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Review on Unconfined Compressive Strength (UCS) of Stabilized Reclaimed Asphalt Pavement (RAP)

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Abstract- The growing emphasis on sustainable construction practices in the transportation sector has intensified interest in the reuse of Reclaimed Asphalt Pavement (RAP). However, due to the aged binder and degraded mechanical integrity, RAP requires stabilization before structural application. Among the various performance measures, the Unconfined Compressive Strength (UCS) test is widely used to evaluate the load-bearing capacity and durability of stabilized RAP mixtures. This review synthesizes findings from recent studies focusing on the UCS performance of RAP stabilized with lime, fly ash, cement and other chemical additives. The influence of mix composition, curing periods, and testing standards is discussed to provide insights into the design of high-performance base materials using RAP.

Keywords– Reclaimed Asphalt Pavement (RAP), Unconfined Compressive Strength (UCS), Flexible Pavement, RAP Stabilization, Lime, Cement, Fly Ash.

1. INTRODUCTION

The recent years have seen a rapid growth in the sustainable construction road sector. Country like India is expanding its infrastructure, but with this growth & advancement comes the growing environmental concerns. One such major challenge is use of Reclaimed Asphalt Pavement (RAP), which is generated during the road repairs. Despite its potential, major proportion of RAP remains unused due to the absence of clear technical guidelines and concerns about its structural performance.

In the United States, the Federal Highway Administration (FHWA) has estimated that from milling and reconstruction projects, approximately 41 million metric tons of RAP are generated annually [1]. Recent industry surveys by the National Asphalt Pavement Association (NAPA) have highlighted that the scale of RAP recycling is about 94.6 million tons of RAP, & it was reused in new asphalt mixtures across the country [2]. The difference between these figures reflects not only freshly generated RAP but also the drawdown of accumulated stockpiles, underscoring the maturity of RAP recycling practices in the U.S.

RAP becomes a good alternative material to be reused in base layers, as it consists of well-graded aggregates coated with aged bitumen. However, RAP lacks a bit in strength and durability. Its performance under load is limited, and without modification, it struggles to meet the mechanical standards required for structural pavement applications. To address this, researchers have explored the stabilization of RAP using binders like lime, fly ash, cement, etc. Among the various mechanical properties, Unconfined Compression Strength (UCS) stands out as one of the most critical indicators, which is used to evaluate the effectiveness of stabilized mixtures. It evaluates the material's ability to withstand axial compressive loads. Studies by researchers have demonstrated that the addition of lime, fly ash, and cement—either individually or in combination—significantly enhances the UCS of stabilized mixtures, with cement showing the most substantial early strength gains and lime–fly ash blends providing robust long-term performance through pozzolanic bonding [3]. Research indicates that stabilized RAP mixtures can achieve UCS values within and even above the target ranges for conventional pavement base materials [4]. The investigation of UCS performance has become crucial because of the vast availability of RAP & the constant increasing need for sustainable infrastructure solutions. This way, the dependency on the virgin resources would decrease, and also the waste would be utilized properly into a reliable construction material, hence contributing to more sustainable road building practices.

2. LITERATURE REVIEW

The use of RAP in pavement construction has grown in recent years, mainly because it offers a more sustainable option than relying solely on fresh materials. But RAP on its own often doesn't perform well structurally. This is largely due to the hardened bitumen and the weathered nature of the aggregates it contains [5] [6]. Because of these issues, many studies have looked into ways to strengthen RAP and improve its engineering properties. One common approach is to evaluate different stabilization methods—such as adding lime, fly ash, cement, and similar materials—and then measure their effectiveness. For this purpose, the Unconfined Compressive Strength (UCS) test is frequently used, as it provides a clear indication of how well the treated RAP can withstand load. The stabilization with different stabilizers has been bifurcated below-

