitative review paper (Jesson, 2011). Because of reviewing a large amount of the papers or articles based on the review questions, the contradiction and gap of knowledge can be easily known as well as can clarify where further research is needed in the future (Jesson, 2011).

2.2 Planning of SLR

This systematic literature review is conducted to determine the usage and effectiveness of UHPFRC in concrete repair and strengthening works. Some basic understanding or background about the title is required because it can help to form a brief overview on how to develop the sections such as objectives, review questions, protocol and methodologies (Bettany-Saltikov, 2016). SLR requires that a clear review protocol must be developed before the starting of the review which consists of planning stage, conducting stage and reporting stage. There are detailed procedures for each stage to ensure the review is carried out smoothly and minimize the author bias when presenting the discussion.

2.2.1 Review Protocol

Before conducting the systematic literature review, a clear protocol is needed as it can be a guide to carry out the review. The preparation of a protocol is an integral component of the systematic review process. It assures that a systematic review is carefully prepared and that what is scheduled is reported before the review begins, fostering transparent review team behaviour, reliability, scientific credibility, and transparency of the final completed review (Shamseer et al., 2015). With the protocol, it will be easy to specify the objectives, review questions and purpose of the project because it is an explicit statement and explanation of the steps that should be taken (Jesson et al., 2011).

In this review protocol, the PRISMA-P (Preferred reporting items for systematic review and meta-analysis protocols) checklist is adopted for the preparation of the protocols. PRISMA-P aims to improve the quality and consistency of systematic review protocols, like the other reporting guidelines giving similar impact to review such as

Cochrane and Campbell. PRISMA-P is a checklist that lets scholars formulate protocols for proposed systematic reviews and meta-analyses by providing them with a minimum list of things to use in the protocol. Before embarking on a review, it provides the rationale for the review as well as the pre-planned methodological and analytic approach (Shamseer *et al.*, 2015). PRISMA-P 2015 checklist contains 17 numbered items and are categorized into three main sections which are administrative information, introduction and methods. However, this review only adopts some items that are listed in PRISMA-P. The SLR is separated into three stages which are the planning stage, conducting stage and reporting stage (Figure 2.1).

