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Research Paper

An Examination of Reclaimed Asphalt Pavement's Role as Aggregate in the Composition of Structural Concrete: An Extensive Overview

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ABSTRACT

The process of renovating flexible pavement produces an extensive amount of reclaimed asphalt pavement (RAP). These aggregates are frequently discarded, whether through legal or illegal means, in nearby locations, thereby creating various challenges for regulatory bodies. The incorporation of these aggregates into portland cement concrete (PCC) mixtures represents an innovative strategy that could yield significant socio-economic and environmental advantages. Nonetheless, the inclusion of RAP aggregates may also adversely impact both the soundness and performance characteristics of the concrete. This paper delivers a detailed and critical evaluation of the practicality of employing RAP aggregates in concrete production, while also pinpointing several shortcomings that must be rectified to enhance sustainability in construction methodologies. This paper is structured in the following manner: it initiates with a detailed characterization of RAP aggregates, followed by an analysis of the characteristics of fresh concrete containing RAP, and culminates in an exploration of RAP containing concrete mechanical and durability characteristics. According to the literature review, it is evident that aggregates derived from RAP are generally of a lower quality than their natural counterparts. This may not pose a significant issue regarding the characteristics of the fresh concrete. The asphalt film and the presence of agglomerated particles within the RAP were identified as key factors contributing to the diminished strength and durability characteristics. The integration of RAP as aggregates has been associated with notable advantages, including improved toughness. Furthermore, existing research suggests that the performance of concrete containing RAP can be enhanced through the processing of RAP in conjunction with using supplementary cementitious materials (SCMs) or fibres.

1 Introduction

Reinforced concrete stands as one of the most prevalent construction materials globally, with the extraction of its raw materials contributing substantially to environmental degradation. This impact is characterized by considerable energy consumption, elevated CO₂ emissions, and the exhaustion of natural resources [1]. A significant concern in this context pertains to the sourcing of aggregates, which constitutes approximately 70% of the concrete's total volume. These aggregates,

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primarily composed of stones and sand, are typically obtained through quarrying or dredging activities in riverbeds [2]. Globally, the maintenance of roads and highways generates millions of tons of RAP, while substantial waste is produced during road dismantling. In the United States alone, the anticipated annual volume of milled asphalt exceeds 100 million tons [3]. The addition of RAP into new hot mix asphalt (HMA) represents a common sustainable practice. Research findings suggest that the use of RAP as a substitute for a portion of natural aggregate (NA) and asphalt binder yields beneficial economic and environmental outcomes [4, 5]. However, the asphalt present in RAP tends to be rigid and requires rejuvenation before its application in HMA, with this rigidity being exacerbated by oxidation during storage [6–9]. Therefore, RAP stockpiles are commonly regarded as inadequate for HMA applications and are usually disposed of in unregulated areas, resulting in substantial environmental concerns [10]. Additionally, there is a global shortage of NA [11]. To address these challenges, researchers are investigating the potential of using RAP as an alternative to NA in the production of concrete. This strategy not only lessens the demand for NA and mitigates greenhouse gas emissions but also safeguards important land, facilitating the advancement of sustainable concrete [12–14]. However, the introduction of RAP to concrete has the potential to detrimentally influence its performance characteristics [15, 16]. The main factors contributing to reducing the general strength of concrete that contains RAP have been identified as the existence of an asphalt coating and the presence of agglomerated particles [17, 18]. Several studies have indicated different methods for the removal of asphalt coatings from the RAP aggregates, which can lead to enhanced material characteristics and improved bonding between cement mortar and the RAP aggregates [19, 20]. An immediate requirement exists for a comprehensive assessment that examines how RAP influences the performance attributes of concrete. Conducting such an evaluation would bring to light the role of RAP as aggregate material in concrete, consequently drawing the attention of engineers and contractors in the field. This study article delivers an in-depth exploration of the different characteristics of concrete that are modified through the utilization of RAP aggregates. In addition, it includes a concise review of the application of SCMs and fibres in augmenting the behaviour of concrete containing RAP.

2 Reclaimed asphalt pavement (RAP)

The term reclaimed asphalt pavement refers to materials that are taken out of old pavement through either milling or full-depth removal due to resurfacing, reconstruction, and rehabilitation, in addition to serving the purpose of facilitating access to underground utilities. They comprise a mixture of asphalt combined with aggregates [21–25].

2.1 The process of reclamation

2.1.1 Reclaiming

The predominant techniques for acquiring RAP involve either the milling of the surface layer of the pavement or the full-depth removal [26–28] as shown in figure 1.



(a)



(b)

Fig. 1 – RAP acquired by (a) milling and (b) full-depth removal.

- Milling, often referred to as cold planing, is a technique that involves the removal of the uppermost layer of pavement utilizing a milling machine capable of extracting up to 50 mm of thickness in a single operation. This approach is employed to either lay down a new surface layer or to enhance and restore the pavement's frictional characteristics [16, 27]. The RAP produced through milling is typically finer, denser, and with little dust impurity as compared to that obtained through the full-depth removal method [19, 29].
- Full-depth removal refers to a technique in which the entire pavement structure, along with portions of the underlying layers, is removed utilizing a rhino horn attachment on a bulldozer and/or pneumatic pavement breakers [16].

2.1.2 Crushing

Once the asphalt material has been collected from the process of full-depth removal, it must undergo a crushing process. It is worth mentioning that asphalt collected by means of milling usually doesn't need this process. The procedure is not designed to crush the stone components again; rather, its primary objective is to separate the RAP that is bonded by bitumen into smaller fractions. Crushing is most effectively performed in colder temperatures, as warmer conditions tend to re-adhere the bitumen. Following the crushing, the RAP is then subjected to sieving to obtain the desired particle sizes [28].

The process of reclaiming RAP is illustrated below in figure 2.

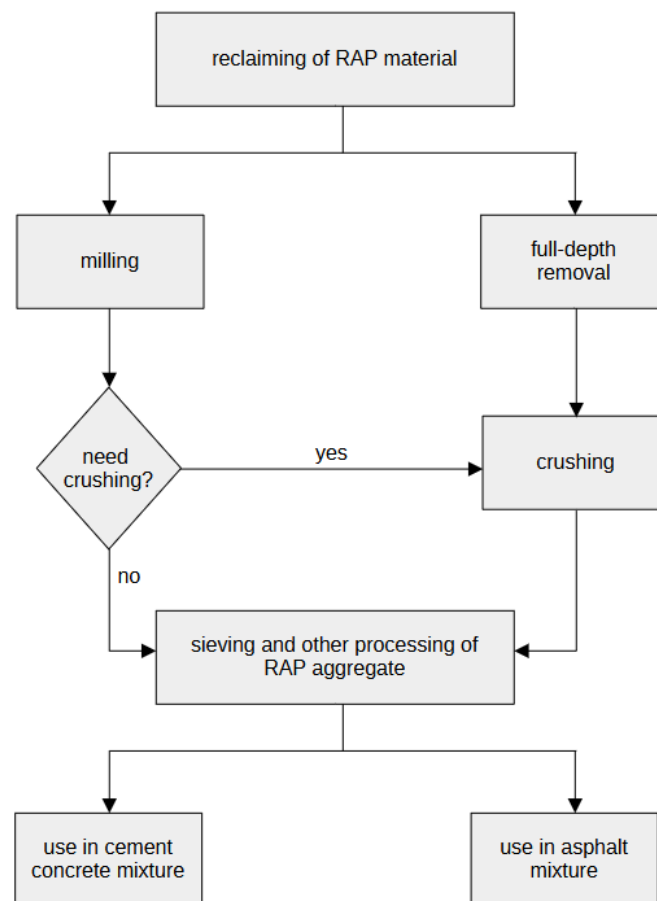


Fig. 2 – Flowchart of the reclamation of RAP materials worldwide.

2.2 Benefits of using RAP

Each year, a substantial quantity of RAP, amounting to millions of tons, is generated globally. Following the reclamation process, RAP is frequently disposed of in landfills or abandoned in open spaces [30, 31]. Figure 3 depicts the subsequent

accumulation of RAP in outdoor settings. Incorporating RAP as a substitute for NA in concrete mixtures presents a variety of advantages, including:



(a)



(b)

Fig. 3 – RAP stockpiles in an open environment.

- RAP has the potential to markedly decrease the reliance on NA [19, 31–36]. Research demonstrates that up to 50% of NA in concrete mixtures can be substituted with RAP as aggregates while maintaining the essential characteristics of the concrete [37].
- Using RAP instead of NA can lower greenhouse gas emissions [30, 38–40]. The extraction and processing of NA are responsible for approximately 1% of total greenhouse gas emissions globally [30, 41]. Incorporating RAP as a partial alternative to these aggregates facilitates a reduction in emissions overall.
- A notable benefit of utilizing RAP as aggregates is the considerable decrease in transportation costs [19, 30, 32, 42]. This advantage is especially pronounced in scenarios where the construction site is located at a considerable distance from the market or quarrying facility, as RAP can be effectively employed directly at the site.
- Preservation of valuable land resources. Using RAP offers two main land-related benefits: it reduces the need for additional land for dumping RAP, which is crucial in densely populated areas, and it helps preserve roadside agricultural farms by preventing the stockpiling of RAP [11, 19, 31, 42–44].
- The addition of RAP in construction has been shown to significantly decrease the overall expenses associated with producing one cubic meter of concrete, with estimates indicating a reduction of around 45% [11, 17, 30, 45]. This financial benefit primarily arises from a diminished demand for NA, coupled with a notable decrease in transportation costs [17, 30, 45].
- Other advantages exist, such as increased toughness with the introduction of RAP to concrete [20, 46, 47]. Furthermore, utilizing stockpiled RAP in concrete mixtures can enhance the visual appeal of highways by minimizing the accumulation of RAP along the roadside. Additionally, a decrease in the size of trucks and convoys transporting NA is likely to improve the flow of traffic on highways to some degree.