2.1 Stabilization with Lime & Fly Ash-

A detailed study in this field was conducted by Barmade et al. [7], who relied on UCS testing to track how the strength of RAP mixtures improved when stabilized with fly ash and lime. The study considered a range of blends where RAP was used at different replacement proportions, ranging from 70% to 80%, and fly ash and lime were added in varying proportions too. A total of nine different combinations were tested, with fly ash content ranging from 10% to 25% and lime content ranging from 5% to 10% by dry weight of RAP. The UCS results clearly demonstrated that both fly ash and lime significantly improved the compressive strength of the RAP mixtures, and that strength gains were more pronounced with longer curing durations. For example, the RFL2 mix (70% RAP + 22.5% fly ash + 7.5% lime) showed the highest UCS after 28 days, reaching values exceeding 4.5 MPa. This is substantially above the 1.7 MPa threshold typically recommended for subbase applications, and even exceeds values commonly required for base layers in moderate traffic conditions. The increase in strength was mainly linked to the pozzolanic reactions that take place between fly ash and lime. Over time, these reactions produce cementitious gels—such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H)—that occupy the voids within the RAP and help bond the particles together. This added bonding helps make up for the naturally low cohesion of aged RAP, which typically has weak particle-to-particle friction because of its old bitumen coating and smoother particle shape. The study also showed that curing time plays a major role in strength development. The UCS values rose noticeably from 0 to 7 days, and then again from 7 to 28 days, with the effect being even more pronounced in mixtures containing higher amounts of lime. This finding underscores the need for adequate curing periods in real-world applications to ensure the material reaches its full strength. It also reinforces the usefulness of UCS testing as a dependable way to track strength development both during and after construction.

Panda and Biswal [8] investigated the ways to improve engineering properties of RAP by stabilizing it with lime and fly ash. A series of laboratory mixes in different proportions were prepared along with adding different stabilizers. Different proportions of these stabilizers and assessed their performance through standard compaction, UCS, and CBR testing. The untreated RAP showed poor strength, with UCS values below 1.0 MPa, reinforcing its limitations as a base course material. Once lime and fly ash were added, however, the mixtures displayed substantial strength improvements. After 7 days of curing, UCS values increased to around 1.8–2.6 MPa, and continued to rise beyond 3.0 MPa at 28 days, depending on the amount of stabilizer used. The study noted that the optimal blend—5% lime and 20% fly ash—achieved the highest strength, surpassing the 1.7 MPa threshold for subbase applications and nearing the 2.8 MPa benchmark commonly associated with base courses in low- to medium-volume roads.

2.2 Stabilization with Lime, Cement, Fly Ash

The study conducted by Saride et al. [9] [10] contributes significantly to the understandings of how various chemical stabilizers affect UCS performance in RAP-based mixtures, with a specific focus on applications in Indian low-volume roads. The study recognises that while RAP offers environmental and economic advantages, its granular structure and presence of aged bitumen often led to insufficient mechanical strength, particulary for structural applications like base and subbase layers. The study also investigates the effectiveness of lime, cement, and foamed asphalt as primary stabilizers, with fly ash used as a secondary additive to enhance pozzolanic reactivity. To tackle this challenge, the authors explored several stabilization approaches using different binders—lime, cement, and blends of lime with Class F fly ash—applied in varying amounts. Their main aim was to see whether these additives could enhance the strength of RAP enough for it to be safely used in low-traffic pavements, particularly in rural settings.