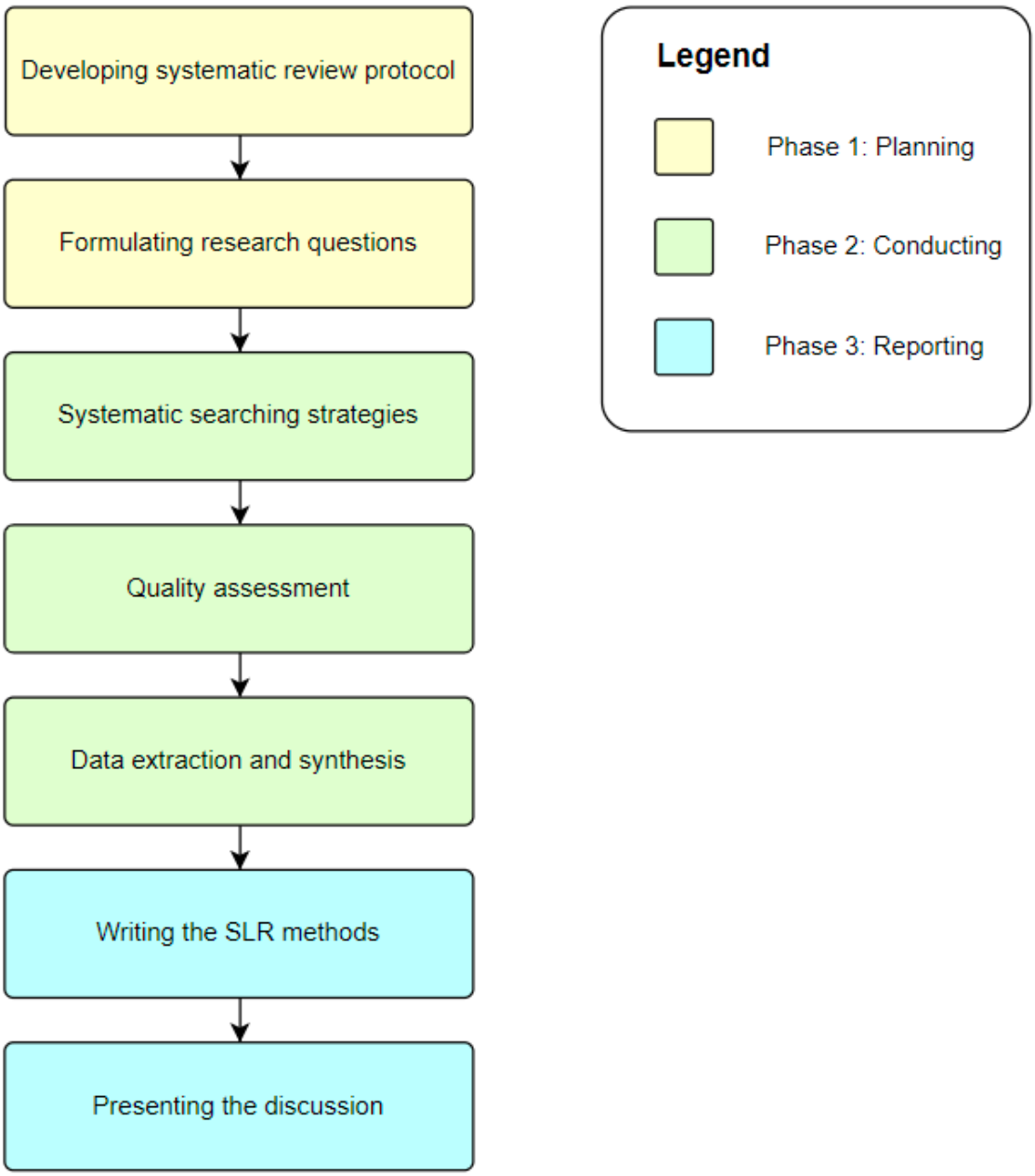

Figure 2.1 Processes of SLR

In the planning stage, once the title of the study has been determined, a review protocol must be formulated. Then, the objectives of the review will be specified to provide clear statement questions or review questions which addressed concerning the participants, interventions, comparators and outcomes. Further discussion of the review questions is presented in section 2.2.2.

In the conducting stage, it is more focused on the searching and processing of the research article. Systematic searching strategies are used to find the related article from the database by using the main term from the topic and objectives. Then, the filtering process for the articles is carried out to exclude the irrelevant and duplicated article, left only the vital article. After the searching of the article from the database, a quality assessment for the selected article will be carried out. Quality assessment is one of the article appraisals to show how much the sensitivity and accuracy of an article can be met with the review questions or objectives. Therefore, it gives less bias and more reliable to the review. For the data extraction part, it is the procedure for data extraction from each article such as the author, the aim of the study and the result of the study. Meanwhile, the data synthesis part is responsible for synchronizing all the articles to find the answer to the review question. Since this systematic literature review is qualitative, the combined result will be categorized under major themes or subthemes (Bettany-Saltikov, 2016). Therefore, the information extracted from each article will be presented in a table so that the contradiction and similarity of each article can be easily shown and reviewed.

In the reporting stage, it is the process to summarize, synthesize, and present the answer to the review questions. In this study, the report will be reviewed under the themes or categories which are thematic analysis. A thematic analysis of literature is a technique of evaluating qualitative data that closely examines the data to define similar themes – concepts, thoughts, and trends of context that appear frequently. Since there will be a

table of thematic synthesized information from each article, it will be easy for us to answer the review questions that are set at the planning stage and can interpret the gap of knowledge among the articles. Apart from this, the recommendations can be done for future researchers about the topic or field to improve their future work.