3 Characteristics of RAP aggregates

The characteristics of RAP aggregates differ based on their source, which in turn influences their efficacy. Table 1 summarizes a comparison of the physical characteristics of RAP aggregates against NA.

3.1 Physical characteristics

3.1.1 Gradation of RAP aggregates

The gradation characteristics of RAP aggregates frequently differ significantly from those of the NA. This variation is influenced by the source of the RAP and the milling techniques employed, including milling speed and the depth of milling

[48, 49]. Numerous studies indicate that coarse RAP aggregates tend to be finer than natural coarse aggregate (NCA) [19, 40, 50–52]. In contrast, the findings indicated that fine RAP aggregates are characterized by a coarser composition relative to standard natural fine aggregates [40, 49]. It is common for the fineness modulus of fine RAP aggregates to be above 3 [52], while there are instances where the figure can exceed 4.4 [49]. The phenomenon in question is attributable to the effects associated with agglomeration, which involves the grouping of fine RAP particles in the vicinity of the edges of coarser RAP particles. As a result, the material produced is coarser and presents a more gap-graded profile than that found in natural fine aggregates [49]. Conversely, coarse RAP aggregates have been noted to exhibit a more well-graded nature compared to NCA [19].

3.1.2 Binder content

The proportion of asphalt surrounding the aggregates is documented to vary between 2% and 7.5% by mass. Several factors contribute to this variation, such as the fraction of RAP, the initial asphalt content, the extraction methodology, stockpiling methods, and the length of service [19, 37, 40, 49, 53, 54]. Several studies have indicated that this asphalt film can yield multiple advantages, including reduced impact value [19, 55], reduced abrasion value [19], and a reduction in the crushing value of aggregates [19].

3.1.3 Water absorption

It is commonly noted that water absorption of RAP aggregates, including coarse and fine, is typically observed to be less than that of NA [19, 40, 47, 52, 56, 57]. This occurrence can be explained by the water-repellent characteristics of the asphalt coating that encases the aggregates [40]. Conversely, some research has reported a greater water absorption capacity in RAP aggregates in comparison to NA [19, 37, 49, 51, 53, 58–61]. The heightened water absorption observed in contaminated RAP can be largely ascribed to the buildup of dust layers on their surfaces.

3.1.4 Unit weight

The unit weight of RAP aggregates is influenced by the specific type of aggregate incorporated within the pavement, as well as the moisture content of the material [51, 62]. Existing studies on RAP aggregates indicate that their unit weight is less than that of the NA [52, 63–65].

3.1.5 Specific gravity

It has been noted that the values of specific gravity of RAP aggregates tend to be less than those of NA. This discrepancy is largely a result of the low-density asphalt coating that encases the aggregates in RAP [20, 33, 37, 40, 46, 53, 58, 62, 66, 67]. The range of specific gravity for NA is usually between 2.4 and 2.8. In contrast, coarse RAP is reported to have a specific gravity that varies from 2.1 to 2.69, while fine RAP is characterized by a specific gravity range of 1.81 to 2.49 [49, 52, 59].

Table 1 - Comparative analysis of the physical properties of NA and RAP aggregates

RAP aggregate characteristic	Compared to NA	References
Grading (coarse)	Finer	[19, 40, 50–52]
Grading (fine)	Coarser and gap-graded	[40, 49]
Binder content	existent	[19, 37, 40, 49, 53, 54]
Water absorption (both coarse and fine)	Higher (when contaminated)	[19, 37, 49, 51, 53, 58–61]
	Lower	[19, 40, 47, 52, 56, 57]
Unit weight (both coarse and fine)	Lower	[52, 63–65]
Specific gravity (both coarse and fine)	Lower	[20, 33, 37, 40, 46, 53, 58, 62, 66, 67]

3.2 Chemical characteristics

RAP is composed of 93% to 97% mineral aggregates and 3% to 7% hardened asphalt cement. Its chemical makeup closely resembles that of NA, with predominant elements including SiO₂, Fe₂O₃, and CaO [68]. The asphalt cement found in RAP consists of a blend of high molecular weight aliphatic hydrocarbons, along with low levels of sulfur, nitrogen, and polycyclic hydrocarbons, as well as a mixture of asphaltenes and maltenes [69]. The asphalt in RAP exhibits viscoelastic characteristics, with its characteristics influenced by temperature and loading conditions. Oxidation processes elevate the viscosity of the asphalt by transforming oils into resins and resins into asphaltenes, resulting in age hardening. This increase in viscosity can mitigate alkali-silica reactions within the aggregates [70]. When incorporated into concrete, the workability of RAP is frequently compromised by the asphalt film that envelops the aggregates. Enhancing the workability of RAP can be achieved by reducing the viscosity of bitumen. Nevertheless, RAP can influence concrete characteristics such as creep and shrinkage, particularly at elevated temperatures, which soften the asphalt and exacerbate creep [71].

4 Characteristics of concrete incorporating RAP

4.1 Characteristics of fresh concrete

The attributes of fresh concrete are crucial, as they are directly associated with the equipment selection for its processing and compaction, and they have a substantial impact on the qualities of the concrete after it has set [72]. Key characteristics in this context encompass workability and slump, and unit weight.

4.1.1 Workability and slump

It is widely recognized that utilizing spherical aggregates that possess a diminished capacity for water absorption can significantly enhance the workability of concrete mixtures. Nevertheless, this claim is not entirely applicable to mixtures that include RAP as aggregates, even considering their reduced absorption characteristics and relative sphericity compared to NA. A variety of research investigations have demonstrated that the addition of RAP generally results in a reduction of the slump value of the mixtures when compared to control mixtures. In contrast, some research has reported improved workability with the addition of RAP. For instance, the investigation by Al-Oraimi et al. [67] revealed that, although RAP and NA exhibit similar water absorption capacities, concrete mixtures composed entirely of coarse RAP demonstrated approximately 80% of the workability of the control mix. Similarly, Okafor [73] noted that, despite RAP's lower water absorption compared to NA, workability was diminished in RAP mixtures. Huang et al. [20] found that the inclusion of coarse and fine aggregates of RAP together may enhance the workability of concrete mixtures, while the addition of either coarse or fine RAP would significantly lower it. The viscous characteristics of the asphalt coating were determined to be a significant factor in the observed decrease in slump value, while the reduced capacity for water absorption was related to the enhanced workability of the combined RAP mixtures. Furthermore, Huang et al. [46] have shown that incorporating a minor proportion of RAP can enhance the workability of concrete mixtures; although a larger percentage of RAP aggregate, particularly fine RAP, may lead to stiffer mixtures with zero slump. A similar finding was noted by Katkhuda et al. [74], where the inclusion of fine RAP significantly reduced workability in comparison to coarse RAP mixtures. Singh et al. [19] observed that coarse RAP produced through the full-depth reclamation method could exhibit an increased capacity for water absorption in comparison to NA. This led to a decrease in the original slump by roughly 30%, although pre-washing the aggregates before usage may improve the slump value by approximately 65%. Huang et al. [46] noted that increased amounts of water-reducing admixture are advantageous to RAP mixtures. Erdem and Blankson [75] discovered that during the mixing process, the adhered asphalt may detach from the aggregate surface, leading to a reduction in the workability of the mixtures by roughly 45% due to water absorption by the RAP surface. In contrast to the aforementioned studies that highlight a reduction in workability, some research suggests that the inclusion of RAP can improve the workability of fresh concrete mixtures. As an illustration, Brand and Roesler [51] found that using RAP aggregates of lower water absorption at a 50% ratio can enhance workability by about 40%. The existing literature presents an ambiguous trend regarding the impact of RAP inclusion on fresh mixtures' workability. Notably, in comparison to fine RAP aggregates, coarse RAP aggregates are associated with a reduced adverse effect on the workability of concrete mixtures [54]. Nevertheless, further research is essential to establish a more definitive understanding. Future studies should explore various factors related to RAP, including shape characteristics, aggregate water absorption, and the effects of milling and processing techniques.

4.1.2 Unit weight

The existence of a lower-density asphalt coating that envelopes the aggregates significantly contributes to a reduction in the total weight of the RAP matrix. Thus, the integration of either coarse or fine RAP, whether employed individually or together, can result in a concrete mix that is distinguished by its lower density. Research conducted by Brand and Roesler [51] demonstrated that a mix comprising approximately 50% coarse RAP could exhibit a 5–6% density reduction compared to the control mix. Additionally, Singh et al. [19] indicated that a mixture consisting solely of 100% coarse RAP, produced through a full-depth removal process, demonstrated a unit weight variation of under 2% with conventional concrete mixtures.

4.2 Characteristics of hardened concrete

This section examines the characteristics of hardened concrete, specifically focusing on mechanical, toughness, and durability characteristics. The influence of integrating RAP as aggregates on the mechanical properties of portland cement concrete (PCC) mixtures is detailed in Table 2, which is based on findings from various studies.

