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Dissertation

**Title: Use of Reclaimed Asphalt Pavement and Fly Ash as
A Sustainable Alternative for Pavement Construction in
India.**

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Author's Declaration:

I declare that the work in this dissertation was carried out following the regulations of UWTSD. The work is original except where indicated by particular references in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the UWTSD.

The dissertation has not been presented to any other university for examination in the United Kingdom or overseas.

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Abstract:

The construction sector, particularly the specialisation of road infrastructure, is witnessing a paradigm shift towards sustainable and environmentally friendly practices by incorporating recycled pavement materials in road constructions. Positioned within this context, this research examines the utilization of Reclaimed Asphalt Pavement (RAP) and Fly Ash (FA) as innovative alternatives for sub-base pavement construction in India. A mixed methodological approach was utilised, combining experimental laboratory assessment with qualitative expert interviews. A detailed laboratory assessment was conducted across six distinct RAP and FA combinations, each stabilising with a consistent 3% cement mix. These combinations were methodically labelled from T1, comprising only RAP, to T6, a uniform mix of RAP and FA.

Empirical data derived from standard IS 2720 tests offers pivotal insights: Optimum Moisture Content (OMC) values consistently rose from 3.9% for CT1 to 6.3% for CT6. Intriguingly, the Maximum Dry Density (MDD) values peaked at CT4 with 1.89 g/cc, followed by a tapering off in subsequent combinations. Delving deeper into structural integrity, the California Bearing Ratio (CBR) values unveiled a direct correlation with including FA, reaching a maximum of 36.3% for T4 but diminishing after that. This trend was mirrored in the Unconfined Compressive Strength (UCS) results, with UCT4 registering a notable strength of 388.0 kPa. Further strengthening the laboratory results, the study engaged with industry experts, whose insights corroborated the practical feasibility and potential advantages of deploying these combinations in real-world scenarios. This study offers cost-effective and sustainable alternatives for sub-base pavement in road construction industries.

Keywords: Asphalt Pavement, Cement, Fly Ash, RAP, Reclaimed, Moisture, UCS, CBS, Compaction

List of abbreviations, symbols, and units of measure

ACP	Asphalt Concrete Pavement
CBR	California Bearing Ratio
CM	Control Mix
CQF	Cemented Quarry Fines
CS	Crushed Stone
CSA	Crushed Stone Aggregate
DD	Dry Density
FA	Fly Ash
FDOT	Florida Department of Transportation
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GSA	Groundnut Shell Ash
HIPR	Hot In-place Recycling
HMA	Hot Mix Asphalt
IRC	Indian Road Congress
IS	Indian Standards
LBR	Limerock Bearing Ratio
LSA	Lime Stone Aggregate
MC	Moisture Content
MDD	Maximum Dry Density
MEPDG	Mechanistic-Empirical Pavement Design Guide
NH	National Highways
NHAI	National Highway Authority of India
OMC	Optimum Moisture Content
PET	Polyethylene Terephthalate
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Coarse Aggregates
RCP	Recycled Concrete Pavement
SH	State Highways
UCS	Unconfined Compressive Strength
VA	Virgin Aggregate

WMA Warm Mix Asphalt

Symbols

W_{cement}	Weight of cement
W_{dry}	Dry weight
W_{FA}	Weight of FA
W_{RAP}	Weight of RAP
W_{water}	Weight of water
W_{wet}	Wet weight
ρ_d	Dry density
cc	cubic capacity
g	grams
kg	kilograms
kPa	kilopascals
m	meters
N	Newtons
w	optimum moisture content

Units of measure

Area	m^2
CBR	%
DD (ρ_d)	g/cc
Load	N
MC	%
MDD	g/cc
OMC (w)	%
UCS	kPa
W_{cement}	g
W_{dry}	g
W_{FA}	g
W_{RAP}	g
W_{water}	g
W_{wet}	g

Chapter 1:

Introduction

1.1 Background

Road infrastructure is critical to the socioeconomic development of any country (Zhang et al 2022). The challenge in countries such as India, where road networks span millions of kilometres, is to maintain and expand these networks in a way that is both economically viable and environmentally sustainable. This context emphasises the importance of sustainable road construction techniques that cater to current demands and address future needs.

Historically, road construction mainly depended on natural resources, from VAs to bituminous binders. The use of these resources has remarkable environmental consequences, from resource depletion to carbon footprints associated with their extraction and processing. As the environmental effects of traditional road construction practices became more evident, the industry's attention started shifting towards more sustainable methods. This shift can be observed globally, but the stakes are high for countries with extensive road networks, like India. India's road network is almost 63,31,791 km long, with NH spanning about 1,44,955 km, SH approximately 1,67,079 km, and other roads approximately 60,19,757 km, the majority of which are flexible pavements with bituminous surfacing (NHAH Report 2023). Such an expansive network needs massive quantities of construction materials, which is becoming increasingly challenging due to the scarcity of natural resources and their rapidly rising costs.

A significant solution to these challenges has been examining and adopting recycled materials in road construction. Among these, RAP has garnered significant attention. RAP becomes a by-product when aged bituminous materials are removed during strengthening, rehabilitation, or reconstruction operations. Once processed, RAP provides a composite of aggregate and asphalt binder, proving an indispensable replacement for more expensive virgin aggregates and binders in HMA production (Valdes et al 2011). However, its utilization could be better. For instance, while RAP increases the stiffness of HMA, it can compromise the ductility and fatigue resistance of the mixture. Nevertheless, adopting RAP has multiple benefits, from cost savings in

road construction to significant reductions in the environmental footprint (Liu et al 2022).

Beyond RAP, the industry has also researched other waste materials, such as RCP, steel slag aggregates, recycled plastics, and PET waste. These materials offer distinctive benefits and pose unique challenges, necessitating research and experimentation to establish best practices. Using geosynthetic materials is another ingenious approach to enhancing road durability while ensuring sustainability. Employed worldwide to stabilise soft soils in road construction, geosynthetics play a crucial role, especially at the interface of subgrade and subbase/base layers, serving functions like separation, filtration, drainage, and reinforcement. Integrating these materials has proven to augment the performance of pavements, particularly in areas with challenging soil compositions or high traffic loads (Al-Saffar et al 2021).

Ultimately, the relationship between road construction and environmental degradation is complex. While roads are pivotal to economic growth and connectivity, their construction has historically contributed to notable environmental damage. The evolution towards sustainable practices becomes essential as the industry stands at this crossroads. Employing recycled materials and innovative technologies is not just a progressive step but a prerequisite to meet the dual objectives of infrastructure development and environmental conservation (Zhao et al 2020).

1.2 Purpose of the research

The ever-increasing demands of modern infrastructure and the need for sustainability have prompted researchers and practitioners to investigate novel road construction solutions. The primary focus of this research lies in examining the potential benefits of employing RAP coupled with FA in the context of pavement sub-base construction. Specifically, this study focuses on the feasibility of a unique combination of RAP, FA, and a 3% cement stabiliser.

It is evident from literature reviews that RAP has shown promising potential in almost every layer of flexible pavement construction. RAP's aggregate and asphalt binder can replace VA and virgin bitumen, one of the most expensive materials used in pavement construction. As a result, incorporating RAP into the production of HMA for wearing

and binder courses can result in significant cost savings, provided the RAP is of high quality and has homogeneous properties.

However, the scope of RAP is broader than just bituminous courses. RAP has relevance in the base and sub-base courses, with some gradation adjustments achieved by adding VAs. Notably, a combination of RAP and a small percentage of cement has been found effective in enhancing the CBR of weak subgrades (Thakur et al 2012). A higher CBR in subgrades can reduce requirements for the subsequent upper layers, especially the bituminous layer, under the same traffic load conditions. This, in turn, can lead to considerable cost savings in pavement construction. Furthermore, with the growth and expansion of road networks, especially the NH projects, vast quantities of RAP are generated, particularly during strengthening and rehabilitation operations. Utilising this RAP for pavement construction could lead to significant economic savings (Milad et al 2020).

Given the above, this study investigates new ways to combine RAP and FA stabilised with 3% cement. The project aims to contribute to developing more environmentally friendly ways to build and take advantage of these methods' economic and environmental benefits together. In a country like India, where many roads and environmental concerns are critical, the results of this study could be beneficial for building roads in the future.

1.3 Research aims and objectives

Recognising the demanding need to discover and develop more environmentally friendly techniques, this study aims to provide significant insights into the effectiveness of combining RAP, FA, and a 3% cement stabiliser for pavement sub-base constructions in India.

Aims:

1. The aim is to identify the optimal ratio of RAP and Fly ash in sustainable highway construction in India.

Objectives:

1. To determine the suitability of RAP and fly ash combinations.

2. To identify the optimal combination of materials which offers the best balance of strength, stability and durability.
3. To evaluate the practical applicability of such combinations as effective pavement sub-base materials.

1.4 Scope of the study

This research focuses on the Indian context, specifically the country's vast infrastructure demands and the growing preference for sustainable methodologies. While the implications of this research have potential resonance at a global level, the findings and conclusions are primarily focused to India's specific road construction challenges and opportunities. Critical Aspects of the Study's Scope are as follows:

1. **Geographical Context:** This study strongly emphasizes the Indian context. With its diverse geographical terrains and rapidly expanding urbanization, India provides a unique platform to assess the efficacy of novel construction techniques. However, the principles and findings could offer insights into global infrastructure endeavors.
2. **RAP and FA Combinations:** The research critically examines six specific RAP and FA combinations, each stabilized with 3% cement. These combinations labeled T1 to T6, span from a 100% RAP (T1) mix to an equal mixture of RAP and FA (T6). The variations in these combinations aim to discern the optimal mixture for pavement sub-base applications, factoring in aspects like strength, stability, and durability.
3. **Laboratory-based Assessment:** Given the novelty of these combinations, this research adopts a rigorous, laboratory-based evaluation approach. Employing standardized IS 2720 tests such as Compaction (IS 2720-8 (1983)), CBR (IS 2720-16 (1987)), and UCS (IS 2720-10 (1991)), the study seeks to obtain objective, empirical data on each proposed blend's performance.

1.5 Limitations

While the study provides a comprehensive laboratory assessment, it is pivotal to note that the scope is restricted to these controlled evaluations. Field implementations, which numerous external factors can influence, are not within the scope of this research.

1.6 Structure of the Dissertation

In the proposed dissertation structure, the research is methodically charted, beginning with a foundation grounded in the broader context of environmental concerns in road construction. This is further developed in Chapter 2, where the literature review explores historical and contemporary sustainable construction practices, notably RAP, FA, and cement stabilization roles. Chapter 3 delves into the research methodology, highlighting the rationale behind the materials selected, their combination proportions, and the significance of each chosen test. Also, the justification of selected questions and their phrasing in questionnaire preparations are discussed. As the dissertation progresses into Chapter 4, the focus sharpens on the performance analysis of these novel combinations, integrating both the experimental data and insights gleaned from expert consultations. The subsequent chapter, Chapter 5, delves deeper, connecting the results to broader implications, making the research practically relevant. Finally, the concluding chapter encapsulates the research's contributions to sustainable construction, offers reflections, and provides future directives.

So as discussed having explained the scope of the research the following chapter presents the literature available on sustainable highway construction.

Chapter 2:

Literature review

2.1 Introduction

To address the core objectives of this study, it becomes pivotal to delve into the existing body of research surrounding road construction materials, namely RAP, FA, and cement stabilizers. The research predominantly pivots towards understanding their integration in road infrastructure, drawing a comprehensive landscape of insights gathered from secondary sources on the utilisation and implications of these materials in pavement constructs. It is imperative to understand this pre-existing knowledge, as it not only underscores the economic and environmental nuances associated with these materials but also emphasises their importance in fostering sustainable road construction. With an ever-increasing focus on sustainable practices, navigating the intricacies of these materials becomes more than a mere technical exercise; it becomes a guide for future constructions. Recognising the gaps and insights from these secondary sources paves the way for this study to venture into primary research, ensuring that the investigation into RAP, FA, and cement stabiliser combinations is pioneering and rooted in established understandings. This literature review, therefore, serves as a bridge, connecting historical perspectives with the study's contemporary objectives and sculpting the trajectory for the next phase of sustainable road construction methodologies, especially in the Indian context.

2.2 Review of RAP in pavements

Transportation is vital for meeting human needs and is connected to sustainability, which aims to meet those needs (Hoy et al 2016). Incorporating reclaimed materials into roadway constructions is emphasised by the rising costs of asphalt pavement materials and the rising cost and shrinking availability of VA. The construction domain consumes vast amounts of raw materials, with over-extraction leading to natural resource depletion. Approximately 15,000 t of VA is required for every kilometre of national highways (Tarsi et al 2020).

Adopting waste material recycling and reuse promotes a more sustainable approach to civil infrastructure construction by addressing technical, socio-economic, and environmental sustainability (FHWA-RD-97-148 2008). Despite generating ample solid waste, a marginal portion finds utilisation in pavement formulations (Zhao et al 2020). Due to the removal of ageing pavements, countless tons of asphalt are discarded

(Dong and Huang 2014). The declining availability of landfill areas for pavement materials has prompted research into alternative cost-efficient materials (Krishna Swamy et al 2011). Adopting asphalt recycling methodologies is recommended to mitigate waste resulting from pavement removal (Serpell and Alarcón 1998). RAP utilisation has been increasingly emphasised, aiming to lessen environmental burdens and conserve natural resources in pavement configurations (Ong et al 2020 and Spreadbury et al 2021).

