EXTENDING THE SERVICE LIFE OF ASPHALT PAVEMENTS VIA PHASE CHANGE MATERIALS: A SYSTEMATIC LITERATURE REVIEW

NGO UK DOONG

SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2022

EXTENDING THE SERVICE LIFE OF ASPHALT PAVEMENTS VIA PHASE CHANGE MATERIALS: A SYSTEMATIC LITERATURE REVIEW

By

NGO UK DOONG

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

August 2022

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2021/2022

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: Extending the service life of asphalt pavements via phase change materials : A systematic literature Review

Name of Student: NGO UK DOONG

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 : 8/8/2022

Approved by:

(Signature of Supervisor)

Name of Supervisor : Assoc. Prof. Ts. Dr. Mohd Rosli Mohd Hasan
School of Civil Engineering
Engineering Campus, Universiti Sains Malaysia
14300 Nibong Tebal, Penang, Malaysia
Tel: +604-5996288 Fax: +604-5996906

Date : 8/8/2022

Approved by:

(Signature of Examiner)

Name of Examiner : Dr Zul Fahmi bin Mohamed Jaafar
School of Civil Engineering
Engineering Campus
Universiti Sains Malaysia

Date : 8/8/2022

ACKNOWLEDGEMENT

At this memorable moment of the successful accomplishment of my bachelor final year project, I would like to acknowledge all those who have, in one way or another, been very helpful throughout the period of my research and subsequent writing of this dissertation.

First and foremost, First and foremost, I do want to express my gratitude to Universiti Sains Malaysia, particularly the School of Civil Engineering, for giving me a platform to conduct my final year project successfully. Without this opportunity, I would not be able to accomplish this review on time.

Next, I would like to express my utmost gratitude to Assoc. Prof. Ts. Dr. Mohd Rosli Mohd Hasan, my research supervisor, for his patient guidance, enthusiastic encouragement and useful critiques of this research work. His valuable suggestions were of immense help throughout my project work. Working under him was an extremely knowledgeable experience for me.

And last, but most of all, a thank you have to say to my family and friends who are directly and indirectly involved, since they have provided me with a great deal of emotional and physical support, which has enabled me to successfully accomplish this project throughout my study.

ABSTRAK

Bahan Ubah Fasa (PCM) yang digunakan dalam bahan turapan asfalt semakin mendapat perhatian dalam meningkatkan ketahanan jalan raya. PCM bertindak sebagai salah satu agen pembaik pulih apabila berlakunya keretakan pada suhu tertentu. PCM telah diaplikasikan di negara beriklim sejuk seperti China yang sering berlakunya masalah keretakan terma. Bagi menentukan pemilihan PCM yang bersesuaian, parameter seperti kestabilan haba, kapasiti haba pendam dan sifat perubahan fasa mesti dipertimbangkan, dikaji dan dianalisis dengan tepat. Kajian literatur sistematik (SLR) ini boleh dijadikan rujukan kepada pembaca dan penyelidik mengenai PCM dari segi potensi bahan yang digunakan, mekanisme, dan perilaku PCM dalam turapan asfalt. Objektif SLR ini adalah untuk mengenal pasti jenis PCM yang boleh digunakan dalam turapan asfalt, menganalisa pelbagai jenis mekasnime dan perilaku PCM sebagai agen pembaik pulih bagi meningkatkan daya ketahanan jalan raya. SLR ini dihasilkan berdasarkan Item Pelaporan Pilihan untuk Ulasan Sistematik dan Meta-Analisis (PRISMA) bagi mengelakkan sebarang keputusan berat sebelah dan meningkatkan kebolehpercayaan data yang dianalisa. Kajian literatur sistematik ini dijalankan berdasarkan dapatan daripada kajian dari tempoh 10 tahun kebelakangan ini (2013-2022) dalam bidang teknologi asfalt. SLR ini diharapkan dapat memberi panduan kepada penyelidik bagi melanjutkan kajian berkaitan PCM dengan lebih mendalam dan dikembangkan ke negara beriklim tropika.

ABSTRACT

Phase Change Materials (PCMs) that were applied in the asphalt pavement is gaining attention on improving the road durability. PCMs act as one of the repair agents when cracking occurs at a certain temperature. PCMs has been applied in cold climate countries such as China where thermal cracking problems often occur. This makes it possible to solve the thermal cracking problem by applying the PCMs as the thermal energy storage in asphalt pavements to regulate the temperature in order to avoid thermal cracking on the asphalt pavements. To select the optimum and relevant PCMs, parameters such as thermal stability, latent heat capacity and phase change properties must be taken into consideration, study and analysis precisely. This systematic literature review (SLR) can be used as a reference for readers and researchers on PCM in terms of the potential of the materials used, mechanisms, and behaviour of PCM in asphalt pavements. The objective of this SLR is to identify the types of PCM that can be used in asphalt pavement, analyse the various types of mechanism and the behaviour of PCM as a repair agent to improve road durability. This review is intended in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) in order to avoid any bias and enhance the dependability of the retrieved data. This systematic literature review was conducted based on findings from studies from the last 10 years (2013-2022) in the field of asphalt technology. It is hoped that this SLR can provide guidance to researchers to further the study related to PCMs in more depth and expanded to tropical countries.