2.2.2 Formulation of Review Questions

The systematic literature review's goal is to update the current status of this research work. This will be accomplished by translating the knowledge gap into a well-constructed research question that can be answered. If the review or research topic is well-formulated, the researcher will have an easier time with data extraction, data synthesis, and report writing during the inclusion and exclusion phase (Xiao and Watson, 2017). In Chapter 1, it was stated that UHPFRC is used in a variety of ways in the building sector. However, the primary focus of this study will be the use of UHPFRC for strengthening and repair operations. The clear formulation of the question is produced from the PICOS acronym, which stands for participants, interventions, comparisons, outcomes, and study designs, according to point number 4 on the PRISMA checklist for 2009 (Liberati et al., 2009). On the other hand, given that the primary goal of the PRISMA project was to promote the production of healthcare interventions, the mentioned component may not be suited for the systematic evaluation of engineering research (Liberati et al., 2009). As a result, the PRISMA checklist that is utilised to create the review question has undergone some changes.

Implementing a more precise review topic can help to prevent an unmanageable review from arising if a research question is too broad (Liberati et al., 2009). As previously stated, research questions emerge from information gaps. The period for this study has been condensed to the most recent five years (2018-2022) in order to analyse the trend and lack of research connected to the use of UHPFRC for repair and

strengthening works. Only one database is used for the study, Scopus, to look for relevant papers to review the trend and the gap in knowledge. To discover relevant papers, search phrase that includes the terms "UHPFRC" and "repair" was used on January 15th, 2022, to scan through the article titles, abstracts, and keywords in Scopus. In addition, the following inclusion criteria is established:

1. Written in English
2. Published between 2018 and 2022
3. Document type: article, conference paper, review
4. Source type: journal
5. Final publication

To make the topic summarising process easier, every downloaded result from Scopus is exported to Mendeley in the form of a pdf file. Approximately 40 non-duplicate papers that met the above criteria were published throughout those five years. According to the graph in Figure 2.2, between the years 2018 and 2022, there was a decreasing pattem in the number of articles with a related topic ("UHPFRC" AND "repair") over these five years. This conclusion is based on the fact that the research reached its peak in 2020 and started to reduce from there. Each publication has been organised according to the year it was first published to make it easier to follow the history of UHPFRC's repair and strengthening application. Each paper's abstract, objectives, and conclusion were examined by the researcher in order to produce a summary of the problem statement, objective, research gap, and suggestion. Following that, all of the materials from each study are summarised by year, and the results are displayed in Table 2.4. As a result, this review will address the following fundamental research topic:

1. In which type of defect or deterioration scenarios of concrete structures is UHPFRC used for repair and strengthening?
2. How effective is UHPFRC when it is used to repair and strengthen the corresponding concrete structures undergoing deterioration or defect?

