

UTILIZING RECLAIMED ASPHALT PAVEMENT AS A REPLACEMENT FOR COARSE AGGREGATE IN ROLLER COMPACTED CONCRETE

Chalermphol Chaikaew¹, Nirachorn Nokkaew², Gritsada Sua-iam³ and Warun Na Songkhla^{4,*}

Received: October 26, 2023; Revised: February 27, 2024; Accepted: March 01, 2024

Abstract

The escalating quantities of waste are coming from old bituminous road pavements in Thailand has led to significant environmental and economic challenges. This research explores an innovative solution by investigating the feasibility of using Reclaimed Asphalt Pavement (RAP) as a substitute for natural coarse aggregate in roller compacted concrete (RCC). This study explores optimal proportions between cement to RAP-specifically at ratios of 1:6, 1:8, and 1:10-to achieve maximum dry density. The research includes essential tests, such as dry density and maximum compressive strength assessments, to determine the suitability of the material for compacted concrete production. Intriguingly, the research reveals that the 1:6 ratio not only has the highest dry density and maximum compressive strength but also may minimize environmental impact. These findings align with the ACI 325.10R-95 standard (1995), presenting a promising alternative for engineering applications and contributing to the responsible use of reclaimed materials.

Keywords: Compressive strength, dry density, reclaimed asphalt pavement, roller compacted concrete, sustainable construction

¹ Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Rattanakosin (RMUTR), Thailand. E-mail: chalermphol.c@rmutr.ac.th

² Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi (RMUTT), Thailand. E-mail: nirachorn.n@en.rmutt.ac.th

³ Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Phra Nakhon (RMUTP), Thailand. E-mail: gritsada.s@rmutp.ac.th

⁴ Department of Civil Engineering, Faculty of Engineering and Architecture, Rajamangala University of Technology Suvarnabhumi (RMUTSB), Thailand. E-mail: warun.w@rmutsb.ac.th

* Corresponding author

DOI: <https://doi.org/10.55766/sujst-2024-01-e02653>

Introduction

To repair asphalt concrete pavement using the milling method requires a substantial amount of asphalt concrete, leading to considerable waste generation as most of the excavated material is often reclaimed or discarded. Research indicates that RAP, or old asphalt concrete, presents a sustainable solution, reducing overall construction costs and minimizing the use of natural resources. Studies show that RAP meets engineering qualifications, both in terms of mechanical and physical properties, and complies with agency standards (Masi *et al.*, 2022). The improvement of pavement material through recycling involves two approaches: (i) milling the original pavement and separating it into stone-cement mix piles and asphalt pavement piles, subsequently mixed with water and cement before grinding, and (ii) machine milling the original pavement and mixing it with water and cement. A study on concrete incorporating RAP as a substitute for coarse aggregate revealed that while the ultimate strength of RAP-mixed concrete was slightly lower than general concrete, it remained within standard limits. Additionally, the failure behavior tests indicated that asphalt-mixed concrete specimens exhibited greater toughness than general concrete (Antunes *et al.*, 2019). Coarse aggregate obtained from RAP removal, especially in smaller sizes, can be reused in engineering works with the addition of an appropriate amount of fine aggregate. This approach contributes to reducing the depletion of natural resources, addressing environmental pollution, and adding value to waste materials through their reuse in roller compacted concrete (Andrew *et al.*, 2022).

To implement RCC technology in Thai roadworks, a Roller Compacted Concrete Pavement (RCCP) was constructed without reinforced steel at Mae Moh, Thailand. One cubic meter of RCCP comprises 180 kg of Portland cement type 1 and 185 kg of lignite fly ash, with a water-to-binder ratio (w/b) of approximately 0.30 by weight, chosen for higher compressive strength, especially in the early stages. Additionally, a water-reducing agent of about 0.7 litre/m³ of concrete is added to facilitate mixing and compression, with a maximum stone size of 20 mm. A sand-to-coarse aggregate mix ratio of 0.5 is assumed to be comparable to traditional concrete roadworks. RCCP technology is poised to reduce concrete pavement costs, particularly in areas with minimal ground subsidence. The reduction in construction time, elimination of reinforced steel (when preparing the pavement layer and foundation), block partitioning, and blinding can save labor, particularly when laying concrete

paver on fresh concrete at about 22-25 cm per layer. This accelerates construction compared to asphalt pavers (Ministry of Transportation, 2006; Ministry of Transport Operation Center, 2019).