TABLE OF CONTENTS

ACKNOWLEDGEMENT ..... **II**

ABSTRAK ..... **III**

ABSTRACT ..... **IV**

TABLE OF CONTENTS ..... **V**

LIST OF FIGURES ..... **VII**

LIST OF TABLES ..... **VIII**

LIST OF ABBREVIATIONS ..... **IX**

CHAPTER 1 ..... **1**

1.1. Background 1
1.2. Problem Statement 2
1.3. Systematic Literature Review (SLR): Review Questions 4
1.4. Objectives Systematic Literature Review (SLR): Review Objectives 4
1.5. Significance of the Systematic Review 5
1.6. Dissertation Outline 6

CHAPTER 2 ..... **7**

2.1. Introduction 7
2.2. Planning of SLR 10
2.2.1. Review Protocol 10
2.2.2. Formulation of Review Questions 14
2.3. Conducting the SLR 17
2.3.1. Systematic Searching Strategies 17
2.3.2. Quality Assessment 23
2.3.3. Data Extraction and Synthesis 32
2.4. Reporting SLR 33
2.5. Summary 34

CHAPTER 3 ..... **35**

3.1. Introduction 35
3.2.1. Descriptive Data Extraction Method 38
3.2.2. Development of piloted data extraction forms 38

3.2.3. Data Extraction Results 40
3.3. Data Synthesis 53
3.3.1. Quantitative Synthesis Method 54
3.3.2. Qualitative Synthesis Results (Demographic and Geographical Data) 55
CHAPTER 4 58
4.1. Introduction 58
4.2. Data and Analysis 58
4.2.1. Demographic Data 59
4.3. Discussion of SLR review question 63
4.3.1. RQ1: What are the potential phase change materials and techniques that applied on asphalt pavements? 64
4.3.2. RQ2: What are the mechanisms of different type of phase change materials on extending the service life of asphalt pavements? 72
4.3.3. RQ2: How phase change materials improve the performance of asphalt pavements in order to extend the service life of asphalt pavements? 88
CHAPTER 5 92
5.1. Conclusion 92
5.2. Recommendations 93
REFERENCES 94

LIST OF FIGURES

Figure 2.1: SLR review protocol 12

Figure 2.2: Flow chart of the review protocol 12

Figure 2.3: Number of papers throughout 2013-2022 (within 10 years) with search string for topic review purpose. 16

Figure 2.4: PRISMA flow diagram 22

Figure 3.1: Graph of the publication by year distribution. 56

Figure 3.2: Numbers of reviewed papers published based on country 57

Figure 3.3: Pie chart of publication by region 57

Figure 4.1: Cumulative number of research papers (2013-2022). 60

Figure 4.2: Polyethylene glycol/graphene oxide aerogel shape-stabilized phase 67

Figure 4.3: Difference of temperature that can be withstand by the types of PCM. 70

Figure 4.4: Latent heat of PCMs of different types of PCM. 70

Figure 4.5: Asphalt mixture thermal conductivity test samples. (Wei et al., 2022) 75

Figure 4.6: DSC curves of PSLPCMs. (Wei et al., 2022) 75

Figure 4.7: Thermogravimetric analysis curves of PSLPCMs (Wei et al., 2022). 76

Figure 4.8: Macroscopic phase change behaviour diagram (Wei et al., 2022). 76

Figure 4.9: The micro-encapsulation process of $CaCO_3$-µPCM 78

Figure 4.10: The micro-encapsulation process of SiO_2-µPCM 78

Figure 4.11: Chemical formulas of raw materials for preparing the MPCM 81

Figure 4.12: Morphology of MPCM (Wang et al., 2021). 83

Figure 4.13: Preparation of EMPCMs (Wang et al., 2021). 83

Figure 4.14: Weight loss at 200°C of different types of PCM. 89

Figure 4.15: Phase change temperature of different types of PCM. 91

Figure 4.16: Enthalpy change of different types of PCM. 91

LIST OF TABLES

Table 2.1: Identification of Keywords 18

Table 2.2: Screening Criteria 20

Table 2.3: Searching Strings Developed for Title 21

Table 2.4: Questions in quality assessment and its description. 25

Table 2.5: The articles assessment scoring mark. 26

Table 2.6: The rate of quality of the articles. 26

Table 2.7: The articles included in the review. 26

Table 2.8: The assessment score of the article 29

Table 3.1: Differences Between Qualitative and Quantitative Criteria concerning this Review Work 36

Table 3.2: Data extraction form with different data field to be filled. 39

Table 3.3: Descriptive data extraction. 40

Table 3.4: Numbers of reviewed papers published based on country 56

Table 4.1: The number of papers with regarded to different types of phase change materials that applied in asphalt pavement. 61

Table 4.2: The number of papers with regarded to its type of application in heat reflective asphalt pavement 62

Table 4.3: The quantity of the article published for a country. 63

Table 4.4: Comparison between three different types of phase change materials. 69

Table 4.5: Mixture gradation (Wei et al., 2022) 74

Table 4.6: Comparison between MPCM and EMPCM 81

Table 4.7: Comparison between secondary wrapping method and pouring method 82

Table 4.8: Comparison of different preparation method 86

LIST OF ABBREVIATIONS

PCMs	Phase Change Materials
SLR	Systematic Literature Review
RO	Review Objectives
RQ	Review Questions
QAC	Quality Assessment Criteria
DE	Data Extraction of a form
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
MPCM	Microencapsulated Phase Change Materials
EMPCM	Epoxy composite Microencapsulated Phase Change Materials
PSLPCMs	Polyurethane Solid–solid Low-temperature Phase Change Materials
PEG	Polyethylene Glycol
LA	Lauric Acid
HMA	Hot Mix Asphalt
CPCM	Composite Phase Change Materials
LHATV	Latent Heat Accumulation Temperature Value
LHTI	Latent Heat Temperature Regulation Index

CHAPTER 1

INTRODUCTION

1.1. Background

Asphaltic concrete pavement is prone to ageing due to oxidation, volatilization, sunshine, and moisture, resulting in fatigue damage to asphalt pavements. Asphalt binder is a temperature-sensitive substance having limited elasticity at low temperatures and highly viscous at high temperatures. The stress cycles generated by temperature changes can stiffen asphalt mixtures, expedite the ageing and shortening the service life of asphalt pavements. By reducing the extreme temperature of the asphalt mixture, phase change energy storage technology has been shown to improve the service life of pavements and minimise maintenance costs (Guo et al., 2020).

In extremely low-temperature environment and highly aged pavement, asphalt pavement breaks and cracks easily. One of the most critical troubles is the temperature dependency as strength, modulus, and shrinkage coefficient can change with temperature. The environmental temperature has an obvious influence on the viscoelasticity and plasticity of the asphalt. Therefore, asphalt pavement is prone to generate deformation like rutting caused by driving load under high-temperature and shrinkage cracking under low-temperature which affect the pavement performance and service.