RAP incorporation curtails waste volumes and addresses road construction material disposal challenges. In the environmental context, recycling imparts a beneficial impact (Tabaković et al 2010). Pavements, essentially quad-layered constructs, encompass a surface course, base layer, sub-base layer, and subgrade layers. The base course is pivotal, translating dynamic load-induced stress to the underlying layers. It serves the dual purpose of draining infiltrated water from the pavement system and preventing the upward migration of fine particles to the surface. As a modern solution, RAP is a reclaimed pavement material characterised by binder-enveloped aggregates (Hoppe et al 2015). Every year, billions of tonnes of RAP are relegated to nearby disposal sites, causing significant environmental consequences (Saride et al 2016). Substituting VA with RAP in road construction aligns with sustainable development principles (Milad et al 2020). This initiative addresses the twin challenges of dwindling natural aggregate reserves and the environmental consequences of asphalt material disposal near construction projects (Huang et al 2009). Additional advantages encompass expedited project timelines and minimised public travel disruptions (Nassar and Nassar 2006).

2.2.1 RAP in pavement systems

RAP, a composite geomaterial, exhibits pronounced reactivity under standard atmospheric conditions. Substituting HMA with RAP is beneficial for technical and economic sustainability strategy. The integration of RAP reduces the overall project costs while ensuring optimal resource allocation. As the RAP content in a project increase, a corresponding decline in GHG emissions is observed (De Lira et al 2015). Field assessments indicate that RAP's performance in flexible road overlays remains impressive, displaying minimal rutting, freezing, and fatigue cracking over 1–2.5 years. Nevertheless, while RAP finds extensive application in roads, it operates as a derivative of VA in terms of both physical and engineering characteristics. Consequently, optimising RAP's properties may necessitate mixture with VA and adjusting proportions

using lime/cement or both (Saride et al 2016). Numerous investigations on RAP suggest that its incorporation with other VAs should typically be capped at 30% in pavement base layers (Aurangzeb and Al-Qadi 2014). For pavements with high RAP content exceeding 30%, the precise design of supplementary additives is imperative to meet end-product specifications. The success in substituting VA with RAP and the resultant product's performance has been attributed to binder content, meticulous gradation, and adept mix design (Taha et al 1999). Furthermore, the mechanical integrity of the RAP aggregate sees enhancement upon stabilisation with cement, compared to a standalone mix with VA (Taha et al 2002). Therefore, leveraging RAP in base or sub-base layers translates to benefits like cost savings on materials, judicious use of aggregate resources, elimination of disposal expenses, and diverting waste from landfill sites (Khan et al 2020).

2.2.2 Characteristics of RAP in Pavement Systems

The characteristics of RAP predominantly depend on the composition of the original material and the asphalt present in the pre-existing pavement. RAP sources span multiple old pavements, leading to potential variability in their quality. Factors such as the frequency of repavements, the history of crack sealing, and previous sealing coats play pivotal roles in defining the RAP's composition. Assessing RAP's physical properties proves essential to distinguish factors influencing its engineering behaviour. Multiple researchers have embarked on laboratory tests focused on RAP, examining characteristics like specific gravity, particle size distribution, gradation, and bulk density (Deniz 2009). The aged bitumen in RAP affects its specific gravity, water absorption capabilities, and gradation. Generally, in dry states, RAP has a greyish hue that darkens when moistened. Particle sizes within RAP can vary, with a typical size being 25 mm. Notably, the bitumen content within RAP was identified at approximately 4.16%, though this varies with the mixture source. Employing RAP exclusively in mixes aligns it with the poorly graded sandy gravel category, suggesting that a 100% RAP pavement might not meet grading requisites (Edeh et al 2013).

Tests pinpointing aggregate-specific gravity are pivotal in gauging material strength and quality, while water absorption tests ascertain the water retention capacities of aggregates. Defined as the weight ratio between aggregate and an equivalent volume of water, the results of water absorption tests directly influence specific gravity. Micro-holes within aggregates reduce the water absorption rate, increasing the specific gravity

(Jayakody et al 2019). A notable deduction is that the RAP composite's specific gravity is less than the fresh aggregate due to the ageing bitumen presence. This aged bitumen seemingly impedes water absorption by sealing RAP voids. The material's unit weight, reflecting weight per volume unit, offers insights into its compactness. Enhanced unit weight corresponds to elevated material density. The aged bitumen's presence in RAP suggests a reduction in the RAP's weight (Sunarjono 2019). RAP appears not as homogeneously sized aggregates but as a mixture of smaller aggregates cohesively bound by bitumen. Based on penetration metrics, RAP can be categorised into active or inactive, with active RAP demonstrating superior cohesion compared to its inactive counterpart or natural substances (Tebaldi et al 2012).

2.2.3 Structure and application of RAP in asphalt pavement

Asphalt pavement is structured with distinct layers, comprising the foundational subgrade and sub-base, the versatile base - which might be unbound granular, asphalt-treated, cement-treated, permeable, or recycled and the surface layers of asphalt (Su et al 2017).

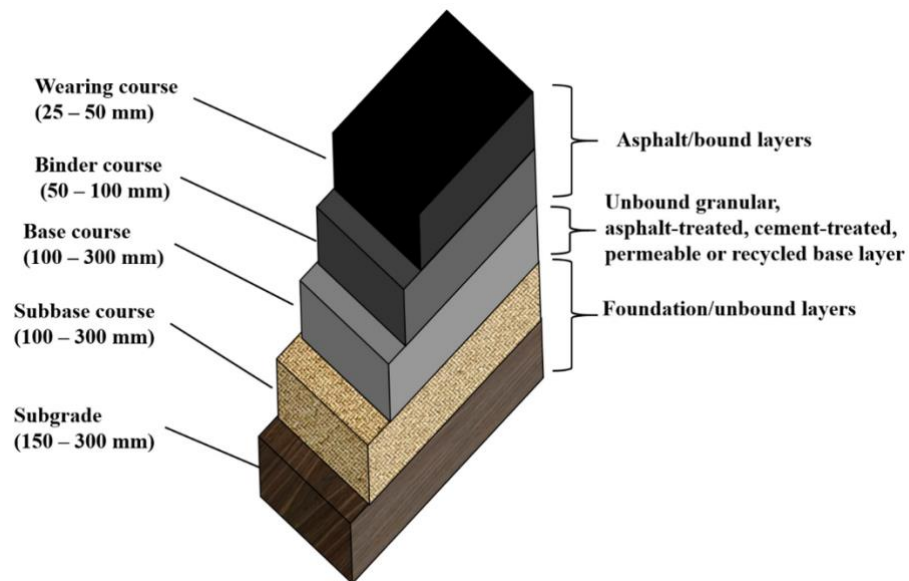


Figure 1. Various layers of typical asphalt concrete pavement (Zhang J et al 2022)

Central to the ACP design methodology is the judicious choice of materials for constructing individual layers. These materials exhibit sophisticated behaviours in response to loading, temperature, and moisture conditions variations. The functional performance of these paving constituents is intrinsically tied to their composition. To optimise the advantages of RAP, transportation agencies in numerous global regions -

such as China, Japan, South Africa, the USA, Europe, and Australia allow its incorporation across multiple ACP layers (Zhang J et al 2022).

2.2.4 Characteristics and utilisation of RAP in surface layers

The topmost layer of any road pavement, known as the surface layer, delivers a smooth, durable, and wear-resistant exterior while ensuring adequate friction for road safety. This layer is designed to withstand water-induced damages and be resilient enough to prevent rutting due to vehicular traffic. RAP's application in road pavement surfaces has gained momentum, primarily attributed to its economic and environmental advantages. RAP commonly finds its place in HMA, which combines VAs, foundational asphalt binders, and potentially a rejuvenator at centralised hot-mix facilities, resulting in a recycled asphalt mixture. Generally, the RAP percentage in surface mixes oscillates between less than 20% and over 50%, contingent on the regulatory guidelines of the concerned nation or agency (Milad et al 2020).

While RAP offers notable economic and environmental dividends in China, its surface course adoption still needs improvement. Research led by Nie (2012) attempted to measure the performance of asphalt mixes, focusing on aspects like fatigue resistance, moisture sensitivity, and temperature-related stability. Despite most RAP mixes meeting set criteria, 30% needed to improve in moisture and low-temperature crack resistance. This research emerged from a Chinese project exploring varying RAP concentrations (0%, 10%, 20%, and 30%) in surface mixes, concluding that a 20% RAP content optimises performance (Nie Y 2012).

By 2013, Japan had already showcased a practical RAP recycling framework, achieving a staggering 99% RAP reuse within two years. Predominantly, a nominal RAP volume was channelled to the base layer, while the bulk found integration into the new HMA-WMA mix, averaging around 47% RAP by weight (West et al 2015). Contrastingly, South Africa permits up to 40% RAP in ACP surface layers, while jurisdictions like Victoria, New South Wales, Tasmania, and New Zealand permit a minimum of 15% RAP content. However, this cap can be expanded if contractors illustrate the application of cutting-edge plant technology alongside stringent quality control mechanisms. Conversely, regions like Queensland, South Australia, and Western Australia do not sanction RAP usage for road surfaces (Tarsi et al 2020).

In the USA, guidelines advocate for a 30% RAP cap, ascertaining the superior structural and functional efficacy of asphalt surface composites. The FHWA designates mixes with RAP content exceeding 25% of the total weight as high-RAP-content mixes. Yet, due to perceived challenges, agencies must demonstrate more support in leveraging high RAP contents for ACP surface layers (Kowalski et al 2010). Although integrating minimal aged RAP binder amounts into fresh HMA enhances the mix stiffness, it may increase potential cracking issues (Al-Qadi et al 2012). Regardless, high RAP usage in the surface layer presents undeniable advantages, including enhanced rutting resistance, resistance to water-induced damages, and fiscal and environmental benefits (Mogawer et al 2012).

Studies suggest that judicious alterations can amplify RAP's application in ACP surface layers without compromising their integrity (Al-Saffar et al 2021 to Zhao et al 2020). Strategies encompassing the deployment of soft binders, rejuvenators or softening agents and employing WMA additives have been cited as effective. Softening agents predominantly diminish the viscosity of the seasoned binder. At the same time, rejuvenators recalibrate the chemical composition of the aged binder, compensating for the depletion of its lightweight molecular fraction during its lifecycle. Selection of these additives necessitates meticulous consideration, underpinned by comprehensive binder and mixture examinations (Al-Saffar et al 2021).

2.2.5 Insights into RAP in base and sub-base layers

Standard base layers in any road pavement can be categorised as unbound granular, asphalt-treated, cement-treated, permeable, and recycled. The sub-base, positioned beneath the base course layer and atop the subgrade, is crucial for distributing the load across the subgrade. Its incorporation is generally limited to scenarios with heavy traffic or notably weak subgrades (Su et al 2017).

While most research spotlighting RAP in asphalt pavements predominantly concentrates on asphalt layers, the potential of RAP in unbound layers, specifically base and sub-base, must be considered. Given the base layer's substantial thickness compared to the asphalt layer, it offers a greater capacity for recycled material consumption, thereby aiding in reducing RAP stockpiles. On the economic front, integrating RAP aggregates into base and sub-base layers as a substitute for virgin aggregates can culminate in material cost reductions of around 30% (Hoppe et al 2015).

Beyond economic and environmental benefits, RAP's presence significantly affects unbound layers' structural dynamics and performance. The modulus of elasticity, a pivotal metric in the MEPDG, indicates resistance against permanent deformation. Standard unbound aggregates typically exhibit an elasticity modulus ranging from 125 MPa to 300 MPa (Arulrajah et al 2011). Prior investigations underscore that RAP aggregates often surpass traditional unbound aggregates in terms of modulus of elasticity, translating to enhanced resistance against rutting. This alteration in the mechanical properties of unbound layers is intrinsically linked to the RAP volume in the mixture (Wen et al. 2010). When deployed as an unbound aggregate, some studies suggest that pure RAP (100%) diminishes strength and increases susceptibility to permanent deformation of the unbound base (Thakur et al 2012). Contrarily, findings from Plati and Cliati (2018) indicate that 100% RAP and a 50% RAP/50% VA combination mirrored modulus of elasticity results typically associated with VA, especially under intensified compaction pressures. There's a consensus in the literature that integrating RAP with VA results in decreased dry density, reduced bearing capacity gauged through the CBR, and increased modulus of elasticity. Nonetheless, a prevalent quandary persists regarding the optimal approach to harness substantial RAP quantities in base layers without compromising their mechanical integrity (Singh et al 2020).

Evidence suggests that employing stabilised granular materials can accommodate higher RAP volumes. Techniques encompassing mechanical stabilisation (like compaction and geotextiles), chemical stabilisation, and cementitious stabilisation (spanning hydraulic, zeolite, and asphalt cement methods) emerge as potential pathways, depending on RAP characteristics and desired end-use requirements (Chhabra et al 2021).