4.2.1 Compressive strength characteristics

Within the field of civil engineering, compressive strength is regarded as the essential design criterion, particularly for applications involving structural concrete. Investigations have repeatedly revealed that integrating RAP into PCC mixtures leads to a reduction in compressive strength as the percentage of RAP increases. It has been determined that the asphalt coating encasing the RAP serves as an obstacle to the bonding between the aggregate of RAP surfaces and the mortar matrix [19]. Furthermore, the high amount of agglomerated particles present in RAP has been linked to a decline in the desirable characteristics of concrete mixtures [19]. Okafor [73] utilized 100% coarse RAP in his research, the outcomes indicated that the compressive strengths were lower in comparison to concrete containing NA. The study by Bensahnoun et al. [37] reported a reduction of approximately 8.5% to 37.2% when 25% to 100% coarse RAP was incorporated into concrete mixtures. The authors recommended using RAP at 50% replacement ratio for producing cement concrete. Soltanabadi and Behfarnia [47] used coarse RAP with (50%-100%) replacement ratios. According to their results, the authors suggested using RAP in concrete mixes when aiming for compressive strength lower than 35MPa. When lower percentages of coarse RAP, ranging from 10% to 30%, were employed, a reduced strength loss of between 8% and 29% was observed [58].

Research conducted on fine RAP has been less extensive compared to coarse RAP, as using the latter is more sought after. The underlying causes of this occurrence are primarily linked to factors including the gap-graded distribution, a higher content of asphalt, and the increased water absorption of fine RAP as opposed to regular fine aggregates, although studies comparing both RAP portions have demonstrated superior performance of concrete containing fine RAP compared to those with coarse RAP [21, 49]. In a study by Huang et al. [46], it was determined that fine RAP mixtures exhibited approximately 66% superior performance compared to coarse RAP mixtures. This finding contradicted the results of an earlier investigation by the same authors [20]. The discrepancy was primarily attributed to the higher concentration of agglomerated particles present in the field coarse RAP, in contrast to the laboratory-produced coarse RAP utilized in the previous study [20].

Applying 100% combined RAP aggregates in concrete mixtures is generally discouraged because of their inferior effectiveness relative to mixtures that incorporate either coarse or fine RAP. Multiple researchers have reported a compressive strength reduction ranging from 62% to 81% in control mixtures as 100% combined RAP was put in PCC mixtures [20, 65, 75, 76]. Erdem and Blankson [75] examined the impact of integrating 100% combined RAP in precast concrete mixtures, noting a 60% decrease in compressive strength.

Given that the compressive strength of concrete is significantly compromised by the use of RAP, researchers have explored alternative methods to enhance this property, such as the incorporation of SCMs and fibres [57, 77–79]. In a study conducted by Singh [77], the authors used SCMs such as silica fume, bagasse ash, and fly ash in RAP concrete. Results showed a slight improvement in compressive strength by about (3%-16%). The failure to achieve better improvement is mainly attributed to the weakness of the bonding between asphalt and cement paste, as applying SCMs didn't enhance that connection [62].

Table 2 - The mechanical properties of concrete after the inclusion of RAP.

Concrete characteristics	Type of fraction	RAP replacement ratio %	Percentage decline at 28 days (%)	References
Compressive strength	Coarse-grade RAP	100%	13%-15%	Delwar et al. [76]
		100%	41%	Huang et al. [20]
		10%-100%	22%–71%	Huang et al. [46]
		10%-30%	8% – 29%	Abedalqader et al. [58]
		25%-100%	8.5%–37.2%	Bensahnoune et al.[37]
		100%	42%	Okafor [73]
		20%-50%	16%–39%	Brand and Roesler [51]
		10%-30%	10%–27%	Paluri et al. [57]
		40%-80%	10.5%-37.6%	Ashteyat et al. [61]
		50%-100%	19%-30%	Soltanabadi and Behfarnia [47]
	Fine-grade RAP	100%	19%–22%	Delwar et al. [76]
		100%	50%	Huang et al. [20]
		10%-100%	15–67%	Huang et al. [46]
	Combined-grade RAP	25%-100%	49–81%	Delwar et al. [76]
		20%-100%	~21%-62%	Said et al. [15]
		100%	60%	Erdem and Blankson[75]
		100%	72%	Huang et al. [20]
Flexural strength	Coarse-grade RAP	100%	35%	Hassan et al.[65]
		100%	26.18%	Singh et al.[19]
		100%	29% -32.5	Al-Oraimi et al.[67]
		10%-30%	7%-20%	Paluri et al. [57]
		45%	25%	Brand et al.[80]
		25%-100%	8%-33%	Bensahnoune et al. [37]
	Fine-grade RAP	10%-30%	27% - 31%	Abedalqader et al.[58]
		25%-100%	17%–42%	Singh et al. [49]
		100%	39.3%	Abraham and Ransinchung [59]
	Combined-grade RAP	100%	45%	Hassan et al. [65]
		100%	26%–36%	Erdem and Blankson [75]
		20%-100%	10.4%-48%	Said et al. [15]
STS	Coarse-grade RAP	20%-50%	27%-52%	Brand and Roesler [51]
		100%	26%	Singh et al. [19]
		10%-100%	15%–57%	Huang et al. [46]
	Fine-grade RAP	10%-100%	7%–55%	Huang et al. [46]
		100%	21%	Huang et al. [20]
		25%-100%	13%-44.4%	Singh et al. [49]
	Combined-grade RAP	100%	50.5%	Huang et al. [20]
		20%-100%	~10% - 45%	Said et al. [15]
MOE	Coarse-grade RAP	20%-50%	16%-30%	Brand and Roesler [51]
		25%-100%	12%- 48%	Bensahnoune et al. [37]
		50%-100%	46% –53%	Soltanabadi and Behfarnia [47]
	Combined-grade RAP	100%	~ 18% – 60%	Erdem and Blankson [75]
		20%-100%	~7%-53%	Said et al. [15]

4.2.2 Flexural strength characteristics

Evidence from existing literature reveals that the flexural strength of concrete mixes incorporating RAP diminishes as the percentage of RAP increases, regardless of the curing age, due to the asphalt coating that surrounds the RAP, resulting in a weakened bond at the interface between the RAP and the cement paste [15, 19, 37, 51, 58, 67, 73, 75]. Several papers [19, 65, 67] reported that the incorporation of 100% coarse RAP into PCC mixtures led to a decrease in flexural strength in the range of 26.18% to 35%. Flexural strength suffered a lower reduction of (4% - 25%) when lower proportions of coarse RAP (20% to 50%) were employed [51, 80]. Furthermore, Bensahnoun et al. [37] reported reductions ranging from 8% to 33% for coarse RAP inclusions from 25% to 100%. Abedalqader et al. [58] found that the decrease in flexural strength for mixtures containing 10%, 20%, and 30% coarse RAP compared to a 100% NCA mix ranged from 27% to 31%. Singh et al. [19] indicated that washing coarse RAP has the potential to mitigate the reduction rate by 4% while employing abrasion and attrition (AB&AT) methods to RAP could further decrease it by 20%. The incorporation of fine RAP mixtures into PCC mixtures has been associated with a reduction in flexural strength ranging from approximately 17% to 42% as fine RAP was introduced in increments of 25% to 100% [49]. Additionally, Abraham and Ransinchung [59] observed a 39.3% decrease in flexural strength when natural fine aggregates were entirely substituted by mass with fine RAP. However, when fine RAP was integrated using a volumetric approach, the observed reduction was notably less, falling between 6% and 25%. Attempts continued by researchers to improve this property, as several researchers [57, 81] introduced steel fibre into the RAP concrete mix. The results led to an improvement in the flexural strength by 45%. These improvements are attributed to the contribution of fibres in bridging the microcracks developed in the specimen.

4.2.3 Split tensile strength (STS) characteristics

The integration of RAP tends to result in a reduced STS in PCC mixtures, regardless of the specific amount used. The study revealed that the use of coarse RAP in PCC mixtures contributed to a reduction in splitting tensile strength, with decreases noted in the range of 15% to 57% [20, 46]. Brand and Roesler [51] reported that the introduction of coarse RAP at levels of 20% to 50% resulted in a decrease that varied from 27% to 52%. However, the research conducted by Singh et al. [19] demonstrated that the incorporation of 100% coarse RAP in PCC mixtures led to a 26% lowering of the splitting tensile strength. Furthermore, the application of coarse RAP after washing and after processing with the AB&AT technique resulted in reducing the drop to that of 19% and 16%, respectively. The literature on fine RAP mixtures reveals a substantial reduction in splitting tensile strength, with decreases varying from 7% to 55% [20, 46, 49, 59]. Huang et al. and Singh et al. [20, 49] specifically noted a decrease of approximately 21–44.4% due to fine RAP incorporation in varying proportions from 25% to 100% for PCC mixture production. Notably, Huang et al. [46] found that fine RAP mixtures could outperform coarse RAP mixtures, with the reduction in STS for PCC mixtures that included fine RAP being between 7% and 55%, compared to 15% to 57% for coarse RAP mixtures. Regarding combined RAP mixtures, a notable decline in splitting tensile strength, with reductions 10% to 50.5%, was observed [15, 20]. The review of existing literature points to the interfacial transition zone (ITZ) weakness and/or issues related to asphalt cohesion as the main culprits. Moreover, the findings indicate a lack of a clear trend in STS among coarse and fine RAP, although it is evident that the inclusion of coarse or fine RAP leads to a reduction in strength. Consequently, further research is warranted to evaluate the optimal fraction of RAP based on its impact on splitting tensile strength. Additionally, a comprehensive investigation into the behaviour of concrete with fine RAP, where higher strengths have been reported in some studies, is essential [46].