To overcome this problem, microencapsulated Phase Change Materials (PCMs) have been developed. The PCMs microencapsulation is a process of coating individual PCMs droplet or particle with a continuous film to produce PCMs microcapsules (Wei et al., 2019). The PCM microcapsules contain two main parts which is a PCMs as the core and a polymer or an inorganic shell as the PCM container.

The PCMs can also be classified by their phase transition temperatures: low-temperature PCMs (melting point 220°C), intermediate-temperature PCMs (melting point 220°C to melting point 420°C), and high-temperature PCMs (melting point >420°C). Paraffin, fatty acids, polymeric polymers, sugar alcohols, and polyalcohol are all examples of low-temperature PCMs. Most organic compounds have melting values below 80°C. Organic PCMs are thus classified as low-temperature PCMs. The majority of inorganic-inorganic eutectic PCMs, on the other hand, are intermediate-temperature PCMs. High-temperature PCMs, such as nitrates, metal carbonates, sulphates, fluorides, and chlorides, can be used in a variety of applications (Peng et al., 2020).

1.2. Problem Statement

Previously, several researches have been conducted in studying the effect of PCMs in cold region. Nevertheless, further studies need to be done for the pavements in tropical areas such as Malaysia. Theoretically, the main purpose of PCMs incorporation is to reduce the extreme temperature during the service life of pavement. Asphalt pavements are exposed to the severe environmental conditions that exist in the atmosphere. Ambient temperature, for example, has a significant impact on the physicochemical parameters of pavement materials.

Asphalt is a temperature-sensitive material that is elastomer at low temperatures and viscous at high temperatures. When the temperature of the pavement surface exceeds the softening point of the asphalt in the summer, the asphalt pavements distort dramatically under repeated vehicle loads, causing rutting, shoving, and other distresses. Simultaneously, due to high or low-stress cycles induced by obvious diurnal temperature

changes, the asphalt becomes hard and brittle, resulting in thermal fatigue damage to the asphalt pavements.

Asphalt pavements are exposed to the severe environmental conditions that exist in the atmosphere. Ambient temperature has a significant impact on the physicochemical parameters of pavement materials. Thermal cracking remains one of the most challenging distresses to predict and reduce in pavements constructed in cold regions. Thermal cracking of asphalt pavement is a common form of deterioration on roads. The cracks are weak zones where water seeps into and damages the road structures. The cracks are the starting point for other forms of deterioration as well. Incorporation of PCMs can restrict both the higher and lower temperature extremities in pavements. Using PCMs in asphalt mixture could increase temperature regulation and reduce thermal degradation due to temperature cycling.

1.3. Systematic Literature Review (SLR): Review Questions

The researcher came up with the review questions which discussed how phase change materials that applied in asphalt pavements in order to extend the service life of the asphalt pavements. Research Question (RQ)1 was formulated to understand potential phase change materials that applied on asphalt pavements. Whereas RQ2 is aimed to differentiate the mechanisms of different type of phase change materials on extending the service life of asphalt pavements. Next, RQ3 was proposed to evaluate the performance of asphalt pavements in order to extend the service life of asphalt pavements.

1. What are the potential phase change materials that applied on asphalt pavements?
2. What are the mechanisms of different type of phase change materials on extending the service life of asphalt pavements?
3. How phase change materials improve the performance of asphalt pavements in order to extend the service life of asphalt pavements?

1.4. Objectives Systematic Literature Review (SLR): Review Objectives

The following objectives are set in this study in accordance to the main concern as stated in the problem statement.

1. To review the potential phase change materials and techniques that applied on asphalt pavements.
2. To differentiate the mechanisms and benefits of phase change materials on extending the service life of asphalt pavements.
3. To evaluate the performance of phase change materials to extend the service life of asphalt pavements.

1.5. Significance of the Systematic Review

In this study, the purpose is to review the potential PCMs that were applied in asphalt pavements. Furthermore, the intention is to differentiate the mechanisms of PCMs on extending the service life of asphalt pavements and also to review the performance and effectiveness of phase change materials of asphalt pavement with phase change materials. For instance, the parameters that are essential to be considered in this project are durability, cost-effectiveness, latent heat, thermal conductivity and lower resources depletion to avoid high temperature hazards, and improve low temperature cracking resistance of asphalt pavement. The use of latent heat storage capacity from PCMs to regulate asphalt pavement temperature is an innovative way to mitigate temperature-related pavement distresses, such as thermal cracking. Hence, the use of PCMs will lower the impact to the environment and also will recue the oxidation of old age pavements by breaking the capsule to close the crack when thermal cracking occurred (Guo et al., 2020).

1.6. Dissertation Outline

The thesis has been organized in five chapters. A brief outline of the various chapters is as follows:

Chapter 1 contains the introduction of the thesis. It gives foreword about the application of phase change materials in asphalt pavements. The chapter gives an overview of the thesis including five important elements: background of the research, problem statements, objective of the study, review questions and the significance of study.

Chapter 2 is enriched with throughout and extensive literature reviews of the study. The chapters provide important theoretical and methodological understanding of related topics based on various researches.

Chapter 3 deals with methodology of the research. This chapter describe the systematic review relies heavily on data extraction and synthesis. The data from the screened research is synthesised, and the review's conclusions are based on that synthesis.

Chapter 4 presents the result and discussion of the study. This chapter commences with research results from the simulation. The results are visualized, analysed and assessed. Comparison of the numerical results with analytical solution and available experiment are carried out and discussed.

Chapter 5 is devoted to conclusions and recommendations. The finding of research is stated in this chapter. This chapter also discuss the limitation and some recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

A literature review is a discussion or summary of previously published information on a topic. It can be a standalone review in a topic area or a component of a research paper or dissertation to provide a distinct perspective on the work (Cronin, 2011). The literature review can be thought of as a straightforward summary of the sources, but it also includes synthesis. The purpose of a summary is to extract the most important information from the sources, but the purpose of a synthesis is to reorganise and reorder the data. A fresh opinion or argument might be inspired by old materials or merged with old ones through information synthesis. Furthermore, a researcher who is already an expert in his subject or capable of interpreting existing knowledge might use the literature review to bring out contradictions and gaps in knowledge in the studied data. As a result, a literature review can make it easier for the reader to find the most relevant and credible material.