Based on this information, the researcher proposes the idea of reintegrating RAP as a substitute for natural coarse aggregate in RCC. This approach facilitates the cost-effective recycling of waste material, serves as a substitute for scarce resources, reduces production costs, and harnesses the recycling potential and capabilities of RAP.

Materials, Specimen Preparation, and Testing

Materials

A commercial Portland cement type 1 from Thailand has a specific gravity of 3.15 according to ASTM C150-07 (2007). RAPs are obtained from the Office of Highway 15 (Prachuap Khiri Khan, Thailand), the Department of Highways. They have restored and maintained the highway to the standard level by renovating the road using Pavement In-Place Recycling, which requires milling of wearing asphalt concrete to a thickness of 5 cm (Chaikaew *et al.*, 2022) as shown in Figure 1.



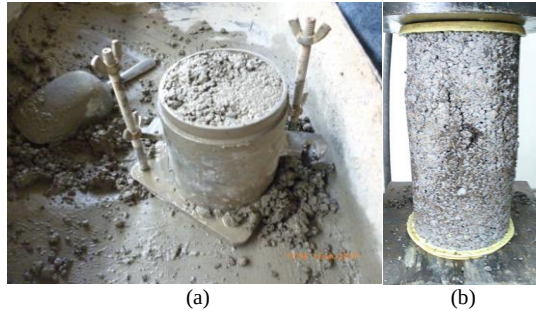
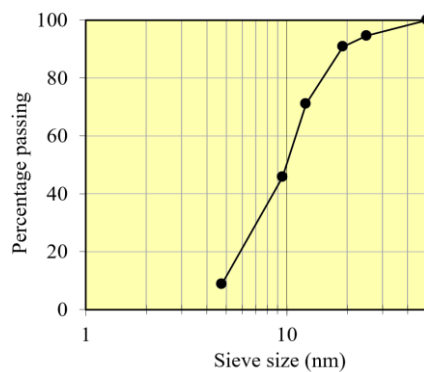
Figure 1. RAP utilized in this study

Mix proportions

The RCC mixtures are designed with varying ratios of cement to RAP and are presented in Table 1. In the 1:6 mix, RAP is utilized at a higher proportion, emphasizing sustainability, with 60% of the aggregate being reclaimed. The 1:8 mix strikes a balance by incorporating 80% RAP, aiming for structural integrity while minimizing natural aggregate use. In the 1:10 mix, a more radical

Table 1 Details of the mix proportions

RCC mixtures	Kg per three specimens	
	Cement	RAP
1:6	10	60
1:8	10	80
1:10	10	100


Figure 2. (a) Modified compaction test and (b) Compressive strength test

Figure 3. RAP sieving test results

approach is taken, with RAP exclusively replacing natural aggregate. These mix proportions explore the potential of RAP as a substitute, address environmental concerns, and test the structural viability of RCC with reclaimed materials.

Specimen Preparation and Testing

In this study, the preparation of specimens involved the meticulous separation of RAP into coarse aggregate material by sieving it through a standard 3/4" sieve, ensuring the exclusion of any fine aggregate. The determination of the mixed size of RAP was conducted through a comprehensive sieve analysis following ASTM C136-06 standards (2006). This process facilitated the selection of suitable coarse aggregate material for subsequent testing.

The modified compaction test, following ASTM D1557-12 standards (2021) and illustrated

in Figure 2(a), was then employed to assess the compaction characteristics of the prepared RAP material. The procedure for testing includes preparing a representative sample of the RAP material. Conduct a Proctor compaction test by compacting the material in layers using a modified effort. Then vary the moisture content for different compaction trials and measure the dry density and optimum water content for each trial. This test provides insights into the material's density and compaction properties under controlled conditions, contributing to a thorough understanding of its suitability for RCC applications. Subsequently, a 28-day compressive strength test was conducted using cylindrical specimens with a diameter of 15 cm and a height of 30 cm, adhering to ASTM C39/C39M-21 standards (2021) and depicted in Figure 2(b). This compressive strength test is crucial for evaluating the material's structural performance and its ability to withstand loads in practical applications.

Results and discussion

Physical Properties of RAP

The physical properties test results of RAP revealed that the saturated surface dry (SSD) density is 2.42 g/cm^3 . The water absorption and Los Angeles crushing values are 0.39% and 28%, respectively, while the specific gravity of new rock from the mill is 2.60 and the absorption is 0.74. The particle size distribution of RAP is shown in Figure 3. The maximum size of RAP was 25 mm, and it also has an angular, cubic, and rectangular shape. The fineness modulus is 6.89, and RAP passing through a 9.5 mm or 3/8" sieve size has a weight of more than 50%. It was found that the size of the RAP is characterized by the distribution of the rather coarse aggregate, as shown in Figure 3 (Chaikaew *et al.*, 2022).