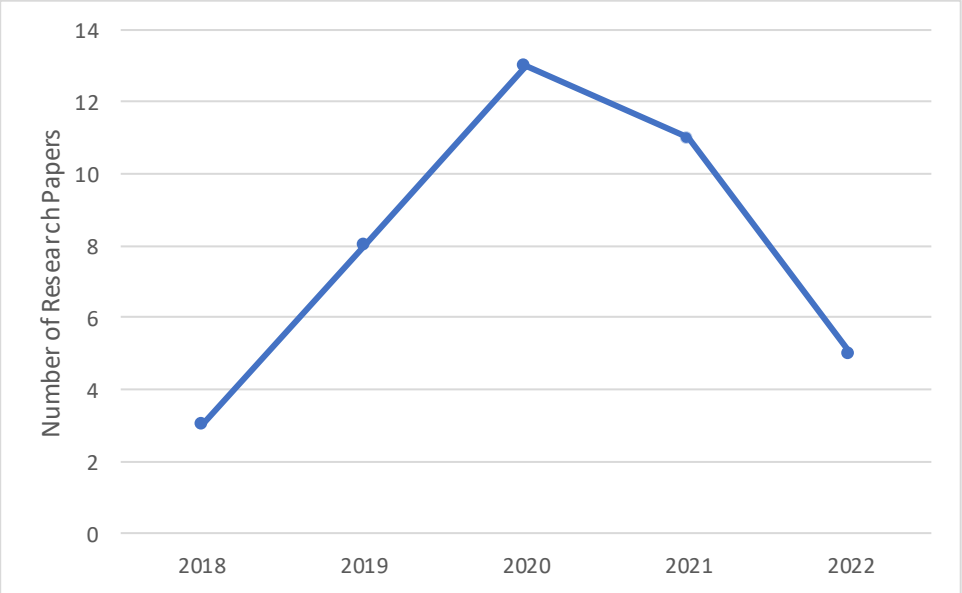

Figure 2.2 Graph of Number of research paper vs searching string "UHPFRC and "Repair"

2.3 Conducting the SLR

A systematic review is a review of the literature that is intended to identify, evaluate, and synthesize the best available information relating to the research questions to provide informative and evidence-based answers (Boland et al., 2017). When conducting the systematic review, it is important to obtain as many as possible studies that are related to the objectives or the review questions. A searching strategy will be applied by defining the synonym for the objectives and the review questions to widen the searching and then filtering for the eligibility article is done. Once finishing the filtering, the quality assessment for the articles included will be done to examine the confidence of review findings for extra evaluation on the methodological quality of the research. Then, data extraction and synthesis for the article will be carried out to obtain and process the necessary information about the study characteristics and findings from the studies.

2.3.1 Systematic Searching Strategies

The PRISMA flow diagram, shown in Figure 2.3, serves as the foundation for the search framework. Identification, screening, eligibility, and inclusion are the four phases depicted in this diagram (Shamseer et al., 2015). Scopus will be the only database searched according to the PRISMA flow diagram. The PRISMA flow diagram illustrates the initial search as a collection of databases, thus it meets the requirements described in the item no. 8 of PRISMA checklist 2009 (Liberati et al., 2009).

The goal of the systematic searching tactics in this systematic review is to identify potential articles from the electronic database, following which the undesirable articles are filtered away. The technique for carrying out the strategized search is divided into

three stages: the identification stage, the screening stage, and the eligibility step. Scopus was the electronic database used in this evaluation throughout the phase including the identification of relevant research. This review contains five searching statements that are dependent on the topic, objectives, and review questions. The topic, objectives, and review questions are used to achieve sensitivity and specificity in searching. This is done by isolating the keyword or main phrase from the sentences and then enriching them with synonym, related, and variation terms. As a result, the search engine can retrieve a large portion of the relevant item while only retrieving a small portion of the irrelevant article, (See also Table 2.1).

Following that, the Boolean operator is used to construct a Scopus searching string by connecting keywords and the enhanced keyword to one another. The Boolean operator "OR" is used for synonyms, related phrases, and variations, whereas the Boolean operator "AND" is used to connect the main term. After checking that all of the keywords and the enriched term are correct, the searching string will be utilised to conduct the search within Scopus. Table 2.2 can be used to find information about the searching strings that are applied to each statement.

Table 2.1: Searching statement with the main term and enriched keyword in identification stage

	Searching Statement	Main Keywords	Enriched Keywords
Topic	A systematic literature review on the utilization of Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) for repair and strengthening application	• Ultra-High-Performance Fibre-Reinforced Concrete • Repair, Strengthening	• UHPFRC, Ultra-High-Performance Concrete, UHPC • Restore, restoration, rebuilding, reparation, servicing, Brace, Reinforce