Traditional and systematic reviews are the two types of literature reviews that are commonly used. The goal of a traditional review is to describe and discuss the issue in the author's preferred manner. The author who is confident in his position will choose the papers that support his position and disregard those that do not. Furthermore, experts in their fields frequently offer an overview in their thesis or article without a clear scientific approach. Failure to use scientific principles to the review will also result in unreliable and unbiased reviewing evidence, resulting in an incorrect conclusion.

The systematic literature review differs from the typical review in that it is more thorough. It necessitates a thorough examination of a huge amount of data in order to

answer the questions of what works and what doesn't. To address the review question, relevant information from the research paper are discovered, selected, and synthesised. Unlike a regular review, a systematic review follows a rigid and well-defined approach for conducting the review. To develop a qualitative review paper, it contains a clearly stated goal, review question, searching strategy, declaring inclusion and exclusion criteria (Cronin, 2011). Because a major portion of the paper or article is reviewed based on the review question, the contradictions and gaps in knowledge can be quickly seen, as well as where further study is needed (Cronin, 2011).

PCMs are materials that change phase states while absorbing or releasing latent heat as part of the process. It has the capability of storing heat and controlling temperature (Guo et al., 2020). PCMs are latent heat thermal energy storage materials which use their chemical bonds for the storage and releasing of energy. The PCMs for energy storage should have a high thermal conductivity and large latent heat. The PCMs absorb a huge quantity of energy without becoming heated when they reach the melting temperature. The PCMs solidify and releases energy when the surrounding temperature drops.

PCMs are substances with relatively high latent heats of fusion. When the ambient temperature rises above its melting point, a given PCMs absorbs heat and turns to the liquid phase while remaining at an almost constant temperature (Hamja, 2018). As a result, the widespread use of PCMs in a variety of industries has given rise to a novel concept for asphalt pavement thermoregulation. A suitable proportion of bitumen mastic yields a homogenous mixture which flows like fluid at high temperature. However, it is in either solid or semisolid state on cooling down to room temperature. The reason bitumen mastic is widely being used in this industry is due to it gives very a low maintenance, has high stability and durability (Santi, 2020).

The PCMs can be classified in many ways, such as composition of materials, energy storage methods, thermal storage temperature and phase. According to the composition of materials, PCMs are commonly divided into inorganic PCMs, organic PCMs and composite PCMs (Jin et al., 2018). Inorganic PCMs can be furtherly divided into salt hydrates, inorganic compounds and metals. Salt hydrates PCMs have many advantages, such as wide application range, low cost, large thermal conductivity, high latent heat capacity and high density (Athukorallage et al., 2018). However, there are two problems in this kind of PCMs which are super cooling phenomenon and phase separation. Inorganic compounds are generally considered unsuitable for applications in PCMs because they own relatively small latent heat capacity and are harmful to the environment and human health. Metals have high melting point, good thermal conductivity a small volume change in phase process, but they are only suitable for high temperature applications (Guo et al., 2020). In physical requirements, PCMs have suitable phase change temperature, large change in enthalpy, large specific heat capacity and thermal conductivity. In terms of chemical requirements, enthalpy have small volume pressure, low vapor pressure, good compatibility with other materials and chemical stability. Economically PCMs are low price, recyclable and abundantly available.

Technically, the latent heat storage differs from sensible heat storage in that it employs the phase transition of materials to store thermal energy. When temperatures are higher than the phase change temperature, the PCM's phase change latent heat characteristic can gather and store solar energy. A considerable amount of latent heat is emitted along with the phase change process when the temperature is lower than the phase change temperature. The service life of an asphalt highway can be prolonged by using phase-change materials and other technologies to modify the pavement (Yang et

al., 2021). Organic paraffin PCMs are compatible with asphalt because they have outstanding thermal performance, no phase separation, and super cooling. It has a low melting point and poor thermal conductivity when compared to inorganic PCMs.

2.2. Planning of SLR

This systematic review is to appraise the use of phase change materials as a thermal storage in asphalt pavements. It is necessary to have a fundamental understanding or background regarding the title in order to build a brief overview of how to develop parts such as the objective, review question, protocol, and methodology (Bettany-Saltikov, 2012). A systematic review, on the other hand, has a specific process for doing the review, and a defined review protocol must be devised before the review can begin. The planning stage, conducting stage, and reporting stage are the three stages that can be summarised in this review procedure from the beginning to the finish of the review. It describes the protocols for each stage so that the review may proceed smoothly and author bias can be minimised when presenting the topic.

2.2.1. Review Protocol

A specific protocol is required before performing a systematic literature review serve as a guide for the review. The creation of a protocol is an important part of the systematic review process. It ensures that a systematic review is thoroughly prepared and that what is scheduled is communicated before the review begins, supporting open review team behaviour, scientific credibility, and transparency of the final finished study (Kamioka, 2019). Because it is an explicit description and explanation of the processes that should be done, it is easier to establish the project's objectives, review questions, and purpose with the protocol (Cronin, 2011).

Review protocol is a pre-set plan that reduces the researcher bias in conducting the review so that the quality of the SLR is enhanced (Xiao & Watson, 2019). This advanced plan before conducting the SLR preventing the researcher from changing the way of review the paper after the studies is identified (Bettany-Saltikov, 2012). Other than this, a review protocol increases the reliability of the review as other researcher or reader that interested in this paper can repeat the procedure to cross-check for validation (Xiao & Watson, 2019). Since the review protocol is well-organized, unique, and varies according to the review topic, usually the protocol will be registered under an international database called PROSPERO, but this applies to health research only (National Institute for Health Research 2021). Therefore, the researcher has by-passed this section even it has been mentioned in the PRISMA checklist 2009 (PRISMA, 2015a).