4.2.4 Modulus of elasticity (MOE) characteristics

The modulus of elasticity (MOE) constitutes a significant mechanical feature of concrete, playing a vital role in the design of structural elements under both service and ultimate loads. This parameter can be derived from the stress-strain curve of concrete, which reflects its mechanical attributes. Research findings reveal that the integration of RAP aggregates consistently results in a lower MOE in PCC mixtures, independent of the proportion utilized. For instance, a study by Brand and Roesler [51] indicated that the reduction in MOE escalated from 16% to 30% as the percentage of coarse RAP increased from 20% to 50%. Further research by Bensahnoun et al. [37] revealed that the inclusion of varying percentages of coarse RAP, specifically 25%, 50%, 75%, and 100% resulted in MOE reductions of 12%, 32%, 36%, and 48%, respectively. Soltanabadi and Behfarnia [47] also observed a decrease in MOE ranging from 46% to 53% for coarse RAP-50% and coarse RAP-100% compared to NCA. They also indicated that while it is possible to achieve the desired compressive strength by

adjusting the mix design and fully replacing NCA with RAP, the MOE continues to decrease. Given that the MOE is indicative of structural stiffness, RAP material shows reduced rigidity in comparison to NCA at ambient temperatures [72].

According to Abedalqader et al. [58], the decrease in MOE is more acute than the decrease in compressive strength. A similar decrease in the MOE was observed in the context of fine RAP mixtures, aligning with the trends observed in coarse RAP mixtures [15].

The addition of combined RAP led to a significant MOE reduction of approximately 18% to 60% [75]. Interestingly, it has been indicated that the thickness of the asphalt film may not serve as the primary influence on the MOE of concrete containing RAP. The reduced bonding strength between RAP aggregates and the cement paste might be a more vital aspect to consider [37, 47].

Based on Table 2, a general recommendation for using RAP in concrete mixes as a replacement for NA, according to the targeted strength, can be shown in figure 4.

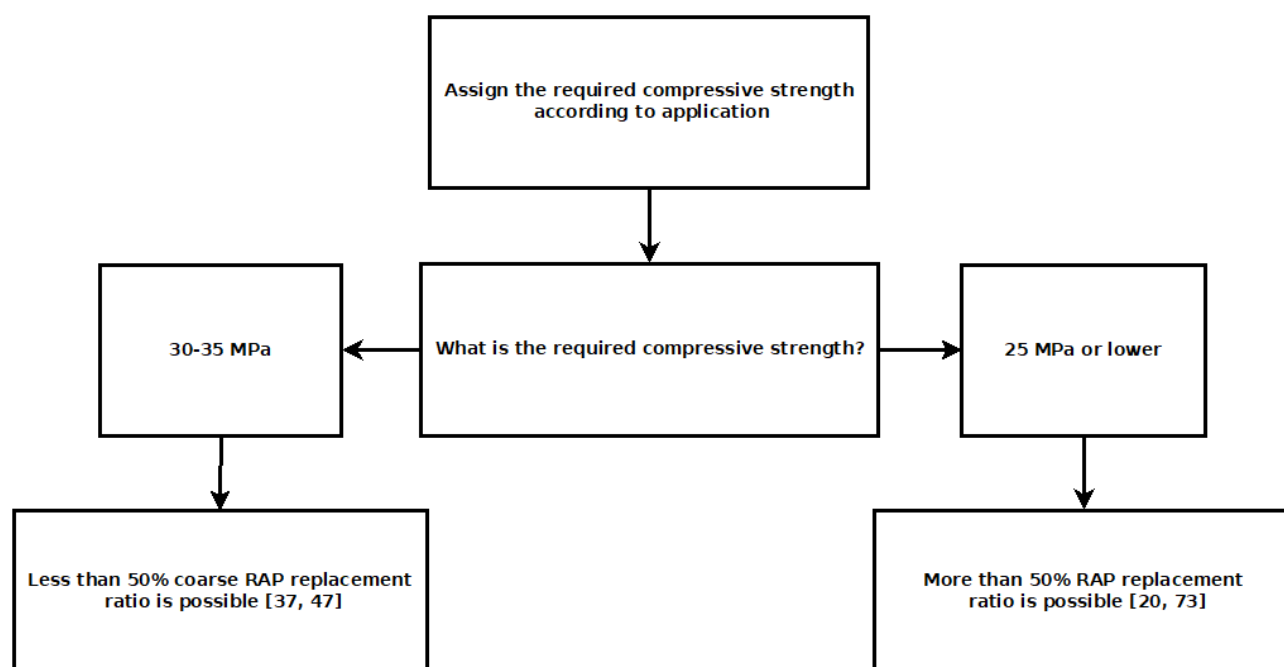


Fig. 4 – General recommendation for using RAP in concrete mixes.

4.2.5 Toughness

The incorporation of RAP into concrete has been shown to positively affect its toughness and ductility. Toughness, which quantifies a material's capacity to absorb energy, can be assessed through the integration of the stress-strain curve [72]. In concrete of medium to high strength grades, a crack typically propagates inside the NA. However, in concrete containing RAP, cracks tend to navigate around the RAP aggregates' surface due to the asphalt coating layer that envelops them (figure 5) [20]. According to several papers [20, 47, 82], specimens containing RAP were capable of withstanding peak loads while undergoing significant displacements. Notably, these RAP specimens did not fail abruptly as the control specimens did; instead, only minor micro hairline cracks were observed on their surfaces post-failure [20]. The toughness index of concrete mixtures that contain RAP was documented as linearly increasing with higher RAP content [20, 47, 83]. In terms of comparing different RAP fractions, fine RAP has been found to exhibit toughness comparable to that of traditional materials, while coarse RAP and combined RAP have shown superior toughness indexes [20]. Although the asphalt coating may negatively impact strength characteristics, the majority of studies indicate its advantageous role in enhancing the toughness of concrete matrices.

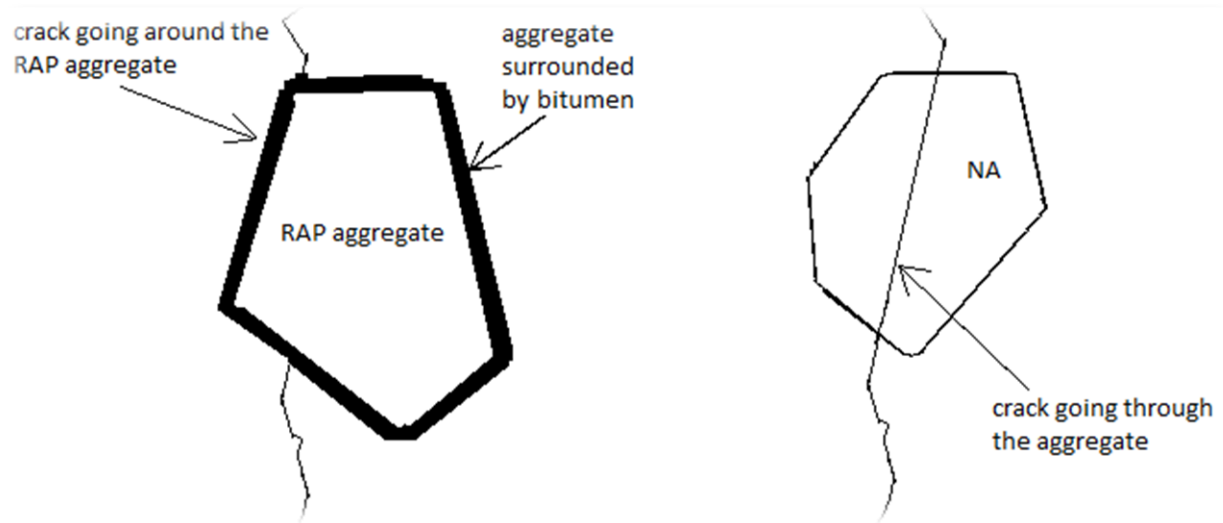


Fig. 5 – The progression of cracks in NA and RAP aggregate [20].

4.2.6 Durability

Concrete durability refers to its ability to endure weathering, abrasion, and chemical exposure while maintaining adequate mechanical characteristics. Various factors influence this durability, including environmental conditions, concrete strength, characteristics of aggregates, cementitious materials, curing methods, and surface treatments [14, 84]. Durability assessments of concrete are crucial, particularly when alternative materials are incorporated into its composition. Current research regarding the durability of structural concrete that includes RAP remains limited [85, 86] and necessitates a more comprehensive investigation. Such studies are imperative to allow both structural and non-structural applications of concrete.

Findings from initial investigations demonstrated that fully replacing NA with coarse RAP led to a decrease in water absorption, sorptivity coefficient, initial water absorption rate, and the overall void content in hardened concrete. However, subsequent research revealed a slight decline in the durability characteristics of concrete when coarse RAP was utilized [19, 77]. This decline is attributed to the inadequate bonding characteristics between the mortar and the aggregates obtained from RAP [17, 65]. According to ASTM C642, the temperature range for drying, set at 110 ± 5 °C, could lead to the melting of the asphalt found in aggregates derived from RAP, which can subsequently lead to pore blockage. To ensure a trustworthy measurement of water absorption and the total permeable voids, the use of reduced drying temperatures, specifically 48 ± 2 °C, is recommended, while the drying should be extended to a duration of 8 days [87]. When 50% fine RAP was integrated into concrete, there was a 20% rise in the volume of permeable voids. In contrast, the use of 100% fine RAP led to a 38% increase in the volume of permeable voids [81]. The interconnected voids in concrete containing RAP can pose durability challenges if subjected to aggressive environmental conditions.

Drying shrinkage is a critical coefficient that significantly influences the initiation and propagation of cracking in concrete. The research undertaken by Brand and Roesler [51] analysed how the addition of RAP influences the drying shrinkage characteristics of concrete mixtures, concluding that there were no substantial differences observed. In contrast, Abraham and Ransinchung [88] discovered that mortar mixtures incorporating fine RAP exhibited greater shrinkage compared to those with NA during the initial drying period. Their findings indicated that the highest rate of shrinkage per day occurred when 75% of the fine NA was substituted with fine RAP. Additionally, Bensahnoune et al. [37] reported that total shrinkage (the sum of autogenous shrinkage, drying shrinkage, and thermal shrinkage) in PCC mixtures increased with the incorporation of coarse RAP at levels of 25%, 50%, 75%, and 100%.