2.2.6 RAP effects on pavement properties

Research findings highlight a potential need for more base layer formation when relying solely on RAP (Bleakley and Cosentino 2013). Consequently, researchers have delved into evaluating the integration of RAP with other supplements, emphasising geotechnical properties like CBR, UCS, and MDD (Al-Saffar et al 2021 to Zhao et al 2020). These characteristics are meticulously examined in subsequent sections. RAP's properties, given its application, can be bifurcated into two distinct categories. One category zeroes in on attributes that bolster RAP's efficacy in flexible pavement (surface

layer) applications, while the other centres around the assessment of RAP as materials for the sub-base/base layers (Singh et al 2020).

2.2.7 Understanding the UCS in Aggregates

The unconfined compression tests are utilised in labs to determine the compressive strength, or UCS, of aggregates deployed in road pavement. Defined as the peak axial stress a sample can bear without lateral confinement, the UCS remains a critical mechanical property of aggregates, providing insights into the pavement's stability against diverse loads. Many researchers have opted for UCS tests to measure pavement shear strength. Due to its incompatibility, Pure RAP necessitates a binder for effective UCS testing (Vidal et al 2013). Studies indicate that enhancing the UCS of 100% RAP can be achieved by stabilising it with additives like cement and FA (Behiry et al 2013, Chhabra et al 2021, Hoyos et al 2011, and Taha et al 2002).

When FA content increases, the UCS of the mixtures tends to improve, possibly due to enhanced bonding amidst the aggregates. This enhancement can be attributed to the increased specific surface area of the FA, resulting in higher water absorption. Two distinct methodologies were explored: the direct addition of FA and the replacement of FA by aggregate weight. The replacement technique revealed that with an increase in FA content up to 30%, UCS values enhanced, after which there was a decline.

Conversely, the additive approach exhibited a consistent rise in UCS values with increasing FA, and UCS values also exhibited growth with the curing time under both methodologies. An increase in UCS was observed with an increase in VA content due to its superior integration with RAP (Saride 2015).

FA's inclusion considerably enhanced the UCS in 100% RAP-FA combinations (Saride et al 2016). The QDTMR suggested caution, advocating against exceeding 20% RAP in RCA. A triad of experiments examined the influence of temperature-sensitive asphalt substances on combined specimens. A consistent decline in UCS and OMC was observed with incremental RAP content from 0 to 20% in RCA (Jayakody et al 2019). Large volumes of RAP, combined with VA enriched with calcium-rich FA in the base or sub-base of flexible pavement, yielded promising results. After undergoing activation with NaOH for around 28 days, almost all combinations met the mandated pavement strength, aligning with the IRC: 37–2012 criteria. An increase in UCS was reported for

80 RAP/20 VA combinations activated with 4% FA, a consequence of the suspension of the non-reactive silica present in FA (Saride et al 2015).

Compared to demolition waste, the observed UCS values in RAP FA combinations were considerably higher due to the RAP's varied quality and exposed surface (Mohammadinia et al 2016). Additionally, with an increment in FA content by up to 40%, MDD and UCS improved (Saride et al 2016). By substituting 100% VAs with a mixture of RAP and cement in a 3/5 ratio, an economical solution may emerge with 7% cement (Taha et al 2002). Encasing RAP with a geocell enhances its strength and modulus, enabling it to withstand static and dynamic loads. An increase in stabilising agent volume and extending the curing period saw an enhancement in the UCS of RAP combinations (Thakur and Han 2015). The addition of cement led to a rise in the UCS of treated RAP (Hoyos et al 2011).

2.2.8 Durability of Stabilized RAP Mixes in Pavement

Durability in the context of pavement refers to its enduring capacity to deliver its designated performance over its lifespan consistently (Lu et al 2009). There's a pronounced emphasis on evaluating the durability of RAP mixes that have been stabilised, more so when the mixture has a high RAP composition. Understanding this durability aspect can substantially decrease the pavement's maintenance expenditure. A compaction examination was instituted to determine the OMC and the MDD of varied RAP-mixture samples. Various mixtures, comprising RAP and VA ratios of 80:20 and 60:40, were amalgamated with 20% and 30% FA and activated with 2% and 4% NaOH solutions (Deepti et al 2015, Saride 2015).

Several tests are executed on different combinations during chosen cycles, including wet and dry cycles and leachate analyses, to discern their long-term durability. Equating the number of cycles to real-world seasonal fluctuations, these tests simulate the stabiliser's expected performance years post the stabilisation phase. As per durability research on RAP mixture, a 60% RAP, 40% RAP, and 2% cement concoction exhibited the most stable outcomes relative to other mix variants. Minor changes in volumetric strain post-specific wet-dry cycles were detected across all RAP mixture. Considering their negligible strength erosion during leaching, all RAP concoctions were recommended with chemical treatments for the pavement's base course (Puppala et al 2017). Even without chemical stabilisers, RAP/limestone composites can likely satisfy

base layers' strength and creep requisites (Athanasopoulou 2014). Chemical stabilisers, when coupled with up to 50% RAP, can bestow the necessary strength and creep performance. The mixture design technique's results can guide in determining the suitable quantity and mixture of chemical amending substances to meet performance prerequisites. CM and RAP combinations up to a weight proportion of 20% exhibited no marked distinction in thermal endurance due to enhanced uniformity. CMs demonstrated superior resistance when juxtaposed with other mixture. The juxtaposition of a bitumen layer and enhanced RAP content results in a weakened bond between the cement adhesive and the inherent compound, potentially impacting the mechanical properties (Jayakody et al 2019).

2.2.9 CBR and Its Significance in RAP-based Pavements

The CBR is a pivotal specification that elucidates the load-bearing capacity of pavements during traffic loading, and it plays an instrumental role in determining pavement thickness (Thakur and Han 2015). The outcomes of CBR tests offer a predictive assessment of a compacting material's durability and mechanical attributes. Surprisingly, 100% RAP fails to meet the desired quality for base courses, thus indicating that its standalone application might need to be more suitable. An intriguing observation is that the CBR values tend to fall short of the expected benchmark as the RAP composition augments. It is, therefore, proposed to cap RAP content at 25% and encourage its amalgamation with VA (McGarrah 2007).

One potential reason for diminished strength is incorporating a bituminous binder exhibiting lower viscosity. This could instigate increased deformation of the asphalt binder enveloping individual aggregate particles, especially during warmer months and under vehicular load pressures. Nevertheless, the influence of RAP content on strength can be influenced by multifarious factors, including the RAP's asphalt content volume, the intrinsic angle of the base aggregate, and the grading specifics of the recycled mixture (Cooley 2005). Remarkably, an increase in RAP mixture from 0% to 25% and then from 50% to 75% corresponded to a drop in CBR values by 50-75%. The gradation metrics and aggregate dimension predominantly impact RAP's strength. Hence, to optimise the base layer's strength in pavements, it's essential to integrate RAP aggregate judiciously with alternative mediums, notably Portland cement (Maher 2005).

Empirical evaluations concerning the load-bearing potential of untreated RAP combined with cement concentrations of 1%, 2%, and 3% have been documented. Scrutiny across multiple lab-scale studies consistently revealed a trend where CBR values increase with an increase in VA proportion. At the same time, a simultaneous increment in RAP content led to a downturn in the CBR values (Taha et al 1999). Aligning with FDOT's criteria for base courses, LBR benchmarks ought to consistently surpass values of 100 for stabilised subgrades and 40. Interestingly, implementing 100% RAP returned LBR values below 100 points. However, a compelling insight was that mixing lime rock with RAP ameliorated both LBR strength and its resistance to deformation. Specifically, combinations of 50% RAP and 50% lime rock, with no stabilising agents, attained soaked LBR values greater than 40. Concurrently, mixtures with 25% RAP and 75% lime rock, without any stabilising additive, approached LBR values closely, touching the 100 points. An essential takeaway is that LBR strength is intricately tied to the duration of curing and the effects of the hydration procedure (Bleakley and Cosentino 2013).

Research into advanced road pavement methodologies reveals intriguing possibilities when combining RAP with RCAs (Seferoğlu et al 2018). Upon juxtaposing these composite outcomes with standards delineated by the Queensland Department of Transport and Highways, scholars recommend a considerable inclusion of RAP, approximately 20%, within the pavement layers. Delving into the merits of crushed clay bricks amalgamated with RCA, the composite showcased a commendable strength profile, marking its aptness as a credible unbound sub-base constituent (Poon and Chan 2006). Enhancing the synergistic mixture of RCA and LSA fosters superior mechanical properties, suggesting its suitability for integration into the foundational layers of paved roadways (Behiry 2013).

Interestingly, a trend emerges where augmenting the RCA concentration in the mixtures while curtailing the RAP percentage increases the CBR values. This implies a quality advantage of RCA over its RAP counterpart. In laboratory and field assessments, optimised CBR values hovering around 78% were attained for composite combinations harbouring a maximum of 15% RAP (Arulrajah et al 2014). An intriguing mechanical behaviour was observed: increased RAP proportions led to decreased CBR values. This is likely attributed to the bitumen-adorned aggregates' propensity to slide against each

other under applied loads. Nonetheless, a balanced 50/50 concoction of RAP and RCA yielded commendable pavement performance metrics (Ayan et al 2014).

Navigating heavy-traffic roadways, a merger of up to 15% RAP with RCA emerges as a viable formula, while a 20% mixture stands out for sub-base applications. An innovative approach to bolster RAP's inherent strength involved its amalgamation with CSAs, with subsequent stabilisation using varying cement concentrations. A concoction of 75% RAP combined with 25% CS, when stabilised with 3% cement, showcased enhanced strength metrics when set side-by-side with a 100% RAP mixture. Further cement stabilisation at 2% for a 50% RAP and 50% CS composite accentuated its CBR values, surpassing the performance of an exclusive RAP mix. Consequently, the research delineates an optimal aggregate replacement blueprint: 75% RAP fortification with 3% cement, ensuring a robust performance matrix for road pavements (Saha and Mandal 2017).

RAP combined with FA manifests exceptional efficacy for dynamic vehicle loads, particularly in the foundational base layer of pavements. An approximate 35% increase in CBR is witnessed when FA volume intensifies from 10% to 40% (Saride et al 2010). This FA-infused RAP consistently outperforms RAP in isolation, registering markedly superior CBR values. This amplified strength can arguably be attributed to the diminutive FA particles occupying voids amid composite constituents, thereby increasing penetration resistance. Enhancing RAP's intrinsic properties by pairing it with VA, subjecting it to chemical treatment using cement and FA, or adopting a closed geocell approach enriches its strength. It bolsters its resilience against both creep and lasting deformations. Existing research data furnishes predictions on the performance of chemically stabilised RAP, predominantly based on CBR examinations (Thakur and Han 2015).

GSA, a milled by-product from nut processing, has been spotlighted for its potential to enhance RAP properties. Given the structural characteristics, like particle distribution range, neither 100% GSA nor 100% RAP could achieve optimal grading. However, a fusion of RAP and GSA paves the way for enhanced grading, thanks to the synergetic interplay between the RAP and GSA granules (Edeh et al 2013). To attain high CBR scores, fortifying RAP with apt additives is imperative (Saha and Mandal 2017).

2.3 Role of FA in Construction

FA has increasingly been spotlighted in construction, specifically pavement engineering. Historically used as supplemental material, its integration with RAP has been instrumental in addressing dynamic vehicle loads, particularly in the foundational layers of pavements. FA's utility is often viewed through volume incorporation, with observations suggesting a distinct increase in CBR by approximately 35% as FA volume scales from 10% to 40%. This increase is attributed to the infilling action of small FA particles within voids present amid composite materials, resulting in enhanced resistance to penetration. FA has also been mixture with RAP, demonstrating pronounced enhancements in penetration resistance and overall strength (Saride et al 2010).

The infusion of FA has demonstrated transformative benefits, especially when juxtaposed with RAP in isolation. The FA-based RAP matrix consistently exhibits superior CBR metrics, underscoring the inherent strength of the combined material. Furthermore, the amalgamation of RAP and FA has showcased a propensity to sustain dynamic vehicular loads, particularly crucial for the base layers of pavements. Additionally, when assessed against the standalone RAP, the FA-centric RAP mixture consistently delivers elevated CBR benchmarks, epitomising its superior load-bearing capabilities (Athanasopoulou A 2014, Hoy et al 2016, Mohammadinia et al 2016, Saride et al 2015 and Saride et al 2016).

While FA's incorporation has revolutionised RAP mixture, challenges persist. An elevated FA content could cause an exponential rise in the filler quantity within the mix. This can be attributed to FA's finer constitution, which possesses an expansive specific surface area, leading to augmented water absorption. Furthermore, while FA in tandem with RAP has manifested exceptional CBR scores, an over-reliance on FA could potentially diminish these scores due to the enhanced bituminous binder's reduced viscosity, which might foster aggregate sliding under vehicular load pressures (Cooley 2005).

2.4 Role of Cement Stabilizer in Pavement Sub-bases

The role of cement as a stabilising agent in sub-bases and its integration into pavement sub-bases has undergone significant evolution, proving essential in enhancing pavements' overall performance and durability. Historically, cement has been

recognised for its unrivalled binding properties, serving as the keystone in various construction methodologies. In the context of pavements, cement has traditionally been utilised as a stabiliser, especially when there's a need to enhance the properties of materials such as RAP. By mixing RAP with VA and introducing cement as a stabilising agent, there has been a notable increase in the strength of the pavement sub-bases. When subjected to optimal proportions, this mixture has consistently yielded superior CBR values, pivotal in gauging a pavement's resilience against dynamic loads (Saha and Mandal 2017).