SLR protocol is followed step by step, as indicated in Figure 2.1. Figure 2.2 shows the flow chart of the review protocol. The protocol lays out all of the processes that researchers must take during the review in order to reduce threats to validity and neutralise author bias. The review methodology is one of the primary aspects that distinguishes SLR from typical literature reviews, therefore it's an important phase in the process. The protocol starts by establishing the review questions (Section 2.2.1). The next step is to decide on a search strategy (Section 2.3.1). The study selection is then determined by the inclusion and exclusion criteria (Section 2.3.1). The quality inspection is carried out (Section 2.3.2). Finally, main study data is gathered to help answer the review questions (Section 2.3.3). In Chapter 4, the data that has been extracted and synthesised is used in the analysis and discussion to reach a conclusion. Moreover, each of these components will be discussed in details in each of the subchapters as follows:

1. Identify review question (Chapter 2, section 2.2.1)
2. Define search strategy (Chapter 2, section 2.3.1)
3. Define quality criteria (Chapter 2, section 2.3.2)
4. Define data extraction (Chapter 2, section 2.3.3)
5. Define data synthesis (Chapter 2, section 2.3.3)

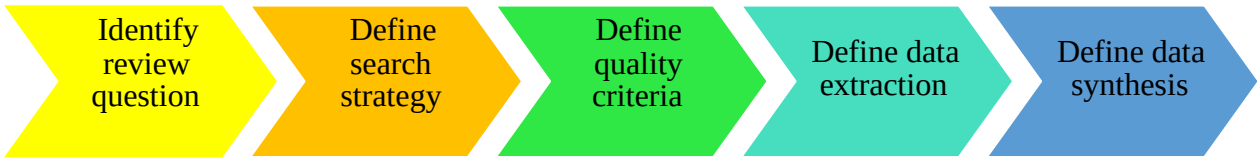

Figure 2.1: SLR review protocol

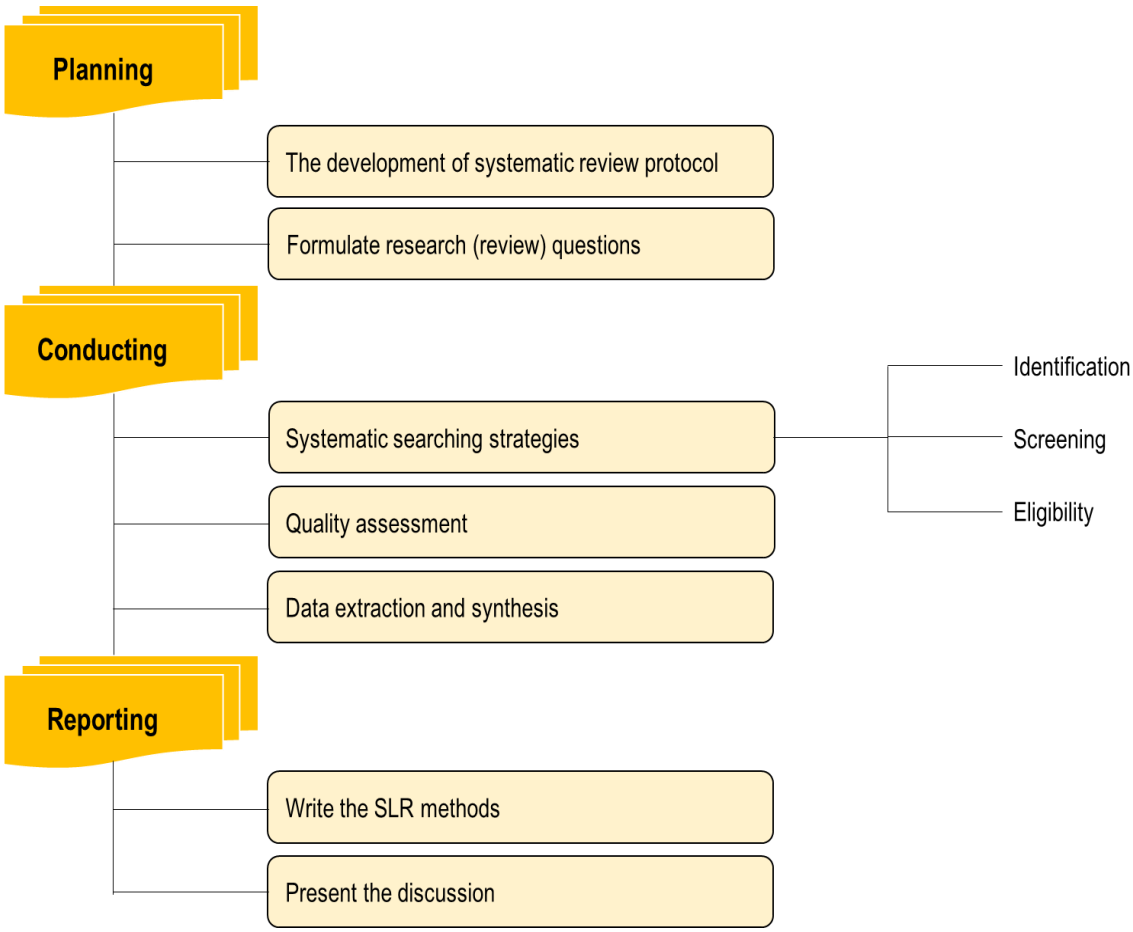

Figure 2.2: Flow chart of the review protocol

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 a clear statement question or review question addressed concerning participants, interventions, comparators and outcomes (PICO). Further discussion of the review question is in section 2.2.2.

In conducting stage, it is more focused on the searching and processing of the research article. Systematic searching strategies are used to finding the related article from the database by using the main term from topic and objective. The articles are then filtered to eliminate extraneous and duplicated content, leaving just the most important content. A quality assessment for the selected article will be carried out after the article has been found in the database. One of the article appraisals is quality assessment, which shows how well an article's sensitivity and correctness can be satisfied with the review query or objective. As a result, the review is less biased and more credible.

The technique for extracting data from each article, such as the author, the study's goal, and the study's result, is referred to as data extraction. Meanwhile, the data synthesis section is in charge of synchronising all of the articles in order to arrive at a solution to the review query. The combined output of this systematic literature evaluation will be grouped under key themes or subthemes because it is qualitative (Bettany-Saltikov, 2012). Hence, the information taken from each article will be presented in a table, allowing for easy comparison and display of the contradictions and similarities of the articles.