They carried out a series of UCS tests on RAP mixtures treated with different percentages of lime and fly ash, and compared the results with those from cement-stabilized mixes. Even small amounts of lime (3% and 5%) produced noticeable improvements in UCS when compared to untreated RAP, which originally showed very low compressive strength and poor cohesion. The lime-treated samples reached UCS values in the range of about 1.2 to 2.1 MPa, depending on the dosage and curing duration, with strength continuing to increase as curing progressed. An important takeaway from their finding is that Fly ash, when used alone, did not significantly contribute to strength improvement. However, in combination with lime, it proved highly effective. Moreover, the gradation of the RAP had a measurable impact on UCS performance, with finer RAP fractions yielding lower strength due to reduced aggregate interlock and higher residual binder content. The synergistic effect of lime-activated fly ash led to increased UCS values and improved long-term strength development. The 28-day UCS of mixes containing 5% lime and 15-20% fly ash exceeded the 1.7 MPa benchmark typically considered acceptable for subbase applications in Indian road design standards. Moreover, the time-dependent gain in strength between 7 and 28 days was especially notable in fly ash-lime blends, further confirming the slower but continuous nature of pozzolanic stabilization. This property is particularly advantageous in the Indian context, where construction timelines may vary, and durability is crucial due to extreme climatic variations. The lime–fly ash systems offered a more balanced performance profile, delivering strength increases steadily over time and showing better moisture tolerance.

2.3 Stabilization with Fly Ash

Mohammadinia et al. [11] evaluated the effectiveness of Class C fly ash in stabilizing RAP. The study evaluated three RAP-to-virgin aggregate (VA) proportions—100:0, 80:20, and 60:40—each blended with fly ash added at 10%, 20%, 30%, and 40% of the dry weight. To track how the mixtures gained strength over time, UCS tests were conducted after 7 and 28 days of moist curing. The results showed a clear pattern: mixtures with higher fly ash contents and longer curing periods consistently achieved higher UCS values. Among all the combinations, the blend with 80% RAP, 20% VA, and 40% fly ash delivered the highest UCS, surpassing the commonly cited 1.7 MPa requirement for subbase materials in low-volume roads. Another key takeaway from the study was the strong influence of curing time. Every mixture exhibited significant strength growth from 7 to 28 days, reflecting the slow but steady strength development that is characteristic of pozzolanic reactions. Unlike cement, which yields early strength, fly ash-based stabilization continues to strengthen over time, offering potential advantages in terms of long-term durability.

In their investigation into sustainable pavement construction, Joshi and Patel [12] evaluated the use of Class C fly ash as a stabilizing agent in flexible pavement layers. Recognizing the growing need to incorporate industrial by-products into civil infrastructure, the study set out to determine whether fly ash could be effectively utilized to enhance the strength and structural capacity of pavement layers composed partially or entirely of reclaimed materials. UCS testing played a central role in the evaluation process, offering quantifiable insights into the load-bearing potential of the stabilized mixtures and serving as a benchmark to assess their suitability for base or subbase applications. To simulate practical field conditions, the researchers prepared cylindrical specimens using various blends of RAP and virgin aggregate, treated with different dosages of Class C fly ash. The results revealed a clear trend of increasing compressive strength with both extended curing duration and higher fly ash content. At 7 days, the UCS values were modest but indicated early strength gain, while the 28-day results showed significant improvements across all mix designs. Among the mix designs studied, those with fly ash content in the range of 20–30% demonstrated the most favorable strength outcomes, achieving UCS values that met or exceeded the minimum thresholds typically required for pavement subbase layers in low- to medium-volume roads.

Horpibulsuk et al. [13] explored the use of fly ash–based geopolymers as a stabilizing agent for RAP, with the goal of upgrading its suitability for use in pavement base and subbase layers. Recognizing that untreated RAP exhibits low strength and poor durability due to the presence of aged binder and smooth aggregate surfaces, the authors explored geopolymerization as a sustainable alternative to traditional cement stabilization. The experimental program involved preparing mixtures of RAP with varying proportions of low-calcium fly ash activated by alkaline solutions, followed by curing under controlled conditions. While untreated RAP typically recorded UCS values well below 1 MPa, rendering it inadequate for structural layers, the fly ash–geopolymer stabilized mixtures achieved UCS values in the range of 1.5–3.0 MPa depending on activator concentration and curing regime. These values not only satisfied the minimum 1.7 MPa requirement for subbase layers but also approached or exceeded 2.5 MPa, the benchmark for base applications in low- to medium-traffic pavements. The increase in strength was mainly linked to the geopolymeric reaction, which produced aluminosilicate gels that helped bond the RAP particles more effectively and reduce internal voids. Beyond the laboratory results, the authors also pointed out an important practical benefit: using geopolymer-stabilized RAP in pavement design could allow for thinner base layers while also reducing the need for virgin aggregates.