The thermal expansion coefficient of concrete plays a crucial role in the behaviour of construction joints during their opening and closing phases. Asphalt materials exhibit considerable thermal expansion, which may result in an elevated thermal expansion coefficient for concrete that incorporates RAP. Research conducted by Thomas et al. [86] indicates that substituting up to 50% of NCA with RAP has a negligible influence on the thermal expansion coefficient of high-strength concrete.

Research has been conducted to evaluate the impact of concrete containing RAP when subjected to aggressive environmental conditions, with particular attention to chloride ion penetration, carbonation, sulfate attack, and the effects of acid exposure [50, 51, 77, 85, 86, 89]. Observations reveal that concrete containing coarse RAP has a lower degree of sensitivity to acidic environments marked by chloride and sulfate ions when compared to concrete mixtures that contain fine RAP. This phenomenon may be explained by the increased porosity and the improved interconnectivity of pores that fine RAP mixtures exhibit [90]. Furthermore, research findings indicate that the implementation of washed or pre-treated RAP significantly increases resistance to both sulfate and chloride attacks [19, 90]. In addition, studies focused on the role of SCMs in the durability of concrete containing RAP reveal that the integration of SCMs can bolster durability by decreasing the porosity of the concrete matrix [77, 87, 91]. The integration of SCMs in concrete containing RAP results in a higher density ITZ, increased calcium silicate hydrate (CSH) formation, reduced portlandite content, and fewer voids, all of which contribute to improved durability of concrete containing RAP [77, 90].

5 Initiatives aimed at improving the characteristics of concrete containing RAP

Studies concerning RAP have revealed that the asphalt film surrounding the aggregates serves as a major obstacle to its sustainable application in concrete mixtures. The presence of this film impedes the direct interaction between the aggregates and the cementitious matrix, which consequently results in a bond of inferior quality between the asphalt and mortar [92], which ultimately compromises the integrity of the concrete. There has been a paucity of endeavours focused on improving the strength attributes of concrete containing RAP via the incorporation of different SCMs, including silica fume, bagasse ash, and fly ash. However, these interventions have yielded only marginal enhancements in strength characteristics [17, 46, 93]. Specifically, the reported improvements in strength are approximately 3–16%. This limited enhancement is primarily attributed to the cohesion failure linked to the asphalt in concrete containing RAP [62, 77, 94, 95], as the addition of mineral admixtures tends to modify only the microstructural aspects without affecting the mode of failure. However, it has been observed that the use of mineral admixtures leads to a notable improvement in durability characteristics [77]. Some investigations have sought to enhance the strength characteristics of concrete containing RAP by lowering the water-cement ratio, achieving improvements ranging from 5% to 33% with a reduction of approximately 20% in the water-cement ratio [46, 76]. Brand et al. [80] conducted a related study in which they added fibres to a blend comprising 45% coarse RAP, but found that this modification resulted in only minor changes to the compressive, flexural, and modulus values. A novel approach to processing RAP for the purpose of improving RAP aggregates' bonding to cement mortar is the implementation of water jets or the use of water baths. This method effectively removes dust particles from the surface of RAP aggregates [19]. Research findings indicate that the strategy of utilizing chemical etching, specifically soaking in turpentine for 24 hours to eliminate the asphalt coating, did not lead to any notable enhancement in the RAP aggregates' bonding strength to cement mortar. [96]. Employing chemical oxidation techniques can effectively modify the surface features of asphalt coating, resulting in improved bonding with the cement mortar. Various chemicals have been tested in many research studies, leading to findings that suggest these chemical treatments improve the characteristics of the bonding between the mortar and the RAP aggregates [94]. While the utilization of these treatments can aid in the thorough or partial eradication of asphalt coating, they are often prohibitively expensive and unsuitable for large-scale applications. Furthermore, the utilization of mechanical methods, particularly AB&AT, has been studied to optimize the bonding characteristics between the RAP aggregates and the mortar. Using such a technique demonstrated effectiveness in improving adhesion, presenting a cost-effective alternative to chemical etching [19, 96].

The scientific efforts of researchers to improve RAP concrete characteristics are targeted at taking advantage of the sustainability and economic benefits that it provides. However, as RAP concrete is generally of lower quality compared to conventional concrete, there are bureaucratic challenges that must be overcome before the practical adoption of this sustainable technology can be utilized [97]. One of such challenges is the lack of regulations or codes about utilizing RAP in structural applications due to the scarcity of research in the subject [16]. This leads contractors and clients to be reluctant about incorporating RAP in their projects. Add to that the low awareness of the potential advantages that using RAP brings to the table. In order to convince the guidelines authorities of producing regulations regarding the subject, deeper and more nuanced investigations are needed.

6 Conclusions

This study conducted a thorough review of research related to RAP usage in PCC mixtures. Findings highlight a number of economic and environmental advantages of incorporating RAP, such as reduced dependence on NA, lower transportation costs, and decreased landfill disposal of RAP, which collectively contribute to lower carbon emissions. However, the study also notes that the existence of asphalt coatings and grouped particles in RAP can negatively impact the overall characteristics of the concrete. Through an extensive literature review, several conclusions have been drawn from this critical analysis:

- Apart from water absorption and specific gravity, the majority of RAP aggregates' physical properties are comparable to those of NA.
- RAP's inclusion in PCC mixtures leads to decreases in unit weight and mechanical properties. Conversely, RAP tends to enhance the toughness of PCC mixtures. However, RAP's effects on slump and drying shrinkage in PCC mixtures remain unclear.
- The reduction in both flexural and tensile strengths when increasing RAP content is less pronounced compared to the compressive strength decline.
- The decline in the MOE is more pronounced than the decline in strength.
- Concrete composed of substituting only coarse RAP yields better strength than that of fine RAP or both coarse and fine RAP.
- The treatment of RAP aggregates, whether through chemical or mechanical means, represents a method for enhancement in bonding potential between RAP aggregate and cement mortar.
- Adding steel fibres to concrete containing RAP showed an insignificant effect on compressive strength, yet it significantly improved both flexural strength and split tensile strength.
- Concrete containing RAP exhibits lower durability than conventional concrete.
- Integrating SCMs into concrete containing RAP showed a notable improvement in durability by decreasing its inherent porous structure.

7 Recommendations

The examination of existing literature regarding concrete mixtures that incorporate RAP revealed encouraging outcomes that warrant additional research. The analysis identified several gaps within the current body of work, and addressing these gaps could facilitate the comprehensive use of all RAP fractions in concrete applications:

- Given that the aggregates' mechanical characteristics can greatly influence concrete structures' performance, additional research is necessary to achieve a thorough characterization of RAP. Such investigations should account for variations in RAP sampling, the characteristics of the adhered asphalt, the original composition of the RAP, the types of parent aggregates involved, and the techniques employed for RAP extraction.
- The existing literature reveals an ambiguous relationship regarding RAP inclusion's impact in determining fresh concrete mixtures' workability characteristics. Consequently, additional research is necessary to explore various factors associated with RAP, including shape characteristics, characteristics of adhered asphalt, the presence of clustered particles, aggregate water absorption rates, and the methods employed in milling and processing. Such investigations are essential to clarify the RAP addition's impact on the fresh concrete mixtures' workability characteristics.
- RAP inclusion in concrete is associated with diminished structural performance, especially regarding compressive strength, flexural strength, and MOE. These characteristics are vital for structural concrete, requiring a balanced assessment of RAP proportions to optimize performance across all parameters.
- While asphalt-cohesion failure is primarily linked to concrete containing RAP, limited research has shown improved performance when mineral admixtures are incorporated. Consequently, a comprehensive study focusing on the microstructural analysis of ITZ is necessary for concrete mixes that include RAP.

- The durability characteristics of concrete containing RAP have received limited attention from researchers, indicating a need for further investigation to comprehensively understand the diverse factors influencing them.
- The diminished performance of concrete containing RAP mixtures is primarily attributed to asphalt coatings and particle clumping. Removing these coatings could enable RAP to perform comparably to new aggregate, highlighting the potential for surface treatment techniques. Nonetheless, there is a need for the advancement of more cost-effective beneficiation methods applicable to all RAP fractions to improve how cement mortar paste interacts with the RAP aggregate.