When RAP is amalgamated with cement in strategic proportions, there's an enhancement in the sub-base's load-bearing capacity. For instance, a mixture of 75% RAP and 25% CS, when stabilised with a 3% cement concentration, yielded heightened strength, surpassing that of a 100% RAP mix. Furthermore, the CBR values of such cement-stabilized mixes underscore the importance of cement, as the observed values were considerably higher than mixes devoid of cement stabilisation (Saha and Mandal 2017). Moreover, cement's importance is further accentuated when addressing the inherent weaknesses of RAP. By introducing cement, potential deformities caused by bituminous binders with reduced viscosity can be effectively countered, preventing aggregate slippage under vehicular loads. Cement's binding properties also ensure a cohesive and robust matrix, reducing vulnerabilities to environmental and load-induced stresses (Cooley 2005).

2.5 Combined Usage of RAP, FA, and Cement in Pavement Construction

The combination of RAP, FA, and Cement in pavement construction has gained increasing attention in recent years. As sustainability becomes integral to modern engineering practices, the amalgamation of these materials presents a compelling narrative, offering economic, environmental, and technical advantages. Modern pavement engineering trends indicate a shift towards utilising RAP with supplementary materials like FA and cement, particularly in the base and sub-base layers of the pavement (Saride et al 2010). RAP, being a recycled material, complements the pozzolanic properties of FA, and when stabilised with cement, a superior-quality aggregate emerges. The CBR values, a pivotal metric in evaluating bearing capacity, have increased by approximately 35% as FA content increased from 10% to 40% (Saride et al 2010).

RAP-FA compounds have showcased remarkable efficacy, especially when subjected to dynamic vehicular loads. Including FA in the RAP mix elevates the CBR and bestows superior strength, surpassing RAP alone. This enhancement is attributed to the filling of voids between composite particles by the finer FA particles, providing increased resistance to penetration. Furthermore, the addition of cement into this mix acts as a pivotal binder, consolidating the benefits of both RAP and FA (Saha and Mandal 2017).

While the merits are significant, the combined usage has its challenges. As RAP content increases in the mixture, CBR values, indicative of load-bearing capacity, tend to decline (Thakur and Han 2015). The bituminous binder in RAP, characterised by lower viscosity, can lead to more significant deformation, especially during warmer months and under continuous traffic loads. Addressing this requires meticulous proportioning of FA and cement to ensure that the intended mechanical properties are achieved without compromising durability (Edeh et al 2013).

2.6 Gaps in Literature

Integrating RAP, FA, and cement in the construction of pavement sub-bases is a developing area of research. However, a careful review of the existing literature indicates some evident gaps that need to be addressed:

1. **Geographical Specificity:** While the application and outcomes of RAP and FA combinations have been explored in various global contexts, region-specific data, especially of Indian subcontinental conditions, remains scant (Saride et al 2010). This gap becomes pertinent given India's unique climate variations, traffic loads, and road construction standards.
2. **Optimal Composition and Strength Balance:** While the literature offers insights into the performance of certain RAP-FA combinations, there needs to be more information on an optimal mixture that assures the right balance of strength, durability, and stability (Thakur and Han 2015). Determining the ideal proportion of RAP, FA, and cement that aligns with road construction standards while ensuring longevity is an area that demands further scrutiny.
3. **Practical Applicability and Scalability:** Transitioning from laboratory-based studies to real-world applications remains challenging. While laboratory findings like CBR values offer promising insights (Edeh et al 2013), the

feasibility of scaling these combinations for broader applications in varying construction scenarios is under-researched.

Given these gaps, this research aims and objectives are well-aligned to address pertinent issues. By focusing on the suitability, strength balance, and practical applicability of RAP-FA-cement combinations, this research endeavours to bridge crucial gaps, significantly contributing to the existing body of knowledge. The emphasis on standard IS 2720 tests, coupled with expert consultations, positions this research at the confluence of academic rigour and real-world relevance, paving the way for sustainable and innovative advancements in pavement construction.

2.7 Assimilation and Understanding

Civil engineering, particularly road construction, has long been recognised for its innovative amalgamation of sustainable materials. RAP, FA, and cement have garnered attention in past studies, albeit with specific identified gaps in comprehension (Saride et al 2010; Thakur and Han 2015).

Existing literature acknowledges the potential of RAP, FA, and cement in constructing pavement sub-bases. However, the nuanced understanding of their combined use, especially in specific geographical contexts such as India, must be more cohesive (Saride et al 2010). The present research endeavours to bridge this gap by determining the suitability of RAP and FA combinations aligned with India's unique climatic and infrastructural conditions. This region-specific focus is a notable contribution, given that materials' performance can vary widely based on environmental factors.

A pivotal area the current study seeks to elucidate is the optimal combination of materials that ensures a harmonious balance of strength, stability, and durability. While certain RAP-FA combinations have been explored, comprehensive research pinpointing the ideal proportion, especially when supplemented with a 3% cement stabiliser, remains scant (Thakur and Han 2015). Addressing this, the research aims to systematically assess the strength, stability, and durability of various mixture, employing standard IS 2720 tests to provide robust, empirical findings. Such systematic evaluations offer insights to guide construction practices, ensuring longevity and cost efficiency.

Study designed by considering the directions of the expert interviews and laboratory evaluations, the research further seeks to enhance real-world applicability by

incorporating expert consultations. The aim here is to validate laboratory findings with pragmatic insights, thereby ensuring the solutions derived are theoretically sound and practically implementable. Finally, with the looming importance of sustainable practices, the amalgamation of RAP, FA, and cement signifies a step towards environmentally conscious construction. By delving into the optimal use of these materials, the present research underscores the commitment to eco-friendly practices without compromising structural integrity.

Chapter 3:

Methodology

3.1 Introduction

The core of any scholarly research is an intricately devised and justified methodology. A well-structured methodology is the backbone, providing a logical sequence to the study and ensuring the results' accuracy and reliability. The essence of such a structure is to lend credibility to the research process, establishing a transparent and replicable framework. This allows researchers to gauge the study's depth, breadth, and thoroughness. Secondly, an explicitly detailed methodology equips other researchers with the tools to replicate or build upon the study, thereby promoting further research in the field. In the context of this dissertation, which examines the potential benefits of employing RAP coupled with FA in pavement sub-base construction, detailing the methodology aids in validating the research's claims and recommendations. It is a testament to the study's thoroughness, emphasising its significance and relevance in sustainable road construction.

This chapter delves into the systematic approach adopted throughout this research. It outlines the techniques employed for the literature search, underscores the rationale behind data requirements, delineates the data collection methods, and sheds light on the analytics involved in interpreting the findings. Furthermore, the chapter delves into the questionnaire format and concludes with a reflective review of the adopted methodology.

3.2 Literature search technique

The chosen literature search technique has been systematic and exhaustive, ensuring that all relevant material related to the study's scope has been assessed. Various databases and journals were accessed to procure the material essential for Chapter 2. Renowned databases like Google Scholar and ScienceDirect were indispensable sources, offering many articles, papers, and studies on using RAP, FA, and their applications in road construction. Alongside these databases, specialised journals focusing on civil engineering, sustainable construction, and environmental conservation provided insights into recent advancements and methodologies.

Furthermore, invaluable contributions were obtained through direct consultations with two eminent professionals in Andhra Pradesh, India. Their expertise in sustainable road

construction augmented the quality of this research. One of the experts shared a detailed project report on FDR, while the other contributed a comprehensive report on HIPR technology. These reports enriched the literature review from their hands-on experience, providing pragmatic insights into the field application of the technologies, their advantages, challenges, and potential adaptations.

Conclusively, the secondary sources employed for Chapter 2 were a mixture of peer-reviewed articles, institutional publications, and real-world project reports. This amalgamation enabled a balanced view, combining theoretical postulates with practical applications, thereby ensuring a comprehensive, well-rounded literature review. The endeavour was not just to grasp the existing knowledge but to identify gaps, laying the groundwork for this research's unique contributions to sustainable road construction.

3.3 Questionnaire/Interview format

A meticulous approach to formulating the interview questionnaire ensures gathering relevant and actionable insights. The process underpinning the development of the questionnaire for the research aimed to delve deep into the professional's experience, perspectives, and insights on sustainable road construction methodologies and the use of recycled materials.

Discussion of Key Elements:

1. **Question Content and Data Required:** The content of the questions pivots around the professional's experience, understanding, and practical application of sustainable road construction methodologies. This approach captures the respondent's expertise and garners specific insights into real-world applications and challenges.
2. **Format of the Questionnaire:** The questionnaire starts with an introduction section that profiles the respondent's professional background. Following this, more in-depth questions probe into the specifics of sustainable construction, focusing on recycled materials' feasibility, practicality, and benefits.
3. **Phrasing of the Questions:** The questions are clear, concise, and open-ended. This allows respondents to provide detailed answers and elaborate on their experiences and insights. Straightforward language ensures that respondents comprehend the questions without ambiguity.

4. **Response Formats:** Given the nature of the questions, the response format is predominantly descriptive. This permits professionals to share their insights, experiences, and recommendations in detail.
5. **Data Collection Method:** The primary mode for data collection is through direct interviews, which allow one to delve deeper into specific topics and clarify doubts in real time.
6. **Data Analysis Technique:** Interview responses are subject to qualitative analysis. By synthesising the insights, patterns, and commonalities across responses, meaningful conclusions can be drawn, subsequently informing the research's findings.

Justification for Question Selection and Phrasing:

- **Professional Experience and Role:** Gauging the respondent's depth of experience sets the context for subsequent answers. The questions in this section ensure that insights are rooted in real-world experience and expertise.
- **Feasibility and Reusability:** Questions targeting the feasibility of constructing pavements out of recycled materials and the potential for reusing materials address the core objectives of the research.
- **Alternative Materials:** Seeking insights on potential alternative materials widens the scope of understanding and captures innovations in sustainable construction.
- **Environmental and Economic Benefits:** These questions underline the dual objectives of the research, probing into both ecological and fiscal advantages of sustainable construction.
- **Quality and Safety Standards:** Ensuring that recycled materials adhere to industry benchmarks is pivotal. This question captures the professional's perspective on maintaining these standards.
- **Success Stories and Challenges:** Real-world instances of successful projects provide tangible evidence of the benefits and challenges of sustainable construction.
- **Stakeholder Collaboration:** This question identifies how industry professionals collaborate to promote sustainable practices.

- Technological Innovations: Understanding the role of technology in promoting sustainability aligns with the research's emphasis on modern, innovative practices.

By meticulously structuring and phrasing the interview questionnaire, the research effectively captures comprehensive insights, shaping the study's direction and enriching its conclusions through triangulation.

3.4 Data requirement discussion

Before beginning the laboratory evaluations of the proposed combinations of RAP, FA, and cement, interviews with professionals ensured the right material selections for targeted sub-base pavement construction. In scholarly experimentations related to construction materials and their potential application, one of the main concerns is the reliability and standardisation of the evaluation methods. Ensuring that the assessment tools resonate with globally accepted benchmarks is pivotal.

The IS (Indian Standard) tests, specifically Compaction Test (IS 2720-8 (1983)), CBR Test (IS 2720-16 (1987)), and UCS Test (IS 2720-10 (1991)), were selected for several compelling reasons. These tests, governed by the Bureau of Indian Standards, are well-acknowledged and have been the mainstay in the Indian construction domain. Their relevance and applicability, especially for materials intended for pavement sub-base applications, have been well-documented over decades. The decision to employ these tests was steered by their widespread acceptance, which would bolster the credibility and universality of the research findings.

Furthermore, this research aimed to measure the effectiveness of combining RAP, FA, and a 3% cement stabiliser in pavement sub-base constructions. This required a careful selection of combinations encompassing various proportions of the critical materials, leading to the formulation of the specific T1 to T6 combinations. These combinations were curated to encapsulate the complete spectrum of potential mixes, from a fully RAP-centric mixture to an even distribution of RAP and FA.

Research Questions: The study aimed to determine:

- The viability of RAP and FA combinations in pavement sub-base constructions.
- The optimal material mixture that balances strength, stability, and longevity.

- The practicality of these combinations as functional pavement sub-base materials.

Data Nature: The research predominantly centred on quantitative data. The rationale was the study's objective nature, which required empirical data (like strength values and stability metrics) to draw conclusive inferences about the material combinations.

Ultimately, the methodological rigour in data requirement and subsequent analysis has been directed by the dual aims of scientific accuracy and practical applicability, ensuring that the findings hold value in theoretical and real-world realms.

3.5 Data collection methods

Given the nature of the research's objectives, the data collection relied heavily on laboratory-based tests. While there are various methods for data collection in pavement research, this study's requirements necessitated specific testing methodologies, predominantly rooted in standard IS tests.

The following are the potential methods for data collection:

Observing the real-time behaviour of materials under natural conditions. Evaluating the performance of materials on actual roads or pavements. Controlled environment testing, following standardised procedures.