Jallu and Saride [14] examined the use of alkali-activated fly ash (AAFA) as a sustainable option for stabilizing RAP. They created RAP–fly ash blends activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions in different concentrations and proportions, and then evaluated their performance through UCS tests conducted at 7 and 28 days of curing. The treated mixtures showed significant strength gains, with UCS values ranging from 2.5 to 4.2 MPa depending on the activator dosage and curing duration. The best results were obtained using a 10 M NaOH solution with a Na_2SiO_3/NaOH ratio of 2.5, where the 28-day UCS exceeded 4 MPa. These strengths were well above the commonly cited 1.7 MPa requirement for subbase layers and also met the 2.1–2.8 MPa range recommended for base courses in low- to medium-traffic pavements. Furthermore, mechanistic pavement design analysis indicated that AAFA-stabilized RAP could reduce the required base thickness by 20–30% compared to untreated RAP, while still satisfying structural capacity requirements.

2.4 Stabilization with Cement

Mostafa et al. [15] examined the use of cement as a stabilizing agent for RAP. Their findings depicted that untreated RAP had very low strength, with UCS values around 0.22 MPa, which clearly indicated that it is not suitable for use as a base material. After stabilizing it with cement, however, the strength improved dramatically. At a 10% cement content, the UCS reached 6.03 MPa, surpassing the 4.9 MPa standard typically required for cement-treated base (CTB) layers. The study further noted that once UCS values exceed this 4.9 MPa threshold, cement-stabilized RAP can effectively replace virgin aggregates entirely in CTB applications while still providing adequate structural performance. From a pavement design perspective, these high strength values also imply that the thickness of cement-stabilized RAP layers can be reduced without sacrificing overall structural integrity. This not only lowers material costs but also offers environmental advantages & sustainability by minimizing the need for virgin aggregates/resources.

Guthrie et al. [4] examined the strength and durability performance of aggregate base materials blended with RAP and stabilized using cement, drawing on materials obtained from the I-84 reconstruction project in Utah. The researchers designed a full-factorial experiment with five RAP contents (0%, 25%, 50%, 75%, 100%) and five cement contents (0.0–2.0% by weight), with three replicates each, to systematically study the interaction effects. Their results showed that UCS values decreased significantly as RAP content increased (from 425 psi at 0% RAP to 208 psi at 100% RAP) but increased sharply with cement addition (from 63 psi at 0% cement to 564 psi at 2% cement). Importantly, the interaction between RAP and cement was significant: higher cement contents (1.0–2.0%) mitigated strength loss due to RAP, while low cement contents (≤0.5%) could not counteract the weakening effect of asphalt-coated aggregates. The authors noted that too much cement could make the base brittle and prone to cracking, while too little would not achieve required pavement support. Notably, 100% RAP required as much as 2% cement to meet criteria, while blends with only 0–25% RAP was either too weak or moisture susceptible. The authors specifically concluded that RAP contents in the range of 50–75% with 1.0% cement are the most practical for field applications because they provide reliable UCS performance and durability with minimal sensitivity to material variability.

Mansoorzadeh [16] investigated the feasibility of using 100% RAP in CTB mixtures. To achieve this, RAP was stabilized with varying cement dosages of 4%, 5%, and 6% by dry weight, and specimens were cured for 7 and 28 days under controlled conditions. The results showed a steady rise in UCS with higher cement contents and longer curing times. At 4% cement, the mixes achieved strengths just above the minimum 1.7 MPa requirement for subbase layers, reaching about 1.8–2.0 MPa at 7 days and increasing to roughly 2.5–2.7 MPa by 28 days. When the cement content was raised to 5%, the UCS values improved further, ranging from 2.5–3.0 MPa at 7 days and approaching 3.5 MPa after 28 days—demonstrating the added contribution of binder in strengthening the RAP. The best results came from the 6% cement mix, where UCS values exceeded 3.0 MPa at 7 days and neared 4.0 MPa at 28 days, placing these mixes well within the acceptable range for base layers in higher-category pavements. The authors also cautioned that although increasing cement dosage enhances strength, excessive binder can lead to brittleness and shrinkage cracking, which may affect long-term durability.