REFERENCES

- [1]- J. Farfan, M. Fasihi, C. Breyer, Trends in the Global Cement Industry and Opportunities for Long-Term Sustainable CCU Potential for Power-to-X. *J. Cleaner Prod.*, 217 (2019) 821–835. <https://doi.org/10.1016/J.JCLEPRO.2019.01.226>
- [2]- L. Bertolini, B. Elsener, P. Pedferri, E. Redaelli, R. Polder, *Corrosion of Steel in Concrete*. 2013
- [3]- A.O. Al-Shujairi, A.J. Al-Taie, H.M. Al-Mosawe, Review on Applications of RAP in Civil Engineering. *IOP Conf. Ser.: Mater. Sci. Eng.*, 1105 (1) (2021) 012092. <https://doi.org/10.1088/1757-899X/1105/1/012092>
- [4]- R. Mariyappan, J.S. Palammal, S. Balu, Sustainable Use of Reclaimed Asphalt Pavement (RAP) in Pavement Applications—a Review. *Environ. Sci. Pollut. Res.*, 30 (16) (2023) 45587–45606. <https://doi.org/10.1007/s11356-023-25847-3>
- [5]- R. Cao, Z. Leng, S.C. Hsu, Comparative Eco-Efficiency Analysis on Asphalt Pavement Rehabilitation Alternatives: Hot in-Place Recycling and Milling-and-Filling. *J. Cleaner Prod.*, 210 (2019) 1385–1395. <https://doi.org/10.1016/J.JCLEPRO.2018.11.122>
- [6]- Y. Paluri, M. Heeralal, P.R. Kumar, A Study on the Use of Reclaimed Asphalt Pavement Aggregates in Pavement Quality Concrete. *Cement Lime Concr.*, 24 (6) (2019) 421–431.
- [7]- H. Al Dughaiishi, J. Al Lawati, M. Bilema, A.M. Babalghaith, N.S. Mashaan, N.I.M. Yusoff, A. Milad, Encouraging Sustainable Use of RAP Materials for Pavement Construction in Oman: A Review. *Recycling*, 7 (3) (2022) 35. <https://doi.org/10.3390/recycling7030035>
- [8]- M. Iwama, K. Hayano, Influence of Combined Aging on the Mechanical and Physical Properties of Reclaimed Asphalt Pavement Mixtures Blended with Rejuvenator Agents. *J. Mater. Cycles Waste Manag.*, 25 (3) (2023) 1417–1433. <https://doi.org/10.1007/S10163-023-01619-6>
- [9]- V.B. Nguyen, V.B. Nguyen, Evaluation of Fatigue Behaviour of Bituminous Mixtures Using a 4-Point Bending Test. *J. Mater. Eng. Struct. JMES*, 11 (3) (2024) 223–232.
- [10]- H. Jahanbakhsh, M.M. Karimi, H. Naseri, F.M. Nejad, Sustainable Asphalt Concrete Containing High Reclaimed Asphalt Pavements and Recycling Agents: Performance Assessment, Cost Analysis, and Environmental Impact. *J. Cleaner Prod.*, 244 (2020) 118837. <https://doi.org/10.1016/J.JCLEPRO.2019.118837>
- [11]- X. Shi, A. Mukhopadhyay, D. Zollinger, Long-Term Performance Evaluation of Concrete Pavements Containing Recycled Concrete Aggregate in Oklahoma. *Transp. Res. Rec.*, 2673 (5) (2019) 429–442. <https://doi.org/10.1177/0361198119839977>
- [12]- S. Debbarma, G.D. Ransinchung, S. Singh, Suitability of Various Supplementary Cementitious Admixtures for RAP Inclusive RCCP Mixes. *Int. J. Pavement Eng.*, 22 (12) (2021) 1568–1581. <https://doi.org/10.1080/10298436.2019.1703981>
- [13]- S. Magar, F. Xiao, D. Singh, B. Showkat, Applications of Reclaimed Asphalt Pavement in India – A Review. *J. Cleaner Prod.*, 335 (2022) 130221. <https://doi.org/10.1016/J.JCLEPRO.2021.130221>
- [14]- K. Vijay, Y. Paluri, M.S. Reddy, I.V. Rao, K. John, N. Dayanand, Performance Evaluation of Reclaimed Asphalt Pavement (RAP) Aggregate in Concrete Pavements: A State-of-the-Art Review. *J. Build. Pathol. Rehabil.*, 8 (2) (2023) 1–11. <https://doi.org/10.1007/s41024-023-00335-w>
- [15]- S. El Euch Ben Said, S. El Euch Khay, A. Loulizi, Experimental Investigation of PCC Incorporating RAP. *Int. J. Concr. Struct. Mater.*, 12 (1) (2018) 1–11. <https://doi.org/10.1186/S40069-018-0227-X>
- [16]- S. Jaawani, A. Franco, G. De Luca, O. Coppola, A. Bonati, Limitations on the Use of Recycled Asphalt Pavement in Structural Concrete. *Appl. Sci.*, 11 (22) (2021) 10901. <https://doi.org/10.3390/APP112210901>
- [17]- S. Singh, G.D. R.N. Ransinchung, K. Monu, P. Kumar, Laboratory Investigation of RAP Aggregates for Dry Lean Concrete Mixes. *Constr. Build. Mater.*, 166 (2018) 808–816.

- <https://doi.org/10.1016/J.CONBUILDMAT.2018.01.131>
- [18]- S. Guo, J. Hu, Q. Dai, A Critical Review on the Performance of Portland Cement Concrete with Recycled Organic Components. *J. Cleaner Prod.*, 188 (2018) 92–112. <https://doi.org/10.1016/J.JCLEPRO.2018.03.244>
- [19]- S. Singh, G.D. Ransinchung, P. Kumar, An Economical Processing Technique to Improve RAP Inclusive Concrete Properties. *Constr. Build. Mater.*, 148 (2017) 734–747. <https://doi.org/10.1016/J.CONBUILDMAT.2017.05.030>
- [20]- B. Huang, X. Shu, G. Li, Laboratory Investigation of Portland Cement Concrete Containing Recycled Asphalt Pavements. *Cem. Concr. Res.*, 35 (10) (2005) 2008–2013. <https://doi.org/10.1016/J.CEMCONRES.2005.05.002>
- [21]- S. Debbarma, M. Selvam, S. Singh, Can Flexible Pavements' Waste (RAP) Be Utilized in Cement Concrete Pavements? – A Critical Review. *Constr. Build. Mater.*, 259 (2020) 120417. <https://doi.org/10.1016/J.CONBUILDMAT.2020.120417>
- [22]- G. Tarsi, P. Tataranni, C. Sangiorgi, The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials*, 13 (18) (2020) 4052. <https://doi.org/10.3390/MA13184052>
- [23]- A. Jamshidi, K. Kurumisawa, T. Nawa, M.O. Hamzah, Analysis of Structural Performance and Sustainability of Airport Concrete Pavements Incorporating Blast Furnace Slag. *J. Cleaner Prod.*, 90 (2015) 195–210. <https://doi.org/10.1016/J.JCLEPRO.2014.11.046>
- [24]- I. Kamal, Y. Bas, Materials and Technologies in Road Pavements - an Overview. *Mater. Today: Proc.*, 42 (2021) 2660–2667. <https://doi.org/10.1016/J.MATPR.2020.12.643>
- [25]- A. Pandey, B. Kumar, Utilization of Agricultural and Industrial Waste as Replacement of Cement in Pavement Quality Concrete: A Review. *Environ. Sci. Pollut. Res.*, 29 (17) (2022) 24504–24546. <https://doi.org/10.1007/S11356-021-18189-5>
- [26]- Q. Yang, H. Yin, X. He, F. Chen, A. Ali, Y. Mehta, B. Yan, Environmental Impacts of Reclaimed Asphalt Pavement on Leaching of Metals into Groundwater. *Transp. Res. D Transp. Environ.*, 85 (2020) 102415. <https://doi.org/10.1016/J.TRD.2020.102415>
- [27]- M. Ansori, I.F. Radam, The Use of Reclaimed Asphalt Pavement as a Foundation for Pavements Based On the Indonesian National Standard. *J. Eng. Res. Appl.*, 5 (2) (2015) 14–18.
- [28]- V. Bark, *Reclaimed Asphalt Pavement in Concrete-A Study of How Concrete Properties Are Changed When Reclaimed Asphalt Pavement (RAP) Is Used as Aggregate*. 2017.
- [29]- W.H. Chesner, R.J. Collins, M.H. MacKay, J. Emery, *User Guidelines for Waste and By-Product Materials in Pavement Construction*. 2002. <https://doi.org/10.21949/1503647>
- [30]- S. Singh, G.D. Ransinchung, S. Debbarma, P. Kumar, Utilization of Reclaimed Asphalt Pavement Aggregates Containing Waste from Sugarcane Mill for Production of Concrete Mixes. *J. Cleaner Prod.*, 174 (2018) 42–52. <https://doi.org/10.1016/J.JCLEPRO.2017.10.179>
- [31]- X. Shi, A. Mukhopadhyay, D. Zollinger, Sustainability Assessment for Portland Cement Concrete Pavement Containing Reclaimed Asphalt Pavement Aggregates. *J. Cleaner Prod.*, 192 (2018) 569–581. <https://doi.org/10.1016/J.JCLEPRO.2018.05.004>
- [32]- S. Singh, G.D. R.N. Ransinchung, P. Kumar, Feasibility Study of RAP Aggregates in Cement Concrete Pavements. *Road Mater. Pavement Des.*, 20 (1) (2019) 151–170. <https://doi.org/10.1080/14680629.2017.1380071>
- [33]- A. Copeland, *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. 2011. <https://doi.org/10.21949/1503647>
- [34]- S.M. Abraham, G.D. R.N. Ransinchung, Laboratory Research on Reclaimed Asphalt Pavement-Inclusive Cementitious Mixtures. *ACI Mater. J.*, 117 (2) (2020) 193. <https://doi.org/10.14359/51722398>
- [35]- M. Fakhri, K. Nasir, E. Amosoltani, A. Ahmadi, Determining Optimal Combination of RCCP Mixture Containing RAP and Crumb Rubber Using Hybrid ANN-GA Method Considering Energy Absorbency Approach. *Can. J. Civ. Eng.*, 44 (9) (2017) 670–677. <https://doi.org/10.1139/cjce-2017-0124>
- [36]- A. Modarres, Z. Hosseini, Mechanical Properties of Roller Compacted Concrete Containing Rice Husk Ash with Original and Recycled Asphalt Pavement Material. *Mater. Des.*, 64 (2014) 227–236. <https://doi.org/10.1016/J.MATDES.2014.07.072>
- [37]- S. Bensahnoune, F. Bouziadi, B. Boulekbache, M. Hamrat, A. Haddi, S. Amziane, Effect of Curing Temperature on the Shrinkage of Concrete Containing Reclaimed Asphalt Pavement: Experimental and Numerical Study. *Transp. Res. Rec.*, 2678 (8) (2024) 992–1008. <https://doi.org/10.1177/03611981231223985>
- [38]- K.H. Yang, Y.B. Jung, M.S. Cho, S.H. Tae, Effect of Supplementary Cementitious Materials on Reduction of CO₂ Emissions from Concrete. *J. Cleaner Prod.*, 103 (2015) 774–783. <https://doi.org/10.1016/J.JCLEPRO.2014.03.018>