Advantages and disadvantages of selected and non-selected methods:

Laboratory Evaluations (Selected Method):

Laboratory experiments ensure controlled environmental conditions, promoting consistency and repeatability. By following standardised procedures, the credibility and reliability of these results are enhanced. These settings enable researchers to isolate specific variables, thus providing a more thorough and precise analysis. However, it's essential to note that lab conditions may only sometimes mirror the complexities of real-world situations. Real-world conditions can vary widely due to unpredictable environmental factors or unique on-ground challenges that might not be replicated in a laboratory setting. Moreover, the scope of laboratory experiments is often constrained by the equipment available and the specific test conditions, which may only encompass some potential scenarios.

Field Observation (Not chosen):

Studying material combinations in real-world settings provides invaluable insights into their behaviour and responses to genuine environmental and load conditions. Such observations can paint a more accurate picture of how materials function in practical scenarios, accounting for all the intricacies and unpredictabilities of the real world. However, while providing a realistic view, these external factors can introduce variability, making results inconsistent. This complexity often makes it challenging to isolate and analyse the specific variables affecting performance, which can be crucial for in-depth understanding and further improvements. Thus, while real-world observations are vital, they come with their challenges that researchers must account for.

Field Testing (Not chosen)

Evaluating materials directly under real-world conditions offers practical insights that can be pivotal for understanding their proper performance. Such evaluations can unearth unforeseen challenges that might remain hidden under the controlled environment of a laboratory. For instance, a material might behave differently on a busy street than in a lab due to factors like vehicular load or pedestrian traffic. However, carrying out these evaluations comes with its own set of challenges. Finding an appropriate location can be a task, and the testing itself might disrupt regular traffic or road usage, leading to logistical issues. Moreover, uncontrollable environmental factors, such as rainfall or temperature fluctuations, can introduce inconsistencies in the results. While real-world evaluations are indispensable, these potential hurdles need careful consideration and planning.

Considering the study's objectives and the need for precision, laboratory evaluations were deemed most appropriate. While field observations and testing could have provided practical insights, the potential inconsistencies and external influences made laboratory testing more apt for this research. The controlled environment of a laboratory ensures that the results are solely indicative of the material combinations' performance, undistorted by externalities. This methodological choice, thus, aligns with the research's intent to discern the optimal mixture for pavement sub-base applications in a systematic and standardised manner.

3.6 Data Analysis Technique

To attain coherent, actionable insights from the collected data, applying rigorous data analysis techniques is of paramount significance. Such techniques not only elucidate patterns within the data but also offer invaluable perspectives into the potential of various recycled material combinations for sustainable road construction.

Evaluation and Interpretation of Test Results:

1. **Objective Analysis:** The laboratory test results, particularly from the Compaction Test (IS 2720-8 (1983)), CBR Test (IS 2720-16 (1987)), and UCS Test (IS 2720-10 (1991)), yield quantitative data. This data ascertains the performance consistency of each material combination.
2. **Comparative Assessment:** The performance metrics of each combination, labelled T1 to T6, are juxtaposed to discern the optimal mixture. Such a comparison is pivotal to measuring the relative advantages of each mix, especially concerning strength, stability, and durability.
3. **Feedback Integration:** The insights from the professional consultations supplement the laboratory results. The combined perspective, amalgamating empirical data with professional expertise, offers a holistic view of the research's objectives.

By meticulously analysing the laboratory test results using the techniques mentioned earlier, the research captures the quantitative aspects of the material combinations and their broader implications for sustainable road construction.

3.7 Review of Adopted Methodology

In scientific research, the methodology stands as the backbone of any research. While the adopted methodology in this study was meticulously designed to yield objective and actionable insights, the process was challenging.

Challenges Faced:

1. **Diverse Sources:** The reliance on both primary consultations and secondary literature sources presented a challenge in ensuring that the data remained consistent and coherent throughout the research.

2. **Laboratory Limitations:** Certain laboratory apparatus and equipment constraints occasionally led to minor variations in test results, especially when evaluating different material combinations.
3. **Time Constraints:** The time-bound nature of laboratory tests, juxtaposed with the need for meticulous analysis, posed challenges in maintaining the desired pace of the research.
4. **Integration of Expert Consultations:** Harmonizing empirical findings with professional insights demanded additional scrutiny to prevent inconsistencies.

Potential Improvements for Future Research:

1. **Expanding the Sample Size:** In future endeavours, expanding the sample size for laboratory tests might offer even more comprehensive insights, reducing potential variances.
2. **Incorporation of Advanced Analytical Tools:** Integrating advanced statistical and analytical tools can streamline the data analysis process, rendering it more efficient.
3. **Broader Consultations:** Engaging with a more comprehensive range of professionals across different geographical regions could infuse the research with more diverse and nuanced insights.

Reliability and Validity:

The methodology adopted was tailored to ensure both reliability and validity. The strict adherence to recognised standards, such as the IS codes for laboratory tests, fortified the reliability quotient. Furthermore, combining laboratory findings with professional insights enhanced the validity, ensuring that the conclusions were grounded in empirical evidence and industry expertise. The next chapter sets out the results obtained using the methodology presented.

Chapter 4:

Results and discussions

4.1 Introduction

In this chapter, the findings derived from the laboratory experimentations are meticulously presented, analysed, and juxtaposed with the insights gleaned from expert consultations. Essential to the dissertation, this chapter bridges the connection between the methodologies described previously and the ultimate findings of the research. It elucidates the performance of various RAP, FA, and cement combinations in terms of their potential use in pavement sub-base layers. The validation of these results with expert opinions is a foundation for recommending potential real-world applications, thus emphasising the research's practical relevance and broader scope.

4.2 Laboratory results

This section provides an exhaustive representation of the empirical findings of laboratory experiments on the diverse RAP, FA, and cement combinations. The outcomes are systematically organised and discussed, anchoring them to the central research objectives at the study's inception. This meticulous arrangement facilitates a clear juxtaposition between the performance indicators of each combination. A keen focus is placed on understanding the underlying factors that brought the T4 combination to the forefront, distinguishing it as the most promising mixture for pavement sub-base applications.

4.2.1 Material combinations

An array of combinations was formulated to understand the viability and performance of RAP and FA when utilised in tandem. A constant 3% cement was used as a stabiliser for each combination. The combinations were structured to investigate the influence of varying RAP and FA proportions on the material's properties. Utilising a weight-by-weight mixing method ensured consistency across the combinations. Table 1 represents the various combinations:

Table 1. Combinations of RAP and FA, cement stabiliser in percentage

Sr. No.	RAP (%)	FA (%)	Cement (%)	Combination Code
1	100	0	3	T1
2	90	10	3	T2

3	80	20	3	T3
4	70	30	3	T4
5	60	40	3	T5
6	50	50	3	T6

Table 1 illustrates the meticulously formulated combinations of RAP and FA, each stabilised using 3% cement. T1 to T6 displays a systematic decrease in RAP content and a corresponding increase in FA content. In all combinations, the 3% cement stabiliser's presence remains constant. The cement acts as a binding agent, providing rigidity and coherence to the mixtures. Its constant presence across all combinations ensures that any observed changes in material properties can be attributed solely to the varying proportions of RAP and FA.

4.2.2 Compaction testing

The compaction test is a fundamental geotechnical laboratory test that assesses the relationship between the aggregates' moisture content and dry density under controlled compaction conditions. This test provided the materials' optimal moisture content and maximum dry density, fundamental properties for any potential pavement sub-base material. The compaction test is done by modified proctor test while considering IS 2720-8 (1983): Methods of test for soils, Part 8 [IS 2720-8 (1983)]. Table 2 details the specimen codes for the compaction tests. Every specimen corresponds to the previously discussed material combinations (T1 to T6). This ensures a comprehensive evaluation of compaction characteristics for each material mix.

Table 2. Compaction test specimen details

Sr. No.	Test	Standard	Specimen Code
1	Modified Proctor Test	IS 2720-8 (1983)	CT1
2	Modified Proctor Test	IS 2720-8 (1983)	CT2
3	Modified Proctor Test	IS 2720-8 (1983)	CT3
4	Modified Proctor Test	IS 2720-8 (1983)	CT4
5	Modified Proctor Test	IS 2720-8 (1983)	CT5
6	Modified Proctor Test	IS 2720-8 (1983)	CT6

The experiment utilised specific apparatus in line with the IS 2720-8 (1983) standards. The core equipment included a cylindrical metal mold with a 100mm diameter and a

volume of 1000cc, complemented by a detachable collar and base plate. The ramming process employed a 6kg rammer designed for a free fall of 450mm. To ensure precise measurements, a balance accurate to 0.1g was used. An oven, integral for specific tests, could consistently maintain temperatures between 105 to 110°C. Additionally, specialised mixing tools were incorporated for thoroughly mixing soil and water, while sample containers were on hand to safeguard against any potential moisture loss.



Figure 2. Compaction testing

Initially, the RAP sample was air-dried and then subjected to pulverisation to dismantle any aggregates. This material was passed through a 4.75mm sieve to ensure consistency. Specimens from T1 to T6, based on the combinations delineated in Table 1, were meticulously prepared. It was imperative to achieve a uniform mixture through rigorous mixing. These samples were then dried in an oven, set between 105°C to 110°C, for 24 hours, ensuring a moisture-free sample. Once dried, each specimen was allowed to cool before being weighed to ascertain its dry weight.

Water was then added judiciously, keeping the optimum moisture content assumed between 4 to 7%. The procedure involved affixing a detachable collar to the mold, which was filled with the specimen in five equal layers. Each of these layers received 25 blows using a rammer for adequate compaction. After the compaction, the collar was removed, the specimens were levelled to the top of the mold, and the final weight was recorded. The weight of the wet compacted specimen was ascertained by subtracting the mold's weight.

A small portion of the compacted specimen was reserved for water content determination. This process was repetitively employed for other specimen samples, each with distinct RAP and FA content ratios stabilised with 3% cement. Conclusively, a plot was constructed that contrasted the moisture content with the dry density of each respective sample. The peak of the graph represents the OMC and its corresponding MDD.

Throughout the experimentation, 2 kilograms of RAP is taken, and FA is added, utilising a weight-by-weight mixing method to ensure consistency across the combinations in Table 1. For the formed RAP+FA, 3% cement is added, utilising a weight-by-weight mixing method. Water is added to the combinations by weight ranging from 60 to 120 grams to conduct four trials (Tr1 to Tr4) for each combination (T1 to T6). The tests are repeated four times for each combination with varying water content added by weight. Initially, the dry weight (W_{dry}) is calculated before adding the water using equation (1), and the wet weight (W_{wet}) is calculated using the weighing machine. The weight of water (W_{water}) is calculated using equation (2)

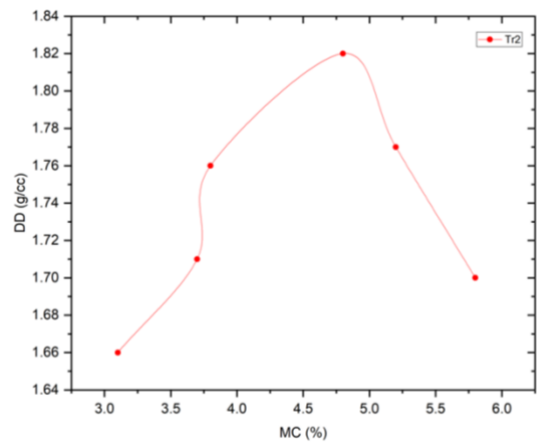
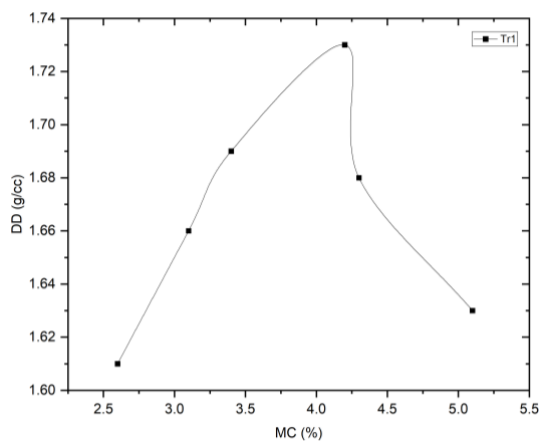
Equation (1): $RAP+FA+Cement = W_{dry}$

Equation (2): $W_{water} = W_{wet} - W_{dry}$

Now, DD and MC for the specimens are calculated using the equations:

$$\rho_d = W_{RAP} + W_{FA} + W_{cement} / \text{Mold volume}$$

$$w = W_{water} / W_{dry}$$



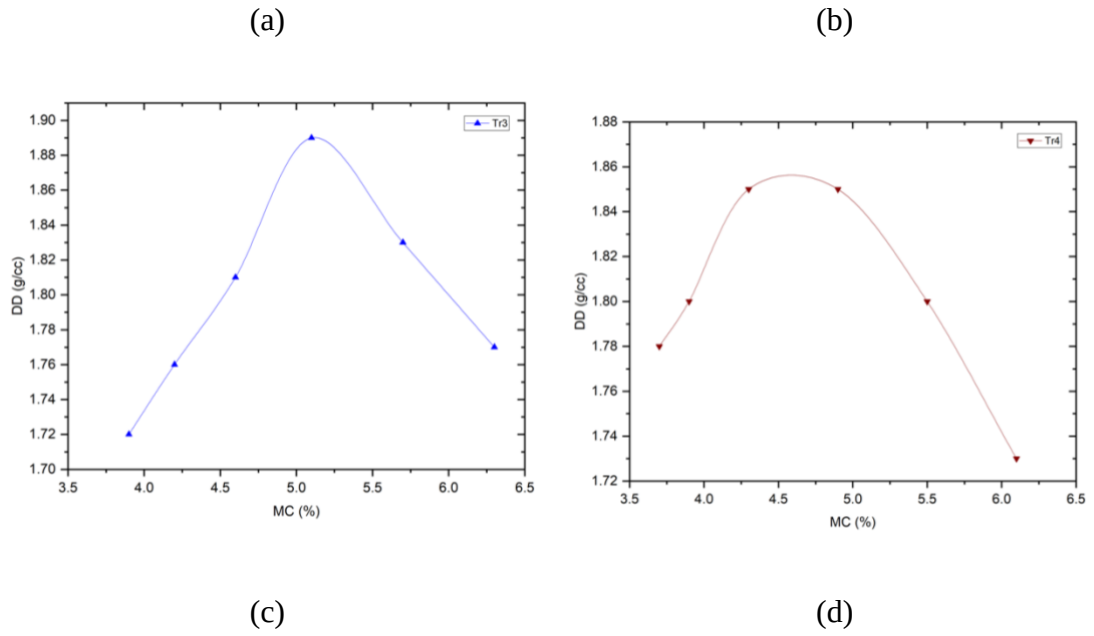


Figure 3. Compaction testing results for T1 to T6 for trails: (a) Tr1 (b) Tr2 (c) Tr3 (d) Tr4

Figure 3 and Table 3 encapsulate the results from the compaction testing of combinations T1 through T6 for four distinct trials: Tr1, Tr2, Tr3, and Tr4. These results provide a comprehensive insight into the behaviour of each combination under the Modified Proctor Compaction test, following the IS 2720 Part 8 standards.