In reporting stage, it is the process to summarize, synthesize, and present the answer to the review questions. The report will be examined under the themes or categories of thematic analysis in this study. A thematic analysis of literature is a

method of analysing qualitative data that examines the data attentively in order to identify common themes – concepts, thoughts, and context trends that recur regularly. Because each article will contain a table of thematically synthesised material, it will be simple for us to answer the review question that was specified during the planning stage and to interpret the knowledge gap between the articles. Aside from that, the advice might be made for future scholars in the field or on the issue to help them enhance their work.

2.2.2. Formulation of Review Questions

A systematic review should define the precise questions, and the answers should provide meaningful information to aid decision-making. These should be stated explicitly and specifically in the protocol. Questions can be very specific or very wide; however, if they are broad, it may be easier to divide them down into a series of similar, more detailed questions. In other words, a well-crafted query can help with many areas of the review process, including determining eligibility standards, searching for articles, gathering data from the articles included in the review, and presenting the results.

The review question is formulated with the goals of this systematic review in mind. One review question is used to each objective to match the review questions with the objective, for a total of three review questions in this systematic review. As mentioned in Chapter 1, there are several types of phase change materials with different mechanisms in asphalt pavements are discussed in this paper. According to the PRISMA checklist 2009 item number 4, the explicit statement of the question is developed from the four major components which are participants, interventions, comparisons, outcomes, and study design (PICOS) (PRISMA, 2015a). However, the

abovementioned element might not suitable for the engineering research systematic review as the initiative of the PRISMA was to assist the development of healthcare intervention (Liberati et al., 2009). Therefore, there are some alterations on the PRISMA checklist in developing the review question.

A broad research question may result in an unmanageable review, but this can be avoided by implement a narrower review topic (Liberati et al., 2009). As mentioned earlier, research questions are developed from the gap of knowledge, in this paper timeline is narrowed to the latest 10 years (2013-2022) for studying the trend and insufficient research regarding the use of phase change materials in asphalt pavements to extend the service life. The researcher only uses one database (Scopus) for searching the related paper to review the trend and the gap of knowledge. To identify the relevant publications, a string was developed ("phase change materials" AND "asphalt pavements") to search within article title, abstract and keyword in Scopus, additionally some inclusion criteria is imposed as follows:

1) Written in English

2) Published between 2013 and 2022

3) Document type: article, conference paper, review

4) Source type: journal (Scopus)

All the result in the Scopus is extracted in the form of references to ease the topic summarisation. There are about 144 publications throughout the ten years with the abovementioned criteria before further screening. From the illustration graph in Figure 2.3, even though there is a small fluctuation between the years 2016 and 2018, it is considered an increasing trend for the number of papers with a related topic ("phase change materials" AND "asphalt pavements") throughout these ten years. All

the papers are arranging according to the year of publication so that the use of phase change materials in asphalt pavements is easier to trace. The researcher had gone through the abstract, objectives, conclusion of each paper to have a summary of a problem statement, objective, gap of study and suggestion. After that, all this information in every paper is summarised according to years. The mentioned subtopic and description in each year are almost varied, only a few topics are in common such as encapsulation.

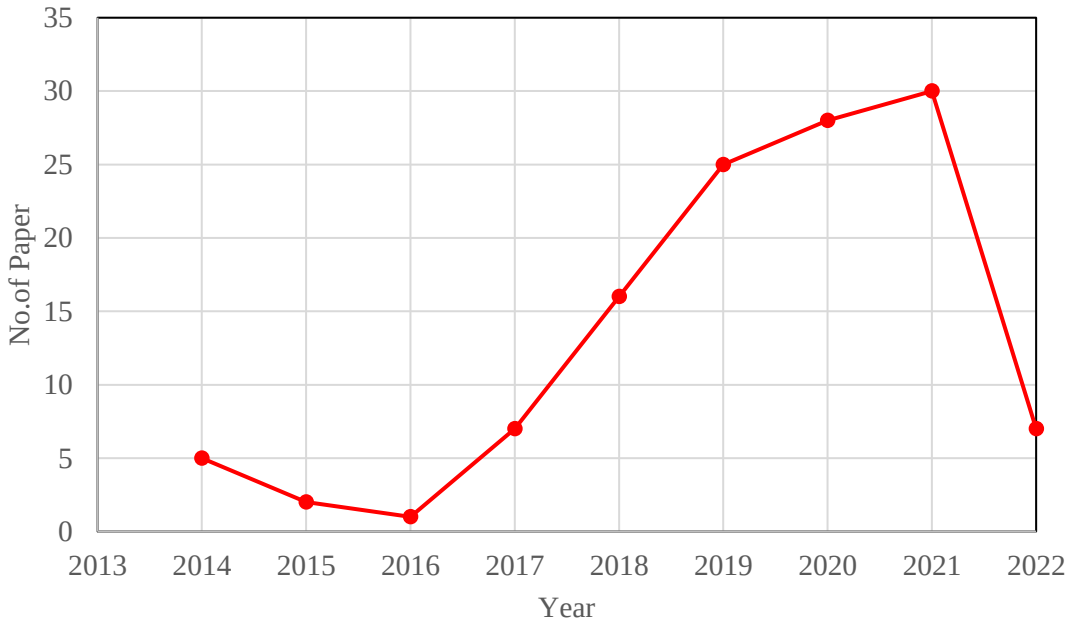

Figure 2.3: Number of papers throughout 2013-2022 (within 10 years) with search string for topic review purpose.

2.3. Conducting the SLR

When doing a systematic review, it's critical to collect as many studies as possible that are relevant to the study's aims or topics. To broaden the search, a searching strategy is used, which includes defining a synonym for the objective and the review question, as well as filtering for eligible articles. After the filtering is completed, the quality of the articles included in the review are assessed to determine the reliability of the review findings and to provide additional feedback on the research's methodological quality. Then, in order to acquire and process the essential information on the study characteristics and findings from the studies, data extraction and synthesis for the article can be outlined.