- [39]- Q. Aurangzeb, I.L. Al-Qadi, H. Ozer, R. Yang, Hybrid Life Cycle Assessment for Asphalt Mixtures with High RAP Content. *Resour. Conserv. Recycl.*, 83 (2014) 77–86. <https://doi.org/10.1016/J.RESCONREC.2013.12.004>
- [40]- S. Debbarma, S. Singh, G.D.R.N. R.N., Laboratory Investigation on the Fresh, Mechanical, and Durability Properties of Roller Compacted Concrete Pavement Containing Reclaimed Asphalt Pavement Aggregates. *Transp. Res. Rec.*, 2673 (10) (2019) 652–662. <https://doi.org/10.1177/0361198119849585>
- [41]- C. Hanson, R. Noland, K. Cavale, Life-Cycle Greenhouse Gas Emissions of Materials Used in Road Construction. *Transp. Res. Rec.*, 2287 (2012) 174–181. <https://doi.org/10.3141/2287-21>
- [42]- X. Shi, A. Mukhopadhyay, D. Zollinger, K. Huang, Performance Evaluation of Jointed Plain Concrete Pavement Made with Portland Cement Concrete Containing Reclaimed Asphalt Pavement. *Road Mater. Pavement Des.*, 22 (1) (2021) 59–81. <https://doi.org/10.1080/14680629.2019.1616604>
- [43]- K. Monu, G.D. Ransinchung, S. Singh, Effect of Long-Term Ageing on Properties of RAP Inclusive WMA Mixes. *Constr. Build. Mater.*, 206 (2019) 483–493. <https://doi.org/10.1016/J.CONBUILDMAT.2019.02.087>
- [44]- M. Kumari, G.D. R.N. Ransinchung, S. Singh, A Laboratory Investigation on Dense Bituminous Macadam Containing Different Fractions of Coarse and Fine RAP. *Constr. Build. Mater.*, 191 (2018) 655–666. <https://doi.org/10.1016/J.CONBUILDMAT.2018.10.017>
- [45]- S. Singh, D. Shintre, G.D.R.N. R.N., P. Kumar, Performance of Fine RAP Concrete Containing Flyash, Silica Fume, and Bagasse Ash. *J. Mater. Civ. Eng.*, 30 (10) (2018) 04018233. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002408](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002408)
- [46]- B. Huang, X. Shu, E.G. Burdette, Mechanical Properties of Concrete Containing Recycled Asphalt Pavements. *Mag. Concr. Res.*, 58 (5) (2006) 313–320. <https://doi.org/10.1680/MACR.2006.58.5.313>
- [47]- R. Soltanabadi, K. Behfarnia, Evaluation of Mechanical Properties of Concrete Containing Recycled Concrete Aggregate and Recycled Asphalt Pavement. *J. Mater. Civ. Eng.*, 34 (12) (2022) 04022348. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004514](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004514)
- [48]- F. Xiao, S. Yao, J. Wang, X. Li, S. Amirkhanian, A Literature Review on Cold Recycling Technology of Asphalt Pavement. *Constr. Build. Mater.*, 180 (2018) 579–604. <https://doi.org/10.1016/J.CONBUILDMAT.2018.06.006>
- [49]- S. Singh, G.D.R.N. R.N., P. Kumar, Laboratory Investigation of Concrete Pavements Containing Fine RAP Aggregates. *J. Mater. Civ. Eng.*, 30 (2) (2017) 04017279. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002124](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002124)
- [50]- M. Berry, B. Kappes, L. Kappes, Optimization of Concrete Mixtures Containing Reclaimed Asphalt Pavement. *ACI Mater. J.*, 112 (6) (2015) 723. <https://doi.org/10.14359/51687854>
- [51]- A.S. Brand, J.R. Roesler, Ternary Concrete with Fractionated Reclaimed Asphalt Pavement. *ACI Mater. J.*, 112 (1) (2015) 155–164. <https://doi.org/10.14359/51687176>
- [52]- N. Hossiney, M. Tia, M.J. Bergin, Concrete Containing RAP for Use in Concrete Pavement. *Int. J. Pavement Res. Technol.*, 3 (5) (2010) 251–258.
- [53]- S. Nandi, G.D.R.N. Ransinchung, Laboratory Investigation of Portland Cement Concrete Paver Blocks Made with Reclaimed Asphalt Pavement Aggregates. *Road Mater. Pavement Des.*, 23 (3) (2022) 546–564. <https://doi.org/10.1080/14680629.2020.1830153>
- [54]- C.G. Papakonstantinou, Resonant Column Testing on Portland Cement Concrete Containing Recycled Asphalt Pavement (RAP) Aggregates. *Constr. Build. Mater.*, 173 (2018) 419–428. <https://doi.org/10.1016/J.CONBUILDMAT.2018.03.256>
- [55]- S. Debbarma, G.D. Ransinchung, S. Singh, S.K. Sahdeo, Utilization of Industrial and Agricultural Wastes for Productions of Sustainable Roller Compacted Concrete Pavement Mixes Containing Reclaimed Asphalt Pavement Aggregates. *Resour. Conserv. Recycl.*, 152 (2020) 104504. <https://doi.org/10.1016/J.RESCONREC.2019.104504>
- [56]- M. Selvam, S. Singh, Material Selection and Mixture Proportioning Methods for Sustainable Roller-Compacted Concrete Pavements. *J. Mater. Civ. Eng.*, 34 (11) (2022) 03122002. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004325](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004325)
- [57]- Y. Paluri, V. Noolu, H. Mudavath, R.K. Pancharathi, Flexural Fatigue Behavior of Steel Fiber-Reinforced Reclaimed Asphalt Pavement–Based Concrete: An Experimental Study. *Pract. Period. Struct. Des. Constr.*, 26 (1) (2021) 04020083. [https://doi.org/10.1061/\(ASCE\)SC.1943-5576.0000540](https://doi.org/10.1061/(ASCE)SC.1943-5576.0000540)
- [58]- A. Abedalqader, N. Shatarat, A. Ashteyat, H. Katkhuda, Influence of Temperature on Mechanical Properties of Recycled Asphalt Pavement Aggregate and Recycled Coarse Aggregate Concrete. *Constr. Build. Mater.*, 269 (2021) 121285. <https://doi.org/10.1016/J.CONBUILDMAT.2020.121285>
- [59]- S.M. Abraham, G.D. R.N. Ransinchung, Strength and Permeation Characteristics of Cement Mortar with Reclaimed