Table 3. Compaction test results of various specimens for four trials

Combination Code	MC (%)	DD (g/cc)	MC (%)	DD (g/cc)	MC (%)	DD (g/cc)	MC (%)	DD (g/cc)
	Tr1	Tr1	Tr2	Tr2	Tr3	Tr3	Tr4	Tr4
T1	2.6	1.61	3.1	1.66	3.9	1.72	3.7	1.78
T2	3.1	1.66	3.7	1.71	4.2	1.76	3.9	1.8
T3	3.4	1.69	3.8	1.76	4.6	1.81	4.3	1.85
T4	4.2	1.73	4.8	1.82	5.1	1.89	4.9	1.85
T5	4.3	1.68	5.2	1.77	5.7	1.83	5.5	1.8
T6	5.1	1.63	5.8	1.7	6.3	1.77	6.1	1.73

The peak of the graph represents the OMC and its corresponding MDD. For the OMC and corresponding MDD, the weights are calculated for RAP, FA, Cement and water using the following equations:

The W_{Cement} in the mix is calculated using:

$$W_{\text{Cement}} = 0.03 \times W_{\text{dry}} \text{ (since 3\% cement is used throughout the study)}$$

The W_{RAP} in the mix is calculated using:

$$W_{\text{RAP}} = (\% \text{ of RAP}/100) \times W_{\text{dry}}$$

The W_{RAP} in the mix is calculated using:

$$W_{\text{FA}} = W_{\text{dry}} - W_{\text{Cement}} - W_{\text{RAP}}$$

The results of the calculations yield are tabulated in Table 4.

Table 4. Compaction test results

Specimen Code	W_{wet} (g)	W_{dry} (g)	W_{water} (g)	W_{Cement} (g)	W_{RAP} (g)	W_{FA} (g)	ρ_d (g/cc)	w (%)
CT1	1787.0 8	1720.0 0	67.08	51.60	1668.4 0	0.0	1.72	3.9
CT2	1833.9 2	1760.0 0	73.92	52.80	1584.0 0	123.2 0	1.76	4.2
CT3	1893.2 6	1810.0 0	83.26	54.30	1448.0 0	307.7 0	1.81	4.6
CT4	1986.3 9	1890.0 0	96.39	56.70	1323.0 0	510.3 0	1.89	5.1
CT5	1934.3 1	1830.0 0	104.3 1	54.90	1098.0 0	677.1 0	1.83	5.7

CT6	1881.5	1770.0	111.5	53.10	885.00	831.9		
	1	0	1			0	1.77	6.3

From Figure 4, a distinct trend emerges in the OMC. Starting from a value of 3.9% for CT1, there is a consistent increase in the OMC values, reaching up to 6.3% for CT6. Such an increasing trend suggests that as the percentage of FA in the mixture rises (as denoted from combinations T1 to T6), the OMC also sees a corresponding increment. Higher FA content requires more moisture to achieve optimal compaction. On the other hand, the MDD values showcase a more varied pattern. The values start at 1.72 g/cc for CT1 and peak at 1.89 g/cc for CT4 before dropping to 1.77 g/cc by CT6. While the MDD for CT4 is the highest, indicating maximum compaction efficiency for the combination T4 (70% RAP and 30% FA), the subsequent drop in MDD for CT5 and CT6 suggests that the compaction efficiency might be reduced beyond a certain proportion of FA.

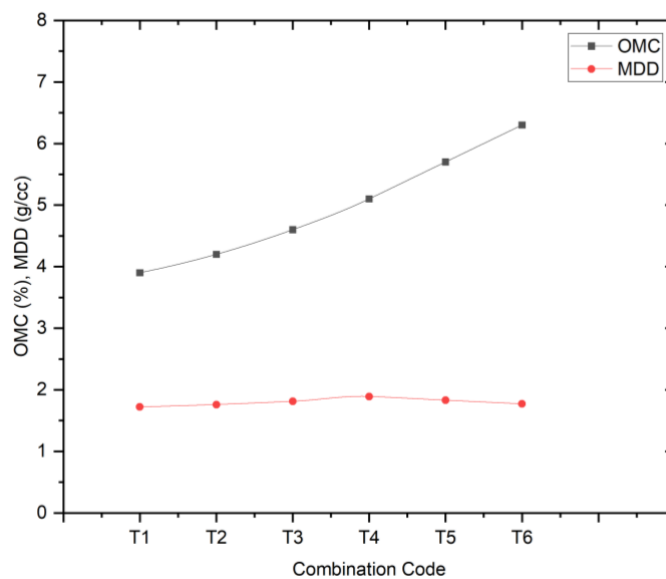


Figure 4. Compaction test results: OMC, MDD Vs Combination code

4.2.3 CBR testing

The CBR test is a laboratory test commonly used in geotechnical engineering to determine the load-bearing capacity of subgrade soils and base materials for road and pavement design. The test provides information about the strength and stiffness of the material under specific loading conditions. The CBR is done for the penetrations of 2.5

mm and 5.0 mm while considering IS 2720-16 (1987): Methods of test for soils, Part 16 (IS 2720-16 (1987)). Table 5 details the specimen codes for the CBR tests.

Table 5. CBR test specimen details

Sr. No.	Test	Standard	Specimen Code
1	CBR Test	IS 2720-16 (1987)	CBT1
2	CBR Test	IS 2720-16 (1987)	CBT2
3	CBR Test	IS 2720-16 (1987)	CBT3
4	CBR Test	IS 2720-16 (1987)	CBT4
5	CBR Test	IS 2720-16 (1987)	CBT5
6	CBR Test	IS 2720-16 (1987)	CBT6

Each specimen corresponds with the material combinations (from T1 to T6) highlighted earlier.

In line with IS 2720-16 (1987) standards, a specific set of apparatus and specifications was utilised for the evaluation process. This included a cylindrical mold measuring 150mm in diameter and 175mm in height, ensuring the right volume for specimen containment. Accompanying this was a spacer disc with a diameter of 148mm and a height of 47.7mm, facilitating the accurate positioning of the sample. For the application of the necessary surcharge, appropriately calibrated weights were used. The testing process also required a penetration plunger of 50mm diameter to assess sample resilience. All samples and materials were weighed using a balance precise up to 0.1g. A critical setup component was the loading machine, engineered to apply a consistent load at a 1.25mm/min rate, ensuring uniform pressure during testing. Finally, mixing tools such as trowels and spatulas were employed to facilitate the preparation of specimens.



Figure 5. CBR test

To evaluate the properties of various combinations, specimens were prepared following the details mentioned in Table 1. The next step involved introducing water to the mix, with the quantity aligned to the OMC derived from the Proctor Compaction Test. Once added to the water, the sample was left to soak for four days, allowing thorough moisture absorption. For compaction, the specimen sampled was methodically placed inside the mold, structured in five distinct layers. Each layer underwent compression through 56 uniform blows, administered by a 4.89kg rammer dropped from a height of 450mm. Following this, the spacer disc was removed, and any excess specimen was trimmed to align flush with the mold's top edge.

The compacted specimen was fully submerged in water to ensure saturation, permitting any potential swelling. This soaking process was maintained for a comprehensive 96-hour period. Subsequently, the mold, with the specimen intact, was positioned on the loading machine. A perforated plate with surcharge weights was placed atop the sample to ensure even load distribution. The penetration process was executed using a plunger, advancing at a consistent rate of 1.25mm/min. Throughout this phase, load values at varying penetration levels were recorded, primarily focusing on the 2.5mm and 5mm

marks. The final task entailed calculating the CBR value by correlating the recorded loads with the predetermined standard loads.

CBR (%) for the specimens are calculated using the equations:

$$\text{CBR (\%)} = \left(\frac{\text{Test Load (at a given penetration)}}{\text{Standard Load (for the same penetration)}} \right) \times 100$$

Given standard loads for penetrations:

- $F_{2.5}$ (Standard load for 2.5 mm penetration) = 1370 kg
- $F_{5.0}$ (Standard load for 5.0 mm penetration) = 2055 kg

Table 6 presents the outcomes of the CBR tests, highlighting the Soaked CBR values associated with each specimen. Correspondingly, Figure 6 visually depicts these findings through respective graphical plots.

Table 6. CBR test results

Specimen Code	Actual load for 2.5 mm penetration (kg)	Actual load for 5.0 mm penetration (kg)	CBR_{2.5} (%)	CBR_{5.0} (%)	CBR_{average} (%)
CBT1	253.45	380.175	18.5	18.5	18.5
CBT2	284.96	427.44	20.8	20.8	20.8
CBT3	330.17	495.255	24.1	24.1	24.1
CBT4	497.31	745.965	36.3	36.3	36.3
CBT5	383.6	575.4	28.0	28.0	28.0
CBT6	300.03	450.045	21.9	21.9	21.9

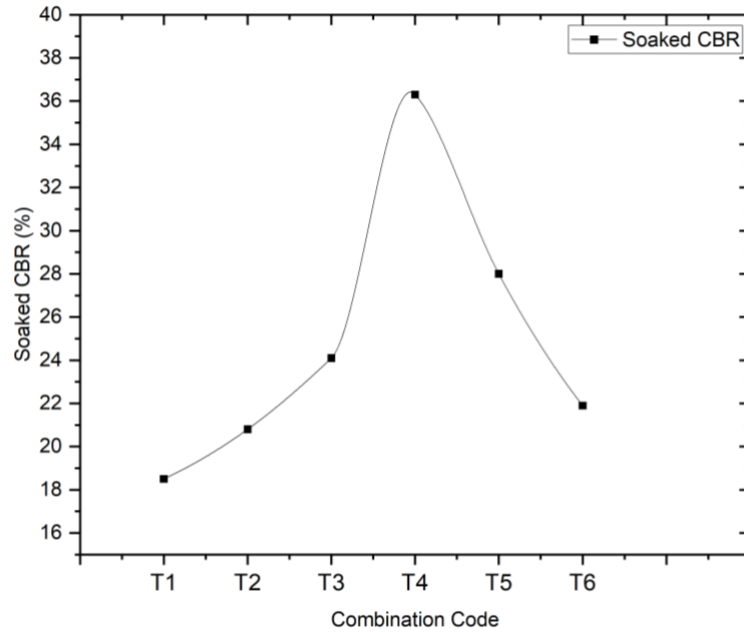


Figure 6. CBR test results

The CBR values denote a material's strength and potential bearing capacity compared to a standard crushed rock. Typically, a higher CBR value indicates better load-bearing capacity. Figure 6 shows a clear progression in the Soaked CBR values from CBT1 to CBT4, with values incrementing from 18.5% to a peak of 36.3%. This suggests that, up to combination T4 (comprising 70% RAP and 30% FA), there's a consistent improvement in the bearing capacity. This could be attributed to an ideal synergy between the components, culminating in an optimal mixture in T4. However, a shift is noticed in the CBR values for CBT5 and CBT6, which register at 28.0% and 21.9% respectively. The drop in these values indicates that beyond a specific proportion of FA, the strength and bearing capacity of the mixture might be compromised. While still showing an enhancement from the baseline CBT1, these values reinforce the importance of an optimal RAP and FA balance.

4.2.4 UCS testing

The UCS test is a laboratory test used in geotechnical engineering to determine the unconfined compressive strength of cohesive soils. The UCS test provides insights into the inherent strength of pavement sub-base materials when subjected to axial loading without lateral confinement. IS 2720-10 (1991): Methods of test for soils, Part 10 (IS 2720-10 (1991)). Table 7 details the specimen codes for the UCS tests.

