CHAPTER I
INTRODUCTION

1.1 Statement of the problem

In general, the structural composition of pavement concrete encompasses distinct layers, namely subgrade, sub-base course, base course, and rigid pavement. This configuration enables the pavement to efficiently sustain the load imparted by wheels and axles, thereby necessitating concrete with robust mechanical properties that ensure its durability and longevity under heavy traffic conditions. Concrete pavement offers a notable advantage in terms of cost, as its maintenance expenses are comparatively low (Pranav et al., 2020). However, several limitations accompany concrete pavement, including elevated greenhouse gas emissions and inherent deficiencies in tensile strength and flexural strength. Moreover, the susceptibility of concrete pavement to temperature variations and fluctuations is primarily attributed to its diminished tensile and flexural strength (Mohod & Kadam, 2016). Consequently, a substantial thickness of the concrete pavement layer is imperative to mitigate crack formation resulting from the applied forces by vehicles' wheels and axles (Khichad et al., 2023).

Concrete serves as the principal construction material extensively employed in civil engineering projects on a global scale. The substantial requirement for coarse aggregate derived from natural stone is vital to meet the substantial demand for concrete production. Presently, the worldwide aggregate gross output amounts to approximately 20 billion metric tons annually, with projections indicating a doubling of aggregate demand within the next 20-30 years (Kalinowska-Wichrowska et al., 2020). However, the extraction and crushing processes associated with natural aggregate entail amplified energy consumption and concurrent release of CO_2, thereby contributing to the escalating concerns of global warming and climate change. This predicament can be predominantly attributed to the heightened emission of greenhouse gases (GHGs) into the atmosphere, including but not limited to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), and argon. Consequently, there exists an imperative and time-sensitive necessity to curtail GHG emissions, with a particular emphasis on reducing CO_2 emissions (Infante Gomes et al., 2021).

The construction industry is currently witnessing a notable shift towards adopting alternative building materials as substitutes for natural resources, aiming to mitigate the environmental impact associated with energy consumption, pollution, and waste disposal. Concurrently, the generation of waste from construction and demolition (C&D) activities has emerged as a global concern. Consequently, the recycling and reuse of such waste materials have emerged as effective measures to diminish reliance on virgin resources and alleviate environmental repercussions (Behera et al., 2014). By recycling building materials, valuable space within limited landfills can be conserved. Notably, concrete waste constitutes a significant proportion, accounting for approximately 50% of the total waste generated. Current practices that involve landfill disposal of construction materials yield substantial volumes of waste originating from construction sites. Recycling concrete waste into recycled aggregates presents a viable approach to curbing concrete waste accumulation (Tam, 2008). Nevertheless, it is crucial to consider the energy requirements entailed in the crushing and sorting of construction and demolition waste (CDW), as well as the transportation of recycled aggregates, as these factors may impact the overall environmental balance. Extensive research has demonstrated that CDW recycling substantially enhances energy efficiency and environmental performance. However, certain quantities of concrete waste still find their way to landfills, with emissions being contingent upon various parameters, such as local conditions during raw material production processes and transportation distances (Collins, 2010). Furthermore, the utilization of recycled aggregates derived from CDW not only aids in conserving natural aggregate resources but also diminishes the demand for landfill space, thereby fostering sustainable construction practices (Martins et al., 2023).

The investigation into the application of recycled concrete aggregates (RCA) has spanned over four decades. The initial phase of this research focused on comprehending the fundamental properties of RCA and its influence on concrete mixtures. The produced concrete incorporating RCA was deemed of lower grade, rendering it unsuitable for structural applications. The high water absorption characteristics of RCA necessitated a higher water content in the concrete mix to attain the desired workability (Frondistou-Yannas, 1997). RCA aggregates possess distinctive physical attributes, such as polygonal shape, rough surface texture, and a significantly larger specific surface area, resulting in reduced workability when higher proportions of RCA are incorporated into the concrete mix. However, this challenge can be mitigated by adequately controlling the moisture content of RCA prior to concrete mixing, thus obviating the need for excessive water addition during operations (Su & Wang, 2000; Tu et al., 2006). Furthermore, the reduction in unit weight consequent to the utilization of RCA also impacts compressive strength. Nevertheless, comparative studies with natural aggregates (Nixon, 1978; Kang & Weibin, 2018) reveal that concrete containing RCA as an admixture can still attain strength development over the curing period comparable to standard concrete. Enhancements in the mechanical properties of high-strength and high-performance concrete incorporating RCA admixtures can be achieved by incorporating supplementary admixtures like silica fume (Hendriks & Pietersen, 2000; Shayan & Xu, 2003; Tu et al., 2006).