RO1	To identify the different cases of concrete deterioration and the corresponding utilization of UHPFRC in the repair and strengthening application.	• Deterioration • UHPFRC • Repair, Strengthening	• Decay, Failure, Collapse, Worsening, Damaged • Ultra-High-Performance Fibre-Reinforced Concrete, Ultra-High-Performance Concrete, UHPC • Restore, restoration, rebuilding, reparation, servicing, Brace, Reinforce
RQ1	In which type of deterioration is UHPFRC used for repair and strengthening?	• Deterioration • UHPFRC • Repair, Strengthening	• Decay, Failure, Collapse, Worsening, Damaged • Ultra-High-Performance Fibre-Reinforced Concrete, Ultra-High-Performance Concrete, UHPC • Restore, restoration, rebuilding, reparation, servicing, Brace, Reinforce
RO2	To compare and assess the effectiveness of the use of UHPFRC in different repair and strengthening applications based on the available literatures.	• Effectiveness • UHPFRC • Repair, Strengthening	• Success, Usefulness, Advantage • Ultra-High-Performance Fibre-Reinforced Concrete, Ultra-High-Performance Concrete, UHPC • Restore, restoration, rebuilding, reparation, servicing, Brace, Reinforce
RQ2	How effective is UHPFRC when it is used to repair and strengthen the corresponding deterioration?	• Effective • UHPFRC • Repair, Strengthening • Deterioration	• Success, Useful, Advantage • Ultra-High-Performance Fibre-Reinforced Concrete, Ultra-High-Performance Concrete, UHPC • Restore, restoration, rebuilding, reparation, servicing, Brace, Reinforce • Decay, Failure, Collapse, Worsening, Damaged

Table 2.2 Searching string for each statement and its number of articles found

	Search Strings (Scopus)	Number of the article (identification stage)
Topic	TITLE-ABS-KEY (("Ultra-High-Performance Fibre-Reinforced Concrete" OR "UHPFRC" OR "Ultra-High-Performance Concrete" OR "UHPC") AND ("Repair" OR "Restore" OR "Restoration" OR "Rebuilding" OR "reparation" OR "servicing" OR "Strengthening" OR "Brace" OR "Reinforce"))	478
RO1	TITLE-ABS-KEY (("Deterioration" OR "Decay" OR "Failure" OR "Collapse" OR "Worsening" OR "Damaged") AND ("Ultra-High-Performance Fibre-Reinforced" OR "Ultra-High-Performance Concrete" OR "UHPC") AND ("Repair" OR "Restore" OR "restoration" OR "rebuilding" OR "reparation" OR "servicing" OR "Strengthening" OR "Brace" OR "Reinforce"))	180
RQ1	TITLE-ABS-KEY (("Deterioration" OR "Decay" OR "Failure" OR "Collapse" OR "Worsening" OR "Damaged") AND ("Ultra-High-Performance Fibre-Reinforced" OR "Ultra-High-Performance Concrete" OR "UHPC") AND ("Repair" OR "Restore" OR "restoration" OR "rebuilding" OR "reparation" OR "servicing" OR "Strengthening" OR "Brace" OR "Reinforce"))	180
RO2	TITLE-ABS-KEY (("Effectiveness" OR "Success" OR "Usefulness" OR "Advantage") AND ("Ultra-High-Performance Fibre-Reinforced Concrete" OR "UHPFRC" OR "Ultra-High-Performance Concrete" OR "UHPC") AND ("Repair" OR "Restore" OR "restoration" OR "rebuilding" OR "reparation" OR "servicing" OR "Strengthening" OR "Brace" OR "Reinforce"))	71
RQ2	TITLE-ABS-KEY (("Effectiveness" OR "Success" OR "Usefulness" OR "Advantage") AND ("Ultra-High-Performance Fibre-Reinforced Concrete" OR "UHPFRC" OR "Ultra-High-Performance Concrete" OR "UHPC") AND ("Repair" OR "Restore" OR "restoration" OR "rebuilding" OR "reparation" OR "servicing" OR "Strengthening" OR "Brace" OR "Reinforce") AND ("Decay" OR "Failure" OR "Collapse" OR "Worsening" OR "Damaged"))	31

The screening stage comprises two phases and is used to filter out irrelevant items from the identification stage based on inclusion and exclusion criteria (see Table 2.3). The first part of the screening stage for articles is limited to the most recent 5 years of publication (2018-2022), article type document, final published document, and English. The second part involves filtering through the titles and abstracts of the remaining articles, as well as reviewing the full text of the articles, if necessary, to ensure that the article can answer the review questions (Bettany-Saltikov, 2016). Because there are five searching statements in this review, the screening stage is completed for each searching statement.