Ghanizadeh et al. [17] conducted an experimental investigation into the performance of cement-stabilized RAP, evaluating whether 100% RAP stabilized with 3%, 4%, 5%, and 6% cement could develop adequate strength for use as a pavement base. Their findings showed a clear, consistent trend of increasing strength with higher cement contents and longer curing periods, reflecting the progression of cement hydration and the formation of stronger cementitious bonds throughout the RAP matrix. At 3% cement, UCS values were the lowest, averaging around 1.5–2.0 MPa at 7 days and improving to nearly 2.5 MPa at 28 days, just above the commonly cited 1.7 MPa threshold for subbase layers. With 4% cement, strengths increased further to approximately 2.0–2.3 MPa at 7 days and 2.8–3.0 MPa after 28 days, indicating better structural performance. The addition of 5% cement delivered a marked improvement, with UCS values reaching 2.5–3.0 MPa at 7 days and nearly 3.5 MPa at 28 days, placing the mixtures within the range suitable for base courses of standard pavements. The best results were observed with 6% cement, where UCS exceeded 3.0 MPa at 7 days and approached 4.0 MPa at 28 days, confirming the potential of cement-stabilized RAP to be used even in higher traffic categories. The authors noted, however, that while UCS gains were significant with higher cement content, practical limitations such as increased brittleness and shrinkage cracking risk must be considered, leading them to suggest that 4–5% cement represents the most balanced dosage in terms of both strength and durability.

Adresi et al. [18] examined how incorporating high amounts of RAP affects the mechanical properties of CTB mixtures. The study prepared mixtures containing different proportions of RAP and cement, with RAP levels set at 0%, 40%, 60%, and 80%, and cement contents of 3%, 5%, and 7%. The findings showed that adding RAP to CTB mixtures produced a mixed effect on UCS. On one hand, the aged bitumen coating the RAP particles weakened the cement–aggregate bond, which tended to reduce UCS. On the other hand, the residual bitumen also offered some adhesion between particles, providing a slight strength benefit at lower RAP contents. This dual behavior was most noticeable in the mixes with 3% cement, where UCS displayed a non-linear pattern and reached its maximum at 40% RAP. Beyond this point, the higher bitumen content acted more like a contaminant, interfering with bonding and leading to a drop in strength. However, when cement content was increased to ≥5%, the influence of bitumen became negligible compared to cementitious bonding, leading to a linear decrease in UCS with higher RAP content, with the best UCS values observed in non-RAP mixes. Overall, the results confirmed that while RAP reduces UCS in CTB mixtures, increasing cement dosage effectively counterbalances this, and mixes with low cement and moderate RAP (around 40%) can even exhibit improved UCS due to the supplementary adhesion effect of aged binder.

2.5 Stabilization with Lime Kiln Dust (LKD)-

The potential use of lime kiln dust (LKD) was examined by Beeghly [19], as a stabilizing agent for RAP and other recycled materials. RAP samples were treated with varying percentages of LKD and compacted at optimum moisture content. After this, UCS testing was conducted on cured specimens. The results depicted that untreated RAP exhibited very low UCS values, typically below 0.5 MPa, confirming its inadequacy for structural applications. However, the addition of 4–6% LKD resulted in substantial strength gains, with UCS values increasing to around 1.7–2.5 MPa, thus meeting the threshold required for subbase applications in low-volume roads. At higher LKD percentages (8–10%), the mixtures achieved UCS values above 3.0 MPa, suggesting they could be used for base course applications. The study also emphasized the practical design benefits of these results: when RAP is stabilized to reach UCS levels above roughly 2.5 MPa, the thickness of the base layer can be reduced by about 25–30% compared with untreated RAP, while still providing sufficient load-bearing capacity.