Optimum Water Content

By incorporating RAP at the proportions of 1:6, 1:8, and 1:10, followed by dry density and modified compaction tests, the investigation revealed optimum water content values of 5.0%, 5.4%, and 6.1%, respectively (Figure 4). The results demonstrate an increasing demand for optimum water content with the rise in substituted coarse aggregate per RAP. The coarse distribution characteristics of the RAP's aggregate size contribute to wider gaps between particles, necessitating a specific optimum water content for proper compaction (Chaikaew *et al.*, 2022). These findings underscore the importance of carefully considering water content in the mix design process,

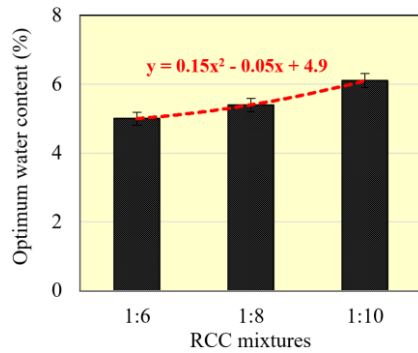


Figure 4. Optimum water content

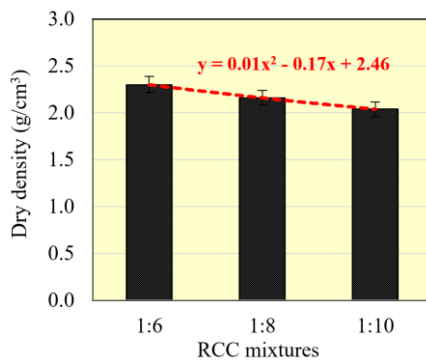


Figure 5. Dry density values

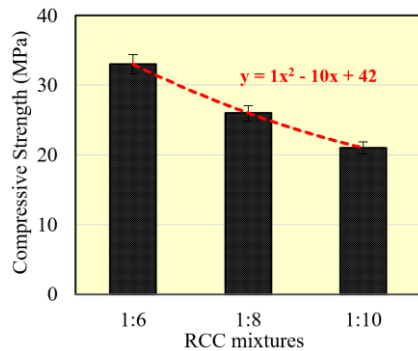


Figure 6. Maximum compressive strength

particularly when incorporating RAP, to ensure the achievement of optimal compaction and overall material performance.

The relationship between the test results of optimum water content for RCC substituting coarse aggregate with RAP at various proportions of 1:6, 1:8, and 1:10 can be expressed by Equation (1) as follows:

$$y = 0.15x^2 - 0.05x + 4.90 \quad (1)$$

Here, y represents the percentage of optimum water content, and x denotes the proportion between cement and RAP.

Dry Density

According to the modified compaction test for RCC using RAP to replace coarse aggregate at proportions of 1:6, 1:8, and 1:10, the dry density values were determined to decrease to 2.3, 2.16, and 2.04 g/cm³, respectively (Figure 5). The results indicate that increasing the substitution of coarse aggregate with RAP in higher proportions leads to a decrease in dry density. Conversely, the maximum dry unit weight decreases due to the higher quantity of RAP, resulting in an increased contact surface area of the aggregate. This decrease is attributed to insufficient cement paste, the bonding material, as the proportion of RAP rises. The bonding strength between the cement paste and aggregate diminishes, impacting the overall dry density and compressive strength of the RCC. The comparison of the relationship with optimum water content reveals that as the amount of RAP increases, the RCC texture develops more gaps between high aggregate particles, necessitating greater water demand. Increased water permeation through these gaps leads to a lower dry density (Daniel and Benson, 1990). Additionally, the insufficiency of binder to fill the growing gaps contributes to this effect. The increased demand for water results in a more liquid texture, weakening the friction force between particles and causing a decrease in dry density (Hunger, 2010; Bittencourt *et al.*, 2021).

The correlation between the test results of dry density for RCC, which substitutes coarse aggregate with RAP at proportions of 1:6, 1:8, and 1:10, can be represented by Equation (2):

$$y = 0.01x^2 - 0.17x + 2.49 \quad (2)$$

In this equation, y signifies the dry density in grams per cubic centimeter (g/cm³), and x denotes the proportion between cement and RAP.