It is beneficial to construct an acceptable research paper selection form throughout both phases in order to standardise the papers that meet the established criteria. Following the completion of the screening stage, the eligibility stage will be carried out. Duplicate articles are removed by exporting the articles into Mendeley, leaving only the remaining articles to be examined. Articles that are irrelevant to the discussion are excluded from the results with their reasoning tabulated in Table 2.4 and the remaining articles for review are listed in Table 2.5. The total number of articles in each stage (identification, screening, and eligibility) is kept track of and is translated into PRISMA flow diagram as shown in Figure 2.3. These search tactics help to ensure that the review is transparent and without bias on one side. Hence, the authenticity of the review's findings will be enhanced.

Table 2.3 Review criteria of the article in the screening stage

Criteria	Inclusion	Exclusion
Timeline	2018-2022	Before 2018
Document type	Article	Conference paper, review, book chapter, conference review, book, note, short survey, editorial and report
Publication stage	Final	Article in press
Language	English	Non-English

Table 2.4 List of inclusion and exclusion paper with criteria

No	Year	Title	Description	Status	Remark
1	2018	First application of UHPC bridge deck overlay in North America		OK	top surface deck crack
2	2018	Extending the lifetime of steel truss bridges by cost-efficient strengthening interventions	not relevant to research question	excluded	
3	2018	Prediction of flexural behaviour of RC beams strengthened with ultra high performance fiber reinforced concrete		OK	overlay
4	2019	Behavior evaluation of ultrahigh-performance concrete beam containing para-aramid fibers	not relevant to research question	excluded	
5	2019	Design of Various Shear Connectors for Repair of Corroded Steel Girders with Ultra-High Performance Concrete		OK	corroded bridge girder ends
6	2019	Chloride penetration at cold joints of structural members with dissimilar concrete incorporating UHPC		OK	corrosion
7	2019	Experimental investigation on the perfomance of historical squat masonry walls strengthened by UHPC and reinforced polymer mortar layers		OK	masonry walls strengthening
8	2019	Embedded carbon fiber-reinforced polymer rod in reinforced concrete frame and ultra-high-performance concrete frame joints	not relevant to research question	excluded	
9	2019	Simplified method to estimate the moment capacity of circular columns repaired with UHPC	not relevant to research question	excluded	

10	2019	Life cycle analysis of strengthening existing RC structures with R-PE-UHPFRC	not relevant to research question	excluded	
11	2019	Investigating the impacts of ultra-fine calcium carbonate in high-volume fly ash concrete for structural rehabilitation for sustainable development	not relevant to research question	excluded	
12	2020	Potential Use of Ultra High-Performance Fibre-Reinforced Concrete as a Repair Material for Fire-Damaged Concrete in Terms of Bond Strength	not relevant to research question	excluded	
13	2020	Life-cycle assessment of strengthening pre-stressed normal-strength concrete beams with different steel-fibered concrete layers	not relevant to research question	excluded	
14	2020	Behaviour of green ultra-high-performance concrete beams with corrosion resistant alloy steel (MMFX) bars	not relevant to research question	excluded	
15	2020	Effect of strengthening methods on two-way slab under low-velocity impact loading	not relevant to research question	excluded	
16	2020	Eco-uhpc as repair material—bond strength, interfacial transition zone and effects of formwork type	not relevant to research question	excluded	
17	2020	Experiment on the Segment Model of a Plain Concrete Arch Bridge Reinforced with UHPC Composite Arch Circle		OK	bridge arch strengthening
18	2020	Experimental Study on Improving the Compressive Strength of UHPC Turntable	not relevant to research question	excluded	
19	2020	Fatigue analysis of partly damaged RC slabs repaired with overlaid UHPFRC		OK	fatigue bridge
20	2020	Illzach Bridge: Innovative Repair of Orthotropic Deck Using Ultra-High-Performance Fibre-Reinforced Concrete—Return After 5 Years		OK	deck crack