- Asphalt Pavement Aggregates. *Constr. Build. Mater.*, 167 (2018) 700–706. <https://doi.org/10.1016/J.CONBUILDMAT.2018.02.075>
- [60]- S. Debbarma, G.D. Ransinchung, S. Singh, Feasibility of Roller Compacted Concrete Pavement Containing Different Fractions of Reclaimed Asphalt Pavement. *Constr. Build. Mater.*, 199 (2019) 508–525. <https://doi.org/10.1016/J.CONBUILDMAT.2018.12.047>
- [61]- A. Ashteyat, A. Obaidat, M. Nabhan, T. Kharabsheh, Flexural Behavior of RC Beams Incorporating Recycled Concrete Aggregate and Reclaimed Asphalt Pavement Exposed to Elevated Temperatures. *Results Eng.*, 22 (2024) 102309. <https://doi.org/10.1016/J.RINENG.2024.102309>
- [62]- X. Shi, A. Mukhopadhyay, K.W. Liu, Mix Design Formulation and Evaluation of Portland Cement Concrete Paving Mixtures Containing Reclaimed Asphalt Pavement. *Constr. Build. Mater.*, 152 (2017) 756–768. <https://doi.org/10.1016/J.CONBUILDMAT.2017.06.174>
- [63]- R.L. Al-Mufti, A.N. Fried, Non-Destructive Evaluation of Reclaimed Asphalt Cement Concrete. *Eur. J. Environ. Civ. Eng.*, 22 (6) (2018) 770–782. <https://doi.org/10.1080/19648189.2016.1219877>
- [64]- R. Franke, K. Ksaibati, A Methodology for Cost-Benefit Analysis of Recycled Asphalt Pavement (RAP) in Various Highway Applications. *Int. J. Pavement Eng.*, 16 (7) (2015) 660–666. <https://doi.org/10.1080/10298436.2014.943217>
- [65]- K.E. Hassan, J.J. Brooks, M. Erdman, The Use of Reclaimed Asphalt Pavement (RAP) Aggregates in Concrete. *Waste Manage. Ser.*, 1 (C) (2000) 121–128. [https://doi.org/10.1016/S0713-2743\(00\)80024-0](https://doi.org/10.1016/S0713-2743(00)80024-0)
- [66]- N. Hossiney, M. Tia, *EVALUATION OF CONCRETE CONTAINING RAP FOR USE IN CONCRETE PAVEMENT*. 2018.
- [67]- S. Al-Oraimi, H.F. Hassan, A. Hago, Recycling of Reclaimed Asphalt Pavement in Portland Cement Concrete. *J. Eng. Res.*, 6 (1) (2009) 37–45. <https://doi.org/10.24200/TJER.VOL6ISS1PP37-45>
- [68]- A. Widayanti, A.A. Soemitro Ria, J.J. Ekaputri, H. Suprayitno, Characterization of Reclaimed Asphalt Pavement (RAP) as a Road Pavement Material (National Road Waru, Sidoarjo). *MATEC Web Conf.*, 181 (2018) 05001. <https://doi.org/10.1051/MATECCONF/201818105001>
- [69]- J. Mary chyne, H. Kiran Sepuri, T.H. K, A Review on Recycled Asphalt Pavement in Cement Concrete. *Int. J. Latest Eng. Res. Appl.*, 4 (2019) 9–18.
- [70]- L.D. Poulikakos, S. dos Santos, M. Bueno, S. Kuentzel, M. Hugener, M.N. Partl, Influence of Short and Long Term Aging on Chemical, Microstructural and Macro-Mechanical Properties of Recycled Asphalt Mixtures. *Constr. Build. Mater.*, 51 (2014) 414–423. <https://doi.org/10.1016/J.CONBUILDMAT.2013.11.004>
- [71]- J.S. Chen, C.C. Huang, P.Y. Chu, K.Y. Lin, Engineering Characterization of Recycled Asphalt Concrete and Aged Bitumen Mixed Recycling Agent. *J. Mater. Sci.*, 42 (23) (2007) 9867–9876. <https://doi.org/10.1007/s10853-007-1713-8>
- [72]- G. Valdés-Vidal, A. Calabi-Floody, R. Miró-Recasens, J. Norambuena-Contreras, Mechanical Behavior of Asphalt Mixtures with Different Aggregate Type. *Constr. Build. Mater.*, 101 (2017) 474–481. <https://doi.org/10.1016/J.CONBUILDMAT.2015.10.050>
- [73]- F.O. Okafor, *Performance of Recycled Asphalt Pavement as Coarse Aggregate in Concrete*. 2010.
- [74]- H.N. Katkhuda, N.K. Shatarat, K.H. Hyari, H.N. Katkhuda, N.K. Shatarat, K.H. Hyari, Structural Engineering and Mechanics. *Struct. Eng. Mech.*, 62 (3) (2017) 357. <https://doi.org/10.12989/SEM.2017.62.3.357>
- [75]- S. Erdem, M.A. Blankson, Environmental Performance and Mechanical Analysis of Concrete Containing Recycled Asphalt Pavement (RAP) and Waste Precast Concrete as Aggregate. *J. Hazard. Mater.*, 264 (2014) 403–410. <https://doi.org/10.1016/J.JHAZMAT.2013.11.040>
- [76]- M. Delwar, M. Fahmy, R. Taha, Use of Reclaimed Asphalt Pavement as an Aggregate in Portland Cement Concrete. *ACI Mater. J.*, 94 (3) (1997) 251–256. <https://doi.org/10.14359/306>
- [77]- S. Singh, G.D. Ransinchung, P. Kumar, Effect of Mineral Admixtures on Fresh, Mechanical and Durability Properties of RAP Inclusive Concrete. *Constr. Build. Mater.*, 156 (2017) 19–27. <https://doi.org/10.1016/J.CONBUILDMAT.2017.08.144>
- [78]- B. Andrew, K.A. Buyondo, H. Kasedde, J.B. Kirabira, P.W. Olupot, A.A. Yusuf, Investigation on the Use of Reclaimed Asphalt Pavement along with Steel Fibers in Concrete. *Case Stud. Constr. Mater.*, 17 (2022) e01356. <https://doi.org/10.1016/J.CSCM.2022.E01356>
- [79]- K. Sree Kumar, S. Subhan Alisha, K. Vijay, S. al, B.S. Al-Shathr, O.A. Eedan, R.M. Hussain, S.R. R Teja Prathipati, T. Santhi Sagar, Y. Paluri, Evaluating the Effect of Steel Fibers on the Mechanical Performance of High-Volume

- Fly Ash Concrete. *IOP Conf. Ser.: Earth Environ. Sci.*, 1130 (1) (2023) 012018. <https://doi.org/10.1088/1755-1315/1130/1/012018>
- [80]- A.S. Brand, A.N. Amirkhanian, J.R. Roesler, Flexural Capacity of Full-Depth and Two-Lift Concrete Slabs with Recycled Aggregates. *Transp. Res. Rec.*, 2456 (2014) 64–72. <https://doi.org/10.3141/2456-07>
- [81]- Y. Paluri, S. Mogili, H. Mudavath, R.K. Pancharathi, A Study on the Influence of Steel Fibers on the Performance of Fine Reclaimed Asphalt Pavement (FRAP) in Pavement Quality Concrete. *Mater. Today: Proc.*, 32 (2020) 657–662. <https://doi.org/10.1016/J.MATPR.2020.03.147>
- [82]- N. Shatarat, A.A. Alhaq, H. Katkhuda, M.A. Jaber, Investigation of Axial Compressive Behavior of Reinforced Concrete Columns Using Recycled Coarse Aggregate and Recycled Asphalt Pavement Aggregate. *Constr. Build. Mater.*, 217 (2019) 384–393. <https://doi.org/10.1016/J.CONBUILDMAT.2019.05.085>
- [83]- A.M. Knaack, Y.C. Kurama, Behavior of Reinforced Concrete Beams with Recycled Concrete Coarse Aggregates. *J. Struct. Eng.*, 141 (3) (2014) B4014009. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001118](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001118)
- [84]- D. Kumar, D. Kumar, V.V.L.K. Rao, L. Parameswaran, Effect of Coarse Recycled Concrete Aggregate on the Microstructural and Durability Properties of Self Compacting Concrete. *J. Mater. Eng. Struct. JMES*, 11 (2) (2024) 155–166.
- [85]- S. Jaawani, A. Franco, G. De Luca, O. Coppola, A. Bonati, Durability of Concrete Containing Recycled Asphalt Pavement (RAP). *Proceedings of the 2nd fib Symposium on Concrete and Concrete Structures*, fib: Rome, Italy, 2021; pp 273–280.
- [86]- R.J. Thomas, A.J. Fellows, A.D. Sorensen, Durability Analysis of Recycled Asphalt Pavement as Partial Coarse Aggregate Replacement in a High-Strength Concrete Mixture. *J. Mater. Civ. Eng.*, 30 (5) (2018) 04018061. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002262](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002262)
- [87]- S. Singh, G.D.R.N. Ransinchung, Durability Properties of Pavement Quality Concrete Containing Fine RAP. *Adv. Civ. Eng. Mater.*, 7 (1) (2018) 271–290. <https://doi.org/10.1520/ACEM20180012>
- [88]- S.M. Abraham, G.D. R.N. Ransinchung, Influence of RAP Aggregates on Strength, Durability and Porosity of Cement Mortar. *Constr. Build. Mater.*, 189 (2018) 1105–1112. <https://doi.org/10.1016/J.CONBUILDMAT.2018.09.069>
- [89]- N. Russo, A. Filippi, M. Carsana, F. Lollini, E. Redaelli, Impact of RAP as Recycled Aggregate on Durability-Related Parameters of Structural Concrete. *Mater. Struct.*, 58 (1) (2025) 1–14. <https://doi.org/10.1617/s11527-025-02582-4>
- [90]- S. Singh, G.D.R.R. N., P. Kumar, Performance Evaluation of RAP Concrete in Aggressive Environment. *J. Mater. Civ. Eng.*, 30 (10) (2018) 04018231. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002316](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002316)
- [91]- S. Singh, G.D. Ransinchung, K. Monu, Sustainable Lean Concrete Mixes Containing Wastes Originating from Roads and Industries. *Constr. Build. Mater.*, 209 (2019) 619–630. <https://doi.org/10.1016/J.CONBUILDMAT.2019.03.122>
- [92]- X. Shi, Z. Grasley, J. Hogancamp, L. Brescia-Norambuena, A. Mukhopadhyay, D. Zollinger, Microstructural, Mechanical, and Shrinkage Characteristics of Cement Mortar Containing Fine Reclaimed Asphalt Pavement. *J. Mater. Civ. Eng.*, 32 (4) (2020) 04020050. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003110](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003110)
- [93]- S.M. Abraham, G.D. Ransinchung, Effects of Reclaimed Asphalt Pavement Aggregates and Mineral Admixtures on Pore Structure, Mechanical and Durability Properties of Cement Mortar. *Constr. Build. Mater.*, 216 (2019) 202–213. <https://doi.org/10.1016/J.CONBUILDMAT.2019.05.011>
- [94]- A.S. Brand, J.R. Roesler, Bonding in Cementitious Materials with Asphalt-Coated Particles: Part I – The Interfacial Transition Zone. *Constr. Build. Mater.*, 130 (2017) 171–181. <https://doi.org/10.1016/J.CONBUILDMAT.2016.10.019>
- [95]- A. Mukhopadhyay, X. Shi, Microstructural Characterization of Portland Cement Concrete Containing Reclaimed Asphalt Pavement Aggregates Using Conventional and Advanced Petrographic Techniques. *ASTM Spec. Tech. Publ.*, STP 1613 (2018) 187–206. <https://doi.org/10.1520/STP161320180008>
- [96]- R.L. Al-Mufti, A.N. Fried, Improving the Strength Properties of Recycled Asphalt Aggregate Concrete. *Constr. Build. Mater.*, 149 (2017) 45–52. <https://doi.org/10.1016/J.CONBUILDMAT.2017.05.056>
- [97]- A. Peduzzi, A. Franco, G. De Luca, O. Coppola, A. Bonati, Economical Assessment of Recycled Asphalt Pavement (RAP) Aggregate for Structural Concrete Production in Italy. *Buildings*, 13 (9) (2023) 2191. <https://doi.org/10.3390/BUILDINGS13092191>