Maximum compressive strength

The test results for the maximum compressive strength of RCC utilizing RAP to substitute coarse aggregate at the proportions of 1:6, 1:8, and 1:10, as illustrated in Figure 6, indicate values of 33 MPa, 26 MPa, and 21 MPa, respectively. It was observed that an increased substitution of aggregate with RAP leads to a reduction in the compressive strength of RCC. Given that RCC functions as a composite material (Al Baghdady and Khan, 2018), the cement paste assumes the role of the bonding material or matrix (Tonoli *et al.*, 2009).

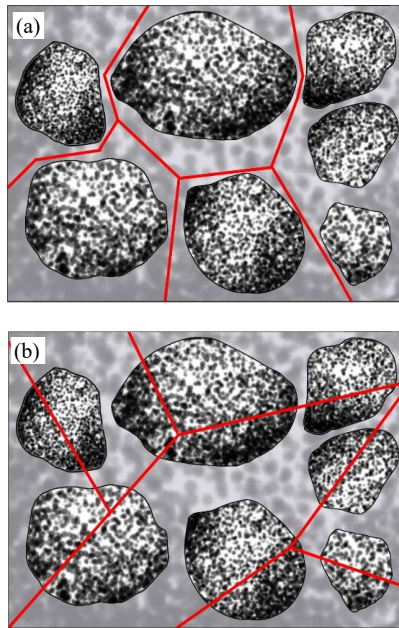


Figure 7. Failure pattern and crack direction

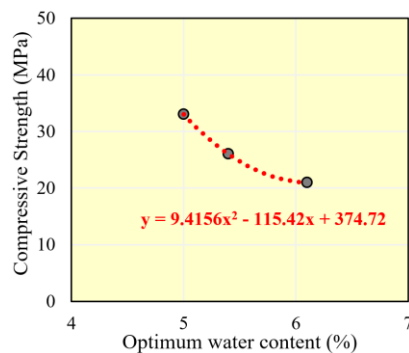


Figure 8. The optimal water content and compressive strength correlation

Consequently, an elevation in the amount of aggregate derived from RAP influences the quantity of cement paste acting as a binder, resulting in diminished adhesive strength to the escalating aggregate content and consequently reducing compressive strength. The density of all test specimens exhibits a parallel relationship with the compressive strength of the roller compacted concrete. These findings emphasize the intricate interplay between material composition, bonding characteristics, and resulting mechanical properties in RCC formulations incorporating RAP.

The relationship between the test results of compressive strength for RCC, substituting coarse aggregate with RAP at proportions of 1:6, 1:8, and 1:10, can be described by Equation (3):

$$y = 1x^2 - 10x + 42 \quad (3)$$

Here, y represents the compressive strength in Megapascals (MPa), and x denotes the proportion between cement and RAP.

Failure Pattern and Crack Direction

Another crucial factor is the observed concrete failure pattern. Concrete failures do not typically traverse the RAP but predominantly occur along the Interfacial Transition Zone (ITZ) (Song *et al.*, 2022). The strength of compacted concrete is primarily dictated by the strength of the contact area (Bentur and Mindess, 2007), as illustrated in Figure 7(a). The surface of RAP aggregate is coated with asphalt rubber, thereby diminishing the physical bonding strength between the aggregate and cement paste. This surface bonding strength significantly influences the strength of RCC. In cases where the concrete exhibits high adhesion between the aggregate surface and the cement paste, and the strength of the cement paste surpasses that of the aggregate, the failure pattern predominantly manifests as cracks propagating through the aggregate particles. This, in turn, contributes to higher concrete strength (Sukontasukkul, 2013), as depicted in Figure 7(b). These observations underscore the intricate relationship between concrete failure patterns and the interplay of various factors, including adhesion and strength characteristics, particularly in formulations involving RAP in RCC.

Correlations Between Water Content, Compressive Strength and Dry Density

Understanding the interrelationships among water content, compressive strength, and dry density is crucial for optimizing the formulation of RCC when substituting coarse aggregate with RAP. This section delves into the correlations derived from Figures 8, 9, and 10, providing valuable insights into the intricate dependencies between these key properties.