21	2020	Numerical modelling of concrete-to-UHPC bond strength	not relevant to research question	excluded	
22	2020	Monitoring of the UHPFRC strengthened Chillon viaduct under environmental and operational variability		OK	bridge deck strengthening
23	2020	UHPFRC technology to enhance the performance of existing concrete bridges		OK	bridge
24	2020	Shear Behaviour of RC Beams Strengthened by Various Ultrahigh Performance Fibre-Reinforced Concrete Systems		OK	RC beam strengthening
25	2021	Confinement effectiveness of CFRP strengthened ultra-high performance concrete cylinders exposed to elevated temperatures		OK	fire-damaged
26	2021	Design and Mechanical Properties of Steel-UHPC Lightweight Composite Decks	not relevant to research question	excluded	
27	2021	Estimating co2 emission savings from ultrahigh performance concrete: A system dynamics approach	not relevant to research question	excluded	
28	2021	Elastic restraint effect of concrete circular columns with ultrahigh-performance concrete jackets: An analytical and experimental study	no full text	excluded	
29	2021	Experimental and numerical investigation on the size effect of ultrahigh-performance fibre-reinforced concrete (Uhfrc)	not relevant to research question	excluded	
30	2021	Full-Scale Model Experimental Study of the Flexural Behavior of Hollow Slabs Strengthened by UHPC		OK	hollow slab strengthening
31	2021	Optimum thickness of uhpfrc overlay for restoration of normal concrete elements	not relevant to research question	excluded	
32	2021	Reactive powder concrete: Durability and applications	not relevant to research question	excluded	

33	2021	Insight into the mechanical performance of the uhpc repaired cementitious composite system after exposure to high temperatures	not relevant to research question	excluded	
34	2021	Shear bond between ultra-high performance fibre reinforced concrete overlays and normal strength concrete substrates	no full text	OK	overlay
35	2021	The mechanical properties and damage evolution of UHPC reinforced with glass fibers and high-performance polypropylene fibers	not relevant to research question	excluded	
36	2022	A review study on sustainable development of ultra high-performance concrete	not relevant to research question	excluded	
37	2022	Bond behavior between concrete and prefabricated Ultra High-Performance Fiber-Reinforced Concrete (UHPFRC) plates	not relevant to research question	excluded	
38	2022	A new EPS beads strengthening technology and its influences on axial compressive properties of concrete	no full text	excluded	
39	2022	Compressive behavior of frp grid-reinforced uhpc tubular columns	not relevant to research question	excluded	
40	2022	Experimental study on surface wrapping strengthening of EPS particles and its concrete performance	no full text	excluded	