Table 7. UCS test specimen details

Sr. No.	Test	Standard	Specimen Code
1	UCS Test	IS 2720-10 (1991)	UCT1
2	UCS Test	IS 2720-10 (1991)	UCT2
3	UCS Test	IS 2720-10 (1991)	UCT3
4	UCS Test	IS 2720-10 (1991)	UCT4
5	UCS Test	IS 2720-10 (1991)	UCT5
6	UCS Test	IS 2720-10 (1991)	UCT6

Each specimen corresponds with the material combinations (from T1 to T6) highlighted earlier.

The testing based on IS 2720-10 (1991) utilised a specified apparatus set and specifications. A loading machine was employed, adept at applying precise axial loads. Cylindrical test molds, typically fabricated from metal, housed the samples. Deformation dial gauges were crucial for accurately measuring axial strain during the procedure. A balance, accurate up to 0.1g, was in use for the weighing requirements. Additionally, various mixing tools ensured the homogeneous mixture of RAP+FA+Cement and water, and to aid in the post-test phase, a sample extruder was utilised to extract the specimen samples from the mold efficiently.

To evaluate the unconfined compressive strength, a systematic procedure was adopted. Initially, a cylindrical specimen sample was prepared, typically measuring 38mm in diameter and 76mm in height. This mixture was compacted into a cylindrical mold to ensure the formation of a uniformly shaped specimen. Once compacted, the specimen was meticulously extracted from the mold. The subsequent step involved positioning the cylindrical sample between the platens of the UCS testing apparatus. Without lateral support, an axial load was applied to the specimen consistently, maintaining a strain rate

of 1% per minute. The loading persisted until the point of the sample's failure, with meticulous documentation of the peak load exerted.

Calculate the UCS using the formula:

$$\text{UCS (kPa)} = \frac{\text{Load at failure}}{\text{Cross-sectional area of the sample}}$$

where the cross-sectional area of the sample: $\pi \times (d/2)^2$

Table 8 presents the outcomes of the UCS tests, detailing the unconfined compressive strength values associated with each specimen. Concurrently, Figure 7 visually represents these results, elucidating the test outcomes for enhanced clarity and comprehension.

Table 8. UCS test results

Specimen Code	Load (N)	Cross-sectional area (m ²)	UCS (kPa)
UCT1	295.1	0.001134	260.2
UCT2	325.1	0.001134	286.7
UCT3	366.8	0.001134	323.5
UCT4	440.0	0.001134	388.0
UCT5	380.3	0.001134	335.4
UCT6	330.7	0.001134	291.6

A higher UCS value signifies superior strength and a higher stress-fetting potential. Figure 7 shows an upward trend in UCS values from UCT1 to UCT4, increasing from 260.2 kPa to 388.0 kPa. This progression suggests that, up to the T4 combination (70% RAP and 30% FA), the material's strength improves consistently. This improvement might stem from an enhanced interlocking and bonding mechanism amongst the components within this particular mixture. However, post-UCT4, a decline in UCS

values is observed. The results for UCT5 and UCT6 are 335.4 kPa and 291.6 kPa, respectively. While these values are still superior to the baseline UCT1, they underscore the possible diminishing returns in strength when the proportion of FA surpasses a specific threshold in the mixture.

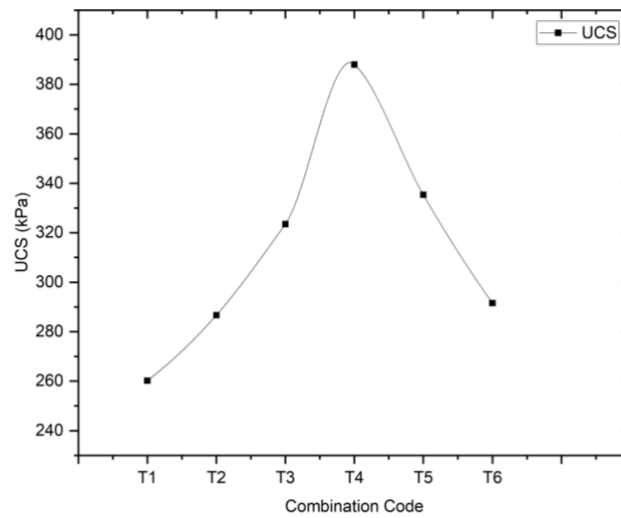


Figure 7. UCS test results

4.2.5 Comparative insights

When examining the laboratory tests conducted on the combinations of RAP, FA, and a constant 3% cement stabiliser, a clear pattern emerges and is represented in Figure 8.

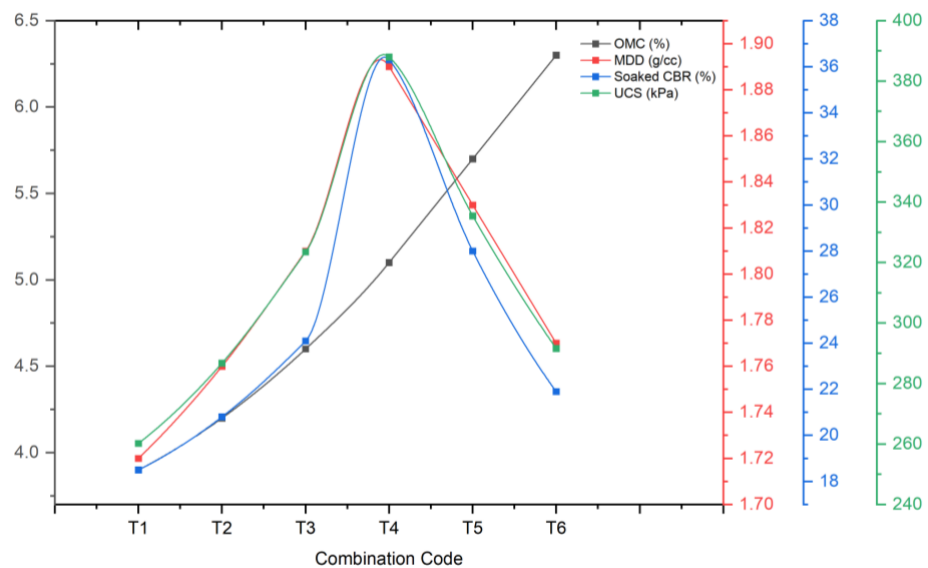


Figure 8. Combinations vs Compaction, CBR and UCS test results

The OMC values observed during the compaction tests consistently increased from CT1 to CT6, ranging from 3.9% to 6.3%. Additionally, the MDD values peaked at 1.89 g/cc for CT4 before descending to 1.77 g/cc by CT6. These metrics highlight that the mixture proportions influence moisture dynamics and material compatibility. The CBR values showed a direct relationship with the FA content up to T4, with an apex at 36.3%. However, there was a noticeable decrease after this combination, as evidenced by the 28.0% and 21.9% CBR values for T5 and T6, respectively. This demonstrates how adding more FA potentially diminishes the mixture's load-bearing capacity. The UCS values followed a trajectory similar to the CBR results. Beginning with a UCS of 260.2 kPa for UCT1, the values rose consistently until UCT4, which exhibited a notable strength of 388.0 kPa. Post this, there was a descent, with UCT6 registering 291.6 kPa. This suggests a correlation between the mixture's resistance to axial compressive stresses and its proportions of RAP and FA.

4.3 Insights from Expert Consultations

Section 4.3 delves into the valuable insights garnered from expert consultations. Recognising that laboratory results and data analysis, though crucial, might need more depth of field experience, the research sought to align its outcomes with the wisdom of seasoned professionals. These professionals, possessing rich experience in environmentally friendly road constructions, provided practical perspectives and concrete project reports that illuminated the potential applications of the study's findings. This section seeks to juxtapose the results with the expert testimonies, aiming to validate or contest the derived conclusions based on real-world experiences and expertise.

4.3.1 Interview response 1

1. Professional Experience and Role:

- How many years of experience does the respondent have in the construction industry?
 - I have over 15 years of experience in the construction industry, with most of my time spent on infrastructure projects.

- What is the respondent's current professional role and associated responsibilities in the construction industry?
 - Currently, I'm serving as a Project Manager. My responsibilities encompass overseeing various stages of construction projects, from planning and budgeting to execution and completion. This also includes liaising with suppliers, contractors, and stakeholders, ensuring projects align with industry standards, and incorporating sustainable practices.
- How frequently is the respondent involved in pavement construction projects?
 - I'm involved in pavement construction projects about 5 to 6 times a year, mainly on sustainable and eco-friendly projects.

2. Questions:

- Is it feasible to construct flexible pavements out of recycled materials?
 - It's feasible. With the advancement of technologies such as HIPR, recycling and reusing existing pavement materials has become much more efficient, mainly where the climate conditions are conducive.
- According to your knowledge, can we reuse or recycle materials in damaged flexible pavements?
 - Certainly. Damaged flexible pavements often have materials that are still structurally sound and can be recycled. Using HIPR technology, we can effectively reclaim the top layers of these pavements and reuse them.
- Can we effectively reclaim the material from a damaged flexible pavement, and if so, from which layer?
 - Yes, we can. With HIPR technology, typically, the top 25 to 50 mm of the pavement surface can be recycled. It involves softening the

asphalt layer with heat, mixing it with new materials (if required) and relaying it on the spot.

- What possible alternative materials can be reused in a road construction project?
 - Beyond the traditional bituminous materials, we can consider rubber from old tyres, FA, plastic waste, and certain industrial by-products.
- Could you explain the environmental and economic benefits of using reused or recycled materials in a road construction project?
 - Certainly. Environmentally, using recycled materials reduces the demand for virgin materials, leading to less quarrying and reduced CO₂ emissions. Economically, it's cost-effective as we save on the purchase of new materials and disposal of old ones. In the long run, Andhra Pradesh benefits from sustainable, durable roadways with reduced maintenance costs.
- How could you ensure recycled construction materials meet or exceed industry quality and safety standards?
 - We conduct rigorous quality checks and lab tests. In IRC, there are set guidelines for the quality of materials used in construction. By adhering to these guidelines and consistently monitoring the recycled material's performance, we ensure it meets the required standards.
- Describe a successful project in which you effectively lowered construction waste through recycling programmes. What challenges did you face, and how did you overcome them?
 - One such project was the reconstruction of a major roadway in Vijayawada. We incorporated HIPR technology and recycled about 70% of road materials. The challenges were mainly in educating the on-ground staff about the technology, but with thorough training sessions and hands-on demonstrations, we achieved our goals efficiently.

- How do you work with suppliers, contractors, and stakeholders to encourage using recycled materials and sustainable construction practices?
 - Communication and education are essential. By organising workshops and meetings presenting recycled materials' economic and environmental benefits. By aligning our objectives with the larger goals of Andhra Pradesh's sustainable development, we've fostered a collaborative approach to green construction.
- Can you provide instances of new technology or methods you've used to simplify on-site construction waste recycling?
 - Beyond HIPR, we've introduced mobile crushers for on-site waste recycling, turning construction waste into reusable aggregate. This has significantly reduced the need for transportation and thereby reduced our carbon footprint.

4.3.2 Interview response 2

3. Professional Experience and Role:

- How many years of experience does the respondent have in the construction industry?
 - I possess experience spanning over 17 years in the construction sector, particularly in infrastructure development.
- What is the respondent's current professional role and associated responsibilities in the construction industry?
 - At present, I hold the title of Senior Project Manager. My primary responsibilities encompass steering construction projects from their conceptual stages to their final execution. This involves a deep interaction with various stakeholders, including suppliers and contractors, ensuring adherence to established industry standards and notably integrating sustainable approaches wherever possible.
- How frequently is the respondent involved in pavement construction projects?

- My involvement with pavement construction projects is relatively frequent, with an estimated 8 to 10 projects annually. A significant portion of these projects revolves around sustainable methodologies and recycled materials.

4. Questions:

- Is it feasible to construct flexible pavements out of recycled materials?
 - Absolutely, and more so now than ever. The FDR technology has made it feasible to recycle almost the entire structure of a worn-out pavement. In Andhra Pradesh, such techniques are gaining momentum, given their economic and ecological benefits.
- According to your knowledge, can we reuse or recycle materials in damaged flexible pavements?
 - Definitely. In fact, with the advent of FDR, even severely damaged pavements can serve as valuable reservoirs of reusable material. The method reclaims the entire pavement structure, turning it into a base for a new pavement.
- Can we effectively reclaim the material from a damaged flexible pavement, and if so, from which layer?
 - With FDR, it's not just about a single layer. The technology allows for the reclamation of the full depth of the asphalt pavement and a predetermined portion of the underlying materials. It gets mixed on-site and set as a new foundation for the roadway.
- What possible alternative materials can be reused in a road construction project?
 - Apart from traditional asphalt, we're looking at materials like rubber from discarded tyres, FA, plastic waste, and certain industrial slags.
- Could you explain the environmental and economic benefits of using reused or recycled materials in a road construction project?