Equation (4), derived from Figure 8, establishes a quantitative relationship between compressive strength (y) and the percentage of optimum water content (x) in the RCC mix. This equation facilitates a deeper understanding of how variations in water content impact the resulting compressive strength can be expressed as follows:

$$y = 9.4156x^2 - 115.52x + 374.72 \quad (4)$$

Equation (5), derived from Figure 9, illustrates the correlation between dry density (y) and the percentage of optimum water content (x) in the RCC mix. This equation provides insights into the trade-offs between water content and dry density,

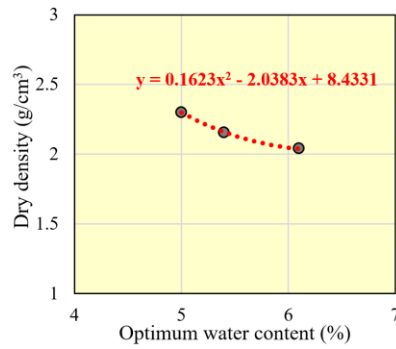


Figure 9. The optimal water content and dry density correlation

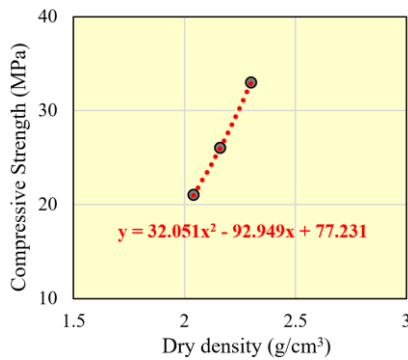


Figure 10 The optimal water content and compressive strength correlation

Table 2. Comparison of study results with ACI 325.10R-95 standard

RCC mixtures	Compressive strength (MPa)	
	This study	ACI 325.10R-95
1: 6	33	> 30 MPa (RCCP)
1: 8	26	> 10 MPa (RCCD)
1: 10	21	> 10 MPa (RCCD)

influencing the overall material characteristics can be expressed as follows:

$$y = 0.1623x^2 - 2.0383x + 8.4331 \quad (5)$$

Equation (6), obtained from Figure 10, delineates the relationship between compressive strength (y) and dry density (x) in the RCC mix. This equation reveals how changes in dry density impact the resulting compressive strength can be expressed as follows:

$$y = 32.051x^2 - 92.949x + 77.231 \quad (6)$$

The presented equations encapsulate the nuanced connections between water content,

compressive strength, and dry density in RCC formulations incorporating RAP. These correlations offer a quantitative foundation for informed decision-making in mix design, paving the way for optimized RCC formulations tailored to specific engineering requirements.

Engineering Applications

The compressive strength of RCC substituting coarse aggregate with RAP at proportions of 1:6, 1:8, and 1:10 can be assessed in comparison to the guidelines outlined in the ACI 325.10R-95 standard (1995), as detailed in Table 2. According to the standard, the proportion of 1:6 demonstrates a relative compressive strength equivalent to Roller Compacted Concrete Pavement (RCCP). RCCP, characterized by high aggregate binder content (Wei *et al.*, 2021), typically exhibits a compressive strength exceeding 30 MPa. This type of compacted concrete is well-suited for use as a primary structural layer. Furthermore, proportions of 1:8 and 1:10 are preferred for engineering applications, with compressive strengths equivalent to Roller Compacted Concrete Dam (RCCD). RCCD is characterized by a lower aggregate binder content and typically exhibits a compressive strength greater than 10 MPa. These proportions, therefore, offer versatility for use in various engineering scenarios.

The varying proportions provide options suitable for applications ranging from high-strength structural layers, such as in RCCP, to lower-strength yet structurally significant uses, akin to RCCD. These findings highlight the adaptability and potential applications of the investigated RCC formulations in diverse engineering contexts.

Conclusions

The demand for optimum water content in RCC increases proportionally with the substitution of a larger quantity of coarse aggregate with RAP, leading to a corresponding decrease in maximum dry density. Notably, utilizing RAP to replace coarse aggregate at the proportion of 1:6 yields the lowest ratio, resulting in both the highest dry density and compressive strength. This significant finding suggests that this specific proportion offers an optimal balance, maximizing both the compacted concrete's strength and density. Furthermore, the test results reveal a direct correlation between the maximum dry density and the highest compressive strength. The proportionality observed indicates that adjustments in mix design impacting dry density are mirrored in the compressive strength of the RCC. Crucially, the study establishes that all mixed proportions of RCC, incorporating RAP,

meet the engineering standards outlined in the ACI 325.10R-95 standard (1995). This applicability supports the versatility and feasibility of using RAP as a substitute for coarse aggregate in RCC for various engineering applications.

Acknowledgements

This research is funded by the Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Rattanakosin Thailand. Special thanks also go to the Department of Civil Engineering, Faculty of Engineering and Architecture, Rajamangala University of Technology Suvarnabhumi Thailand for supporting the apparatus. All the authors declare no conflict of interest.

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