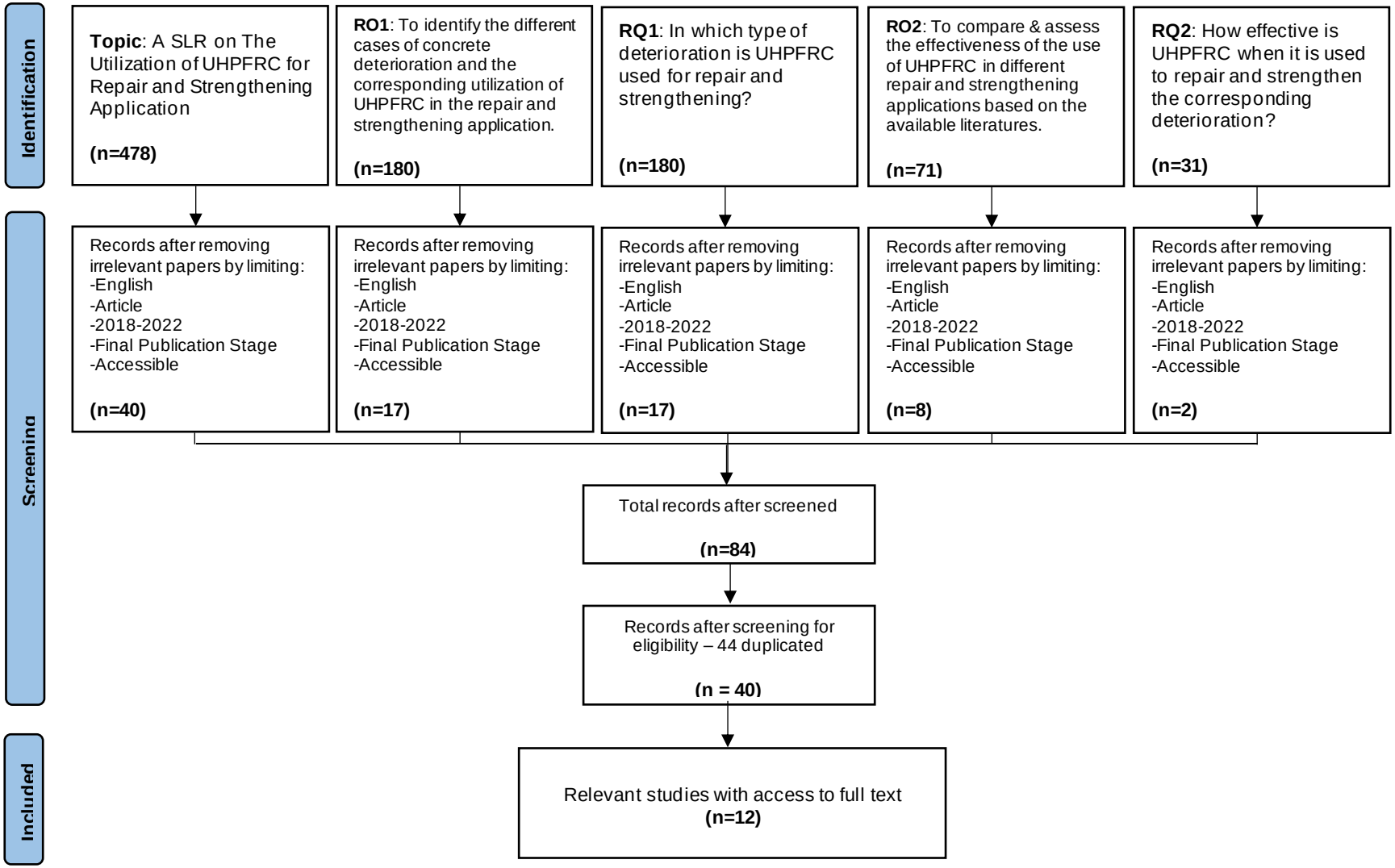

Figure 2.3 Flow diagram of retrieved articles in systematic searching strategies

Table 2.5 List of articles included in the review

No	Year	Title
1	2018	First application of UHPC bridge deck overlay in North America
2	2018	Prediction of flexural behaviour of RC beams strengthened with ultra high performance fiber reinforced concrete
3	2019	Design of Various Shear Connectors for Repair of Corroded Steel Girders with Ultra-High Performance Concrete
4	2019	Chloride penetration at cold joints of structural members with dissimilar concrete incorporating UHPC
5	2019	Experimental investigation on the performance of historical squat masonry walls strengthened by UHPC and reinforced polymer mortar layers
6	2020	Experiment on the Segment Model of a Plain Concrete Arch Bridge Reinforced with UHPC Composite Arch Circle
7	2020	Fatigue analysis of partly damaged RC slabs repaired with overlaid UHPFRC
8	2020	Illzach Bridge: Innovative Repair of Orthotropic Deck Using Ultra-High-Performance Fibre-Reinforced Concrete—Return After 5 Years
9	2020	Monitoring of the UHPFRC strengthened Chillon viaduct under environmental and operational variability
10	2020	UHPFRC technology to enhance the performance of existing concrete bridges
11	2020	Shear Behaviour of RC Beams Strengthened by Various Ultrahigh Performance Fibre-Reinforced Concrete Systems
12	2021	Full-Scale Model Experimental Study of the Flexural Behavior of Hollow Slabs Strengthened by UHPC