These studies collectively highlight UCS as a critical performance parameter and confirm that well-designed stabilized RAP blends can meet structural and sustainability goals in modern pavement design.

3. CONCLUSION

The collective findings across the reviewed studies emphasize that stabilization of RAP with chemical additives such as cement, lime, and fly ash significantly improves its UCS, thereby enhancing its suitability as a base/subbase material in flexible pavements. Cement consistently yields the highest UCS gains, with strengths exceeding 3–4 MPa at 28 days when dosages of 5–6% are used, though issues of brittleness and shrinkage cracking remain a concern. Lime and fly ash, while slower to react, contribute through pozzolanic activity, leading to gradual strength gain over curing time, with UCS values in the range of 1.7–3.0 MPa depending on dosage and curing conditions. Studies also show that partial replacement of RAP with virgin aggregates improves particle interlock and bonding, further enhancing UCS. The interplay between cementitious bonding from stabilizers and the aged binder coating on RAP particles is a critical factor: at low cement dosages, moderate RAP contents (30–40%) sometimes show improved UCS due to residual bitumen adhesion, whereas at higher RAP levels (>75%), the bitumen coating acts as an impurity and reduces strength unless sufficient stabilizer is used. Overall, the literature demonstrates that while untreated RAP alone is insufficient for structural layers, stabilization with cement, lime, or fly ash allows UCS thresholds for pavement bases and subbases to be met, offering a technically sound and environmentally sustainable solution.

- Cement stabilization of RAP consistently produces the highest UCS, with >3 MPa at 28 days achievable at 5–6% cement, making it suitable for base layers.
- Lime and fly ash stabilization led to slower but steady UCS development due to pozzolanic reactions, often reaching 1.7–2.5 MPa at 28 days, adequate for subbase and low-volume road applications.
- Blended stabilizers (lime + fly ash) enhance long-term UCS, leveraging lime activation of fly ash, while reducing reliance on cement.
- Partial RAP replacement with virgin aggregates improves UCS by providing angular aggregates for interlock, particularly beneficial at lower stabilizer dosages.
- At low cement contents (~3%), mixes with ~40% RAP sometimes show peak UCS values due to the supplementary adhesion effect of aged binder;

however, beyond this, bitumen coating reduces bonding quality.

- At higher cement contents (≥5%), UCS trends become linear, dominated by cementitious bonding, and non-RAP mixes generally outperform RAP-rich ones.
- Stabilized RAP mixtures provide a sustainable alternative to virgin aggregate bases, balancing strength, cost, and environmental benefits, provided that cement content and RAP proportion are optimized.

4. LIMITATIONS OF THE STUDY

- In most of the studies, the short-term UCS values (7-28 days) is evaluated, while the long-term performance (90 days and more) under field curing condition is less explored.
- Majorly, the researches were conducted under controlled laboratory conditions, which may or may not fully replicate the field conditions & variability like traffic loading, temperature variations, etc.
- Assessments like life cycle cost analysis, carbon footprints, etc. were rarely integrated with the testing, making it difficult to establish holistic sustainability benefits.
- Lastly, this paper relies primarily on the UCS testing as the mechanical indicator. Other performance related tests were not investigated.

5. FUTURE SCOPE

This study paves the way for further research focused at optimizing the use of chemical or mineral stabilizers to enhance the performance of weak soil subgrades. Future investigations can focus on improving the load-bearing capacity of subgrades by strategically using chemical or mineral stabilizers, thereby contributing to a longer pavement lifespan. Additionally, the sustainable and cost-effective properties of chemical or mineral stabilizers provide potential to reduce pavement thickness and overall construction costs. Further studies may also explore various types of chemical or mineral stabilizers, diverse soil conditions, and different loading scenarios to develop more efficient and durable pavement design strategies.

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