Thailand holds the distinction of being the world's leading producer of natural rubber latex (NRL) derived from the rubber tree, Hevea brasiliensis. NRL, a natural polymer with inherent elastic properties, has garnered attention as a viable substitute for synthetic polymers in NRL polymer-modified concrete. Extensive research has confirmed its efficacy in enhancing the tensile and flexural strength of cement mortars, cement pastes, concrete, and stabilized cement soils (Sukmak et al., 2020; Tran et al., 2022; Yaowarat et al., 2018; Yaowarat et al., 2021). However, limited studies have explored the application of natural rubber latex (NRL) to enhance the flexural strength of recycled concrete aggregate (RCA) for pavement use. The focus of this research is to address this gap and pursue environmentally friendly solutions, which align with the primary objective of promoting sustainability.

To investigate this, the research adopts the TSMA two-step mixing method to prepare RCA concrete samples. The influence of the water-to-cement ratio (w/c) and rubber-to-cement ratio (r/c) on both compressive strength and flexural strength is examined. Advanced analytical techniques, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD), are employed to analyze structural changes and mechanical properties. The study presents the mechanical properties of RCA concrete and highlights the improvements in compressive strength and flexural strength achieved through the incorporation of NRL in the RCA-NRL concrete samples, adhering to the stipulations set by the Department of Highways of Thailand. This research serves as evidence of the effective utilization of recycled construction and demolition waste (CDW) alongside natural rubber latex (NRL) for the development of sustainable pavement technologies.

In recent years, sustainability considerations have become an integral component of pavement material design, extending beyond conventional mechanical performance criteria. Rigid pavement concrete, while offering superior durability and structural capacity, is associated with significant environmental impacts, primarily due to the intensive use of Portland cement and natural aggregates. Cement production alone is responsible for a substantial proportion of global anthropogenic CO_2 emissions, largely attributed to both the calcination of limestone and the high energy demand of clinker production. Consequently, reducing cement content has been widely recognized as one of the most effective strategies for lowering the carbon footprint of concrete.

Fly ash (FA), a by-product of coal-fired power generation, has been extensively utilized as a supplementary cementitious material to partially replace cement in concrete. The incorporation of FA not only reduces cement consumption and associated CO_2 emissions but also contributes to improved long-term performance through pozzolanic reactions, which refine pore structure and enhance microstructural densification. From a sustainability perspective, the use of FA promotes industrial symbiosis by diverting waste from landfills and converting it into value-added construction materials. However, the interaction between FA and recycled concrete aggregate (RCA), particularly under the influence of polymeric modifiers such as natural rubber latex (NRL), remains insufficiently understood in the context of rigid pavement concrete.

In parallel, the environmental benefits of RCA utilization are closely linked to life-cycle considerations. Although RCA production requires energy for crushing, sorting, and transportation, numerous studies have demonstrated that, when evaluated over the entire life cycle, recycled aggregates generally exhibit lower environmental impacts than virgin aggregates, especially in regions where natural aggregate resources are scarce or transportation distances are long. The combined use of RCA and FA therefore represents a promising low-carbon strategy, provided that mechanical performance requirements can be satisfied.

Beyond environmental impacts, economic feasibility is a critical factor governing the practical adoption of sustainable pavement materials. While FA and RCA are often lower-cost alternatives to cement and natural aggregates, the incorporation of NRL introduces additional material costs that must be justified by performance improvements. From a cost-performance perspective, enhancing flexural strength, ductility, and fatigue resistance may allow for reduced pavement thickness or extended service life, ultimately offsetting higher initial material costs. Consequently, sustainability assessment of pavement concrete should not be limited to material substitution alone but should consider the balance between cost, performance, and durability.

Life-cycle thinking provides a comprehensive framework for evaluating the overall sustainability of pavement materials by integrating mechanical performance, environmental impact, and economic cost throughout the material life span. Rather than focusing solely on early-age strength or material quantities, life-cycle-oriented approaches emphasize performance-based design, CO_2-equivalent emissions, and long-term durability. In this context, simplified life-cycle indicators, such as embodied CO_2 emissions per cubic meter of concrete and material cost per unit volume, offer practical tools for comparing alternative mix designs during the material selection and design stages.

Despite growing interest in low-carbon concrete technologies, limited studies have simultaneously addressed mechanical properties, fatigue performance, microstructural behavior, CO_2 emissions, and cost efficiency of FA–NRL–RCA concrete for rigid pavement applications. The lack of integrated assessment hampers the development of clear design guidelines and limits the broader implementation of sustainable pavement materials. Therefore, a holistic evaluation framework that incorporates life-cycle thinking is essential to identify optimal concrete mixtures that satisfy structural requirements while minimizing environmental impact and cost.

In response to these challenges, the present study adopts a performance- and sustainability-oriented approach to evaluate rigid pavement concrete incorporating RCA, FA, and NRL. By quantifying mechanical performance, microstructural characteristics, CO_2-equivalent emissions, and material costs, the study aims to provide practical insights into the life-cycle implications of alternative pavement concrete mixtures. The outcomes are expected to support decision-making in the design of low-carbon, cost-effective, and durable rigid pavement systems aligned with sustainable infrastructure development goals.