- Environmentally, the more we recycle, the less strain we put on our natural resources, which leads to reduced environmental degradation and lower CO₂ emissions. Economically speaking, recycling with FDR drastically cuts down on material costs, and when you factor in the longevity of such pavements, the maintenance expenses are also optimally reduced.
- How could you ensure recycled construction materials meet or exceed industry quality and safety standards?
 - Assurance comes from consistent quality checks and strict adherence to established standards. Especially in Andhra Pradesh, we rely on comprehensive guidelines set by the Indian Roads Congress (IRC). Every batch of recycled material undergoes rigorous testing to ensure it meets, if not exceeds, these standards.
- Describe a successful project in which you effectively lowered construction waste through recycling programmes. What challenges did you face, and how did you overcome them?
 - One that stands out is a roadway project, the Strengthening of Gajjaram - Hukumpeta road. We reclaimed and recycled about 80% of the pre-existing road materials through FDR technology. The initial challenge was aligning our teams to this novel approach, but with comprehensive training and interactive sessions, we mastered the technique, leading to significant savings and waste reduction.
- How do you work with suppliers, contractors, and stakeholders to encourage using recycled materials and sustainable construction practices?
 - Building trust through transparency is my approach. Detailed presentations on the benefits and real-world success stories from within Andhra Pradesh have been instrumental in getting everyone on board with sustainable construction.
- Can you provide instances of new technology or methods you've used to simplify on-site construction waste recycling?

- Apart from FDR, we've been experimenting with portable recycling plants that can be brought directly to the construction site. This helps immediately recycle waste, reducing transportation needs and the associated environmental footprint.

4.3.3 Expert insights to validate/invalidate findings

The study primarily focused on evaluating the relationship between varying mixture proportions and the compatibility and strength of the resulting material. The results indicate:

1. OMC values increased consistently from CT1 to CT6.
2. MDD values peaked at CT4.
3. CBR values increased with the addition of FA until T4.
4. UCS values peaked at UCT4 and decreased after that.

Relating Outcomes to Expert Insights:

1. The Trend in OMC:

Both experts acknowledge the feasibility of reusing and recycling materials in flexible pavements, emphasising sustainable and recycled methodologies. The rise in OMC with increasing mixture proportion might reflect the inherent moisture retention properties of the reused materials.

Expert Insight Validation: The experts mentioned that HIPR and FDR technologies involve adding or reusing specific amounts of moisture during recycling. The upward trend of OMC might directly result from the nature of recycled materials, which resonates with the experts' advocacy for reclamation technologies.

2. Peak in Maximum MDD:

The peak at CT4 indicates optimal compactibility. Both experts discuss the reuse of materials like FA in pavement construction.

Expert Insight Validation: The fact that the MDD peaked at CT4 before descending supports the experts' emphasis on determining the right mixture and proportions. Even if sustainable, too much of certain recycled materials can alter the desired properties, as seen in CT5 and CT6.

3. CBR values and FA Content:

The CBR values directly correlated with the FA content, peaking at T4.

Expert Insight Validation: The second expert's mention of FA as an alternative material is particularly relevant. FA has cementitious properties that can improve the strength of the mix. However, after a certain threshold (post-T4), the added FA might dilute the mix's structural integrity, reducing CBR, which aligns with the expert's insights on the balance of materials.

4. UCS trends:

UCS values peaked at UCT4 and then dropped subsequently.

Expert Insight Validation: In line with CBR, the UCS values trend highlights the critical point at which added FA or any other recycled material starts diminishing the mixture's overall strength. Both experts stress the importance of adhering to established standards and quality checks to ensure the structural soundness of recycled pavements.

4.4 Recommendations based on results

Expert consultations played a crucial role in the strategic development and mapping of laboratory findings to real-world applications. The outcomes underline the need for a balanced approach when incorporating recycled materials in pavement construction. While sustainability and recycling are imperative for the environment and cost efficiency, an excess of certain materials, like FA, can counterintuitively degrade the pavement's strength and durability.

Both experts' emphasis on rigorous testing, adherence to guidelines, and the innovative use of technologies like HIPR and FDR suggests that the construction industry is well aware of the challenges posed by these new methodologies. Their insights testify to the industry's commitment to striking the right balance between sustainability and structural integrity.

Furthermore, the study's results emphasise the importance of continuous monitoring, especially when introducing new materials or changing proportions in pavement mixes. As both experts highlighted, ensuring these recycled pavements' quality and safety is of utmost importance, not just for the immediate project but for the long-term sustainability and durability of our infrastructure.

Chapter 5:

Conclusions

5.1 Introduction

Chapter 5 delves into the cumulative insights and recommendations derived from the extensive research undertaken on the potential of RAP and FA in pavement construction. With sustainability as its motive, this chapter offers a comprehensive evaluation of the research aims, summarising the essential findings and highlighting their implications for industry professionals and future research directions. Through a systematic examination of the results, coupled with expert insights, this chapter aims to underscore the broader impact of the study, casting a vision for a more sustainable and innovative future in pavement construction in India's infrastructural landscape.

5.2 Evaluation of research aims

The primary objectives of this research revolved around determining the suitability of RAP and FA combinations, identifying the optimal mixture for strength and durability, and evaluating the practical applicability of these combinations as pavement sub-base materials.

Through extensive laboratory tests, the research successfully ascertained the viability of various combinations of RAP and FA, mainly when stabilised with a 3% cement content. This was reflected in the OMC trends and peaks in MDD values for specific combinations. The study findings, particularly the peaks observed in MDD, CBR, and UCS values for certain combinations like CT4 and T4, provided clear evidence towards identifying combinations that offer the best balance of desired properties. Expert consultations validated laboratory findings, emphasising the practical feasibility of the identified combinations in real-world scenarios. The experts' endorsement of novel recycling techniques, such as HIPR and FDR, further attests to the practical implications of the research findings.

A concise recap of the significant discoveries:

There was a consistent rise in OMC values across combinations, ranging from 3.9% in CT1 to 6.3% in CT6. MDD values observed a pronounced peak at 1.89 g/cc for CT4, indicating an optimal compactability mixture. CBR and UCS values displayed trends directly influenced by the mixture proportions, particularly the amount of FA incorporated. Specifically, CBR values peaked at T4 with 36.3%, while UCS values

reached their zenith at UCT4 with 388.0 kPa. Expert insights provided robust validation for the laboratory outcomes, especially underscoring the importance of determining the right mixture proportions and the potential of recycling technologies in pavement construction.

5.3 Summary of research findings

Expert consultations played a vital role in strategically designing and mapping the laboratory insights to real-world applicability. Professionals with more than a decade of experience in the construction sector emphasised the feasibility of constructing flexible pavements using recycled materials. Both highlighted the prominence of HIPR and FDR technologies in effectively recycling worn-out pavements. Their exposure to Andhra Pradesh's construction landscape indicated the region's increasing adoption of these sustainable practices. Notably, FA was highlighted as a pivotal alternative material, aligning with the research findings on its impact on strength properties.

OMC values consistently increased, shifting from 3.9% in the CT1 combination to 6.3% in CT6. This upward trend emphasises the mixture proportions' significant role in influencing moisture dynamics in pavement compositions. The study pinpointed CT4 as a pivotal combination, where MDD values peaked at 1.89 g/cc. This peak signal optimal compatibility and underscores the delicate balance required in mixture proportions to achieve optimal structural integrity. Further strengthening this observation, CBR values peaked at T4, recording 36.3%, and UCS results exhibited their highest at UCT4, marking 388.0 kPa. The study discerned a direct correlation between adding FA and the strength properties of the mixture. This correlation manifested in the increasing CBR and UCS values up to certain mixture thresholds (T4 and UCT4, respectively), after which introducing more FA seemed to compromise the blend's structural strengths.

Incorporating insights from professionals, the validation of the increasing values in OMC values can be attributed to the inherent moisture retention properties of recycled materials. The peak in MDD at CT4 aligns with experts' emphasis on striking the right balance in mixture proportions. Similarly, the trends observed in CBR and UCS values are consistent with the experts' notes on maintaining structural integrity even when incorporating sustainable materials.

5.4 Recommendations

Potential changes in pavement construction practices based on findings:

The research findings, especially the observed peaks in MDD, CBR, and UCS values for combinations like CT4 and T4, underscore the necessity of meticulously determining mixture proportions. Emphasis should be on balancing RAP, FA, and other materials to achieve the desired strength, durability, and compatibility properties. With expert insights highlighting the potential of technologies like HIPR and FDR, construction practices should pivot towards adopting these modern methodologies. Such technologies not only advocate recycling but also elevate the structural qualities of the resulting pavements.

Practical implications and directions for industry professionals:

The benefits of using recycled materials, both from an ecological and economic standpoint, have been well-documented in this research. Industry professionals must lean into these findings, promoting sustainability as an afterthought and a core principle. Engaging all stakeholders in the construction process, including suppliers, contractors, and policymakers, is crucial. Regular communication, sharing of research findings, and collaborative problem-solving can amplify the adoption of sustainable practices and ensure the collective push towards eco-friendliness.

Beyond the environmental benefits, professionals should be acutely aware of the economic advantages that come with the use of recycled materials. Reduced costs, especially regarding material procurement and disposal, can lead to significant savings, which, coupled with the longevity of such pavements, makes for a compelling economic argument. As research and technology evolve, professionals should remain adaptable and willing to re-evaluate and recalibrate their practices. This adaptability, when coupled with a foundational commitment to sustainability and quality, can redefine the future of pavement construction.

5.5 Suggestions for further research

Areas where subsequent studies can focus to further this research:

- 1 Longevity and Durability Assessment: While this study has provided insights into the immediate strengths and compatibility of different mixture, future research could delve into the long-term performance of these pavement combinations. Assessing their durability under varied climate conditions, traffic loads, and geographical challenges can provide more holistic conclusions.

- 2 Environmental Impact Analysis: The current research underlines the eco-friendly use of recycled materials in pavement construction. However, a detailed environmental lifecycle analysis, considering aspects like CO₂ emissions, energy consumption, and impact on water resources, can further quantify the ecological benefits of these practices.
- 3 Socio-economic Implications: Building on the economic benefits outlined, future studies can delve deeper into the socio-economic implications of wide-scale adoption of these construction practices, particularly concerning job creation, cost savings for municipalities, and the broader economic ripple effects.
- 4 Alternative Binders and Materials: While this research focused on RAP, FA, and a 3% cement stabiliser, subsequent studies can explore the potential of other binders and recycled materials. Understanding how alternatives like bio-binders or industrial by-products fare in similar tests can further expand the repertoire of sustainable construction materials.

Potential areas that future studies could explore:

1. Behaviour Under Stress: Beyond the basic strength tests, future research could simulate real-world stresses like freeze-thaw cycles, chemical spill resistance, and fatigue to see how these pavement combinations behave under diverse stressors.
2. Integration with Modern Construction Technologies: As the construction industry continues to evolve, integrating findings from this research with modern construction technologies like 3D printing or automated construction methods can be a promising area for research.
3. Sensitization and Policy Framework: Given the sustainability implications of these findings, future research could focus on sensitising policymakers and developing a policy framework. Such a framework can advocate and incentivise adopting sustainable practices in pavement construction across regions.
4. Economic Modelling: Future studies can simulate the financial implications of transitioning entire cities or regions to these sustainable construction practices by developing detailed economic models. Such modelling can be invaluable for government bodies and large construction firms.

5. Consumer and Societal Perception: Understanding public perception and societal acceptance of roads constructed using recycled materials can provide insights into potential challenges and strategies to overcome them. It can guide how these construction methods are communicated and marketed to the general public.

5.6 Conclusion

The broader impact of this study resonates beyond mere technical findings. By exploring the fusion of recycled asphalt pavement with FA, stabilised with a 3% cement mix, this research has paved the way for a future where road construction doesn't come at the expense of the environment. The study's findings underscore the feasibility of using recycled materials and highlight the tangible benefits, from enhanced strength and durability to economic cost savings.

The expert consultations further affix the practical applicability of these findings. By harmonising laboratory-based results with on-ground experiences, this research bridges the gap between theory and practice. This lays the groundwork for a future where sustainable construction practices may become mainstream industry standards.

Moreover, with a geographical lens focused on India, the implications of this research become even more profound. In a nation poised for rapid infrastructural development, the findings offer a roadmap that balances the scales of development and sustainability. But beyond the subcontinent, this research's principles and findings could apply to other regions globally. The aim is to identify the optimal ratio of RAP and Fly ash in sustainable highway construction in India

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Appendix

Declaration of AI Use

I hereby declare that I have ethically used various AI tools while being supervised to assist me with my academic writing and learning, to improve the quality of my writing by eliminating grammatical errors, improving paraphrasing, and supporting the expressions and use of the English language as well as improvements to the sentence level to make my dissertation look much professional. I hereby declare that the entire research work submitted is my own and that any content paraphrased has been adequately cited to prevent the spread of false information. In addition, I have extensively used various AI tools to reduce plagiarism and rephrase, rewrite, and restructure my content in a way that complies with the dissertation writing style the university has specified, adhering to ethical AI usage.

During the course of completing the task, I made use of AI in the following ways:

- To select scientific literature – NO
- To develop research questions on the topic – NO
- To develop aims and objectives of the study – NO
- To develop the methodology proposed in the study – NO
- To identify testing standards used in the study – NO
- To plot the graphs – NO
- To perform numerical calculations – NO
- To interpret the results – NO
- To generate reports shared by industry professionals – NO
- To support written English – YES
- To paraphrase, rephrase, rewrite, and restructure content and sources – YES
- To design the interview questionnaire - NO