2.3.1. Systematic Searching Strategies

The search framework is according to the PRISMA flow diagram which consists of four steps (identification, screening, eligibility, and included) as shown in Figure 2.4 (PRISMA, 2015b). According to the PRISMA flow diagram, the initial search is made up of several databases, due to the access granted from the researcher's side, Scopus will be the only selected database to search. Although the final included article is sourced from one database, it does not influence the result of the search and this fulfils the criteria in PRISMA checklist 2009 (item no 8) (PRISMA, 2015a).

The relevant scholarly materials (previous study) for this review work were identified using systematic searching procedures. As a result, the exact search strings were employed to accomplish that purpose. The search strings utilised in this review study were created using the following technique and criteria.

1. Identification: Derive the main keywords from the topics, review objectives and review questions.

2. Determine the synonyms, related terms, or alternate terms for the main keywords.
3. Check the keywords in all relevant papers that the researchers were using, then use them for the initial searches on the relevant databases.
4. Incorporate alternative spelling and synonyms using Boolean “OR”.
5. Link the main terms using Boolean “AND”.
6. Pilot different combination of the search terms.

2.3.1.1. Identification

Identification is a sub-process of SLR that is used to enrich the keywords linked to this study so that different searching algorithms can be utilised to identify more related and topic-focused articles. Otherwise, the database can miss other potentially relevant articles. The enhanced keywords from the title and review questions are given in Table 2.1

Table 2.1: Identification of keywords

Section	Main keywords	Enriched keywords
Title: A systematic review for Extending the Service Life of Asphalt Pavements Via Phase Change Materials	Phase Change Materials Asphalt Pavements Service Life	Phase Change Materials = PCM Asphalt Pavements = bituminous, bitumen, blacktop Service Life = mean life, shelf life, serviceable life
RQ1: What are the potential phase change materials that applied on asphalt pavements?	Phase Change Materials	Phase Change Materials = PCM

RQ2: What are the mechanisms of different types of phase change materials on extending the service life of asphalt pavements?	Mechanism Phase Change Materials	mechanisms = procedure, process, operation, method Phase Change Materials = PCM
RQ3: How phase change materials improve the performance of asphalt pavements in order to extend the service life of asphalt pavements?	Phase Change Materials Performance	Phase Change Materials = PCM

2.3.1.2. 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. All the identified articles need to be screened based on the inclusion and exclusion criteria. This screening can be done automatically from the sorting function available in the selected databases. The standard criteria considered in the inclusion and exclusion setup are timeline, publication types, and language.

Screening is conducted for excluding the irrelevant and incomplete articles. Furthermore, to ensure the quality of the review, only articles with empirical data published in journals, books, or book chapters are included. Moreover, only articles published in English are incorporated in the review to avoid confusion in understanding. Generally, the filtering process is based on the timeline, publication type and language as shown in Table 2.2 below.

Table 2.2: Screening criteria

Criteria	Inclusion	Exclusion
Timeline	2013-2022	Before 2013
Publication type	Review Papers, Research Articles, Journal	Conference proceeding, newspaper, book chapter
Language	English	Non-English
Subject Area	Engineering, Material Science, Chemistry, Structures	Physics & Astronomy, Computer Science

From Table 2.2, the articles from the past ten years were considered since the contents are assumed to be suitable for the current studies. The publication type also considered the review papers to update on the latest existing review status of phase change materials. Next, only English articles were considered to narrow down the scope and to avoid the misinterpretation of the content in the non-English articles. Finally, the related subject area was also included to filter out the unrelated.

2.3.1.3. Develop Searching Strings

In developing the searching strings, the enriched keywords from Section 2.3.1(a), and the screening criteria set from Section 2.3.1(b) were used and applied. Next, follow the searching strategies in Section 2.3.1 to initiate the searching. For the results, Table 2.3 shows the searching strings for the title, RQ1, RQ2 and RQ3.

Table 2.3: Searching strings developed for title

Section	Search String (Scopus)	Number of the article (identification stage)
Topic	TITLE-ABS-KEY((“PCM” OR “Phase Change Materials”) AND (“asphalt pavements” OR “bitumen”) AND (“service life” OR “serviceable life”))	7
RQ1	TITLE-ABS-KEY((“potential”) AND (“PCM” OR “Phase Change Materials”) AND (“asphalt pavements” OR “bitumen”))	13
RQ2:	TITLE-ABS-KEY((“mechanisms” OR “procedure” OR “process” OR “method” OR “operation”) AND (“PCM” OR “Phase Change Materials”) AND (“asphalt pavements” OR “bitumen”))	58
RQ3:	TITLE-ABS-KEY((“durability” OR “strength” OR “toughness”) AND (“PCM” OR “Phase Change Materials”) AND (“asphalt pavements” OR “bitumen”) AND (“performance”))	12

2.3.1.4. Eligibility and Inclusion

Eligibility is the process conducted by comparing the article of different searching topic to exclude the irrelevant and duplicated article. Eligibility is the third sub-process where the authors manually monitored the retrieved articles to ensure all the remaining articles after the screening process are aligned with the criteria. This process can be done by reading the title and abstract of the articles.

In this stage, the quality assessment can also be performed to finalize the articles to be included in the review process. The quality assessment is the process in which the student assesses each included full- text paper using appropriate quality assessment criteria. The criteria can be developed based on the review objectives or review questions. All procedures involved in systematic searching strategies were then reported using the PRISMA flow diagram as in Figure 2.4:

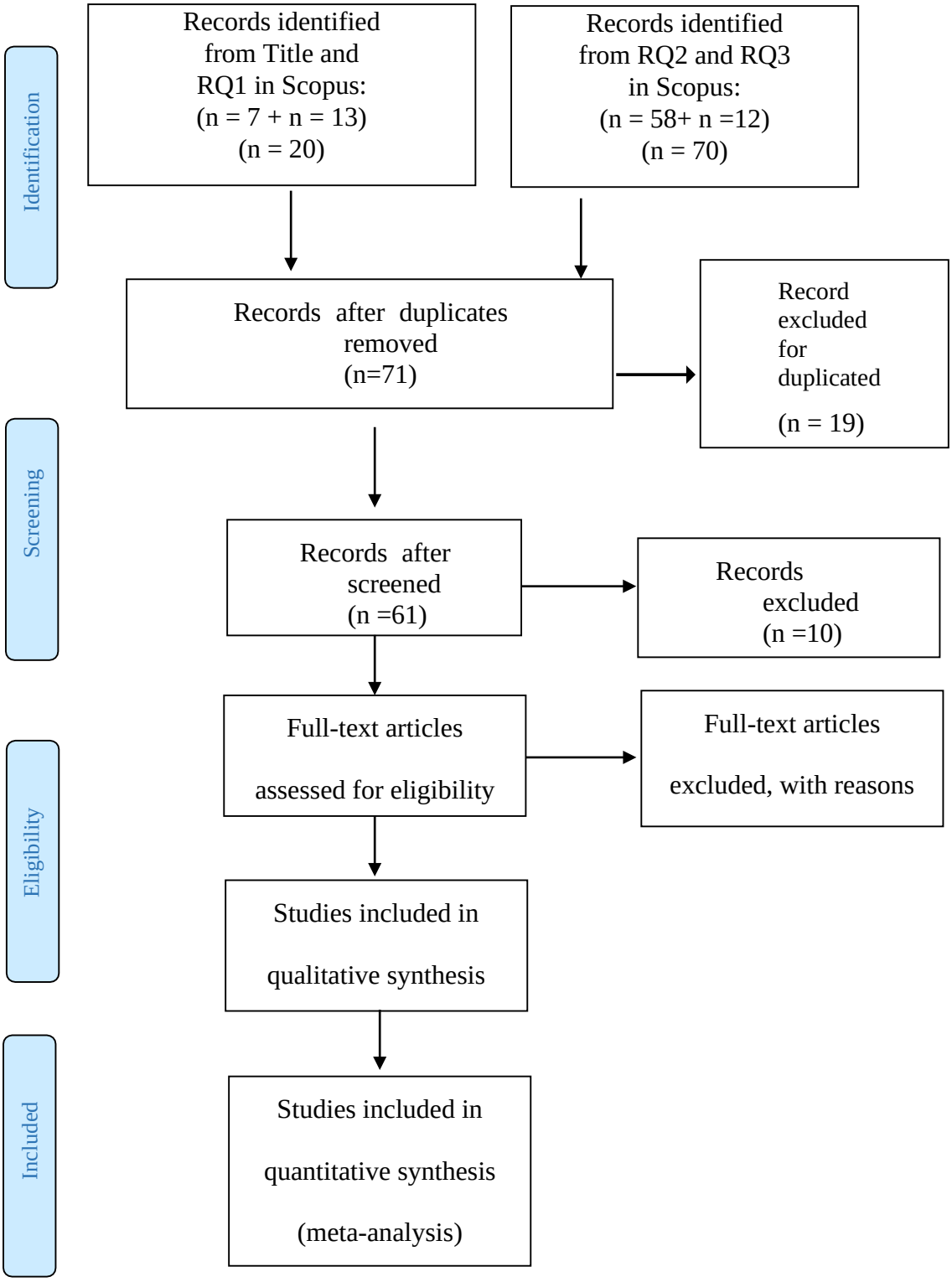

Figure 2.4: PRISMA flow diagram

The result from each search string after a filter is extracted out in the form of reference format, then transfer to Microsoft Excel to identify the duplicates. With the aid of the function applicable in Microsoft Excel, 47 duplicates paper was detected and the left will undergo last screening to obtain the inclusion paper to be reviewed in this study. Inclusion and exclusion criteria often establish based on either the review question or objectives (Kitchenham & Charters, 2007). Any irrelevant studies must be excluded (Liberati et al., 2009).

There are two key steps recommended by (Jesson et al., 2011), can achieve the describe criteria as above mentioned. In the first steps, a researcher will read the title, abstract, and maybe the introduction and conclusion from the article to eliminate some misleading paper that obtains from the search engine. Subsequently, a researcher will identify whether there is key information required for the data extraction. All the irrelevant paper will be precluded including papers that cannot be accessed in full. There are about 55 papers left to be reviewed, but all of this paper needs to carry out quality assessment before it is finalized for extracted and synthesized.

2.3.2. Quality Assessment

The quality assessment is the methodological quality of the chosen literature, where applicable, in order to avoid publications with poor methodological (Strukelj & Niehorster, 2018). The validity and quality of the review studies determine the quality of the systematic review, which means the review is devoid of biases and the conclusions are close to the truth (Bettany-Saltikov, 2012). As a result, in the systematic analysis, such inadequate research or study should be identified as such or altogether omitted.

Caldwell et al. (2011) developed an assessment methodology that was utilised to evaluate the methodological quality of the research in this review. When reviewing

a research article for assessment purposes, this appraisal framework can provide clarity and fairness (Caldwell et al., 2011). It's also a framework that integrates quantitative and qualitative appraisal questions into a single package. The framework begins with questions that answer both quantitative and qualitative research and gives a guideline with a detailed explanation of each item (see Table 2.4). However, because this is a qualitative systematic review, the quantitative question in the framework will be omitted, and only the qualitative portion of the review will be addressed.

The overall score for each study is determined by adding one point for each "yes" and zero points for "no," "can't answer," and "not applicable," yielding summary scores ranging from 0 to 10. (Referred Table 2.5). This assessment assigns a score of 0–4 to poor quality articles, 5–7 to moderate quality articles, and 8–10 to high quality articles to rate their quality. In addition, there will be 51 articles that need to be evaluated (Referred Table 2.6).

According to the assessment, 49 of the 51 articles are of good quality, with ratings ranging from 8 to 10. There are two articles with a score of 7 that is rated as average quality (Referred Table 2.8). When compared to the other questions, "Is the conclusion comprehensive?" receives the lowest score. This question is answered correctly in 10 articles, but not in 7 others. This is because those articles are exempt from including a recommendation for future research in the conclusion section. The advice for additional research, on the other hand, should be included in the study since it makes it easier for the researcher to answer the unknown, thereby filling a knowledge gap in a certain subject. Finally, all 51 articles have a mean score of 9.41, indicating that they are appropriate for review.