1.2 Objectives of the study

1.2.1 To evaluate the feasibility of using Recycled Concrete Aggregate (RCA) as coarse aggregate in rigid pavement concrete modified with Natural Rubber Latex (NRL).

1.2.2 To investigate the combined effects of Natural Rubber Latex (NRL) and Fly Ash (FA) on the mechanical properties of RCA-based concrete, including compressive strength, flexural strength, ductility, and fatigue resistance.

1.2.3 To examine the influence of key mix design parameters, namely rubber-to-binder (or cement) ratio, water-to-binder ratio, and FA replacement level, on the performance of RCA–NRL and RCA–FA–NRL concretes.

1.2.4 To characterize the microstructural and mineralogical changes induced by the incorporation of RCA, FA, and NRL using SEM, EDX, and XRD analyses, and to relate these changes to mechanical and fatigue behaviors.

1.2.5 To assess the environmental and economic performance of the proposed concretes by evaluating CO_2-equivalent emissions and material costs based on life-cycle-oriented indicators, and to identify optimal mixtures for sustainable rigid pavement applications.

1.3 Organization of the dissertation

This thesis comprises five chapters, each outlined as follows:

Chapter 1: Introduction. This chapter provides an overview of the background, the significance of the problem, the study objectives, the composition of the thesis, and references to relevant research.

Chapter 2: Literature Review. In this chapter, relevant literature is reviewed, including topics such as experimental materials, concrete pavement, recycled concrete coarse aggregate, and the application of natural latex to enhance concrete properties. The chapter also explores the historical utilization of recycled concrete in construction projects.

Chapter 3: This chapter presents the findings of the study on the Enhancing the Flexural Strength of Concrete Pavements with Recycled Aggregate Using Natural Rubber Latex Additive. The study procedures involved the preparation of materials, including ordinary Portland cement (OPC), fly ash, natural stone coarse aggregate (NA), recycled concrete coarse aggregate, and fine aggregate from natural sand. Concrete mixes were designed with water-to-cement ratios (w/c) of 0.3, 0.4, and 0.5. Specimens for compressive strength testing were prepared following BS 1881–108 (BS 1983) standards, sized at 150 x 150 x 150 mm. For flexural strength testing, specimens measuring 100 x 100 x 400 mm, according to ASTM C78-02 (ASTM 2002) standards, were used. The concrete samples were divided into natural aggregate concrete and recycled aggregate concrete, with the addition of natural rubber latex in varying weight ratios per cement (r/c) of 0.0, 0.5, 1.0, 1.5, and 2.0 percent, respectively. The compressive and flexural strengths were tested, and the deflection of concrete samples during the flexural strength test was recorded. A comparative analysis was conducted to evaluate the compressive and flexural properties of natural aggregate concrete and recycled concrete, aiming to identify suitable properties for practical implementation. The microstructure of concrete samples was investigated using scanning electron microscopy (SEM), energy-dispersive chemical composition analysis (EDS), and X-ray diffraction analysis (XRD).

Chapter 4: The integration of Recycled Concrete Aggregate (RCA) and Fly Ash (FA) offers a sustainable approach to reducing natural resource use and carbon emissions in pavement concrete. This study examined the influence of Natural Rubber Latex (NRL) on the mechanical and environmental performance of FA–RCA concrete. Tests included compressive strength, flexural strength, flexural fatigue, and microstructural analysis (SEM and EDX), along with CO_2-equivalent emission calculations. Results showed that moderate NRL contents (r/b = 0.5–1.0%) improved flexural strength and fatigue life, especially at 15–25% FA, while excessive latex reduced strength due to hydration retardation. Microstructural analysis confirmed matrix densification at optimal NRL levels and film-induced hydration barriers at higher dosages. The mix with 25% FA and 0.5% r/b achieved the lowest emissions (304.63 kg CO_2-e/m^3) and highest fatigue life, while 20% FA yielded the lowest material cost. All mixtures met Thai pavement strength requirements. Overall, optimized FA–NRL–RCA concrete enhances structural performance and reduces carbon footprint, supporting its use as a low-carbon pavement material.

Chapter 5: This study showed that Natural Rubber Latex (NRL) and Fly Ash (FA) can effectively improve the performance and sustainability of RCA-based pavement concrete. Optimal NRL contents enhanced flexural strength and fatigue life, while excessive latex reduced compressive strength by hindering hydration. FA replacement at 20–25% improved long-term strength and significantly lowered carbon emissions. The mix with 25% FA + 0.5% r/b provided the best environmental performance, while 20% FA offered the lowest material cost. All optimized mixtures met Thai rigid pavement strength requirements.

1.4 References

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