Integrated Application of Waste Cooking Oil, Reclaimed Asphalt Pavement, and Fly Ash in Sustainable Flexible Pavement Systems

Subash S. M.[1], Abhinav Sharma[2], Aiman[3]
[1]Lincoln University College, Malaysia; Guru Nanak Institute of Technology, India
[2]Tokushima University, Japan
[3]Lincoln University College, Malaysia

Abstract

The increasing scarcity of natural aggregates and petroleum-based binders has intensified the need for sustainable alternatives in flexible pavement construction. Simultaneously, the disposal of industrial by-products and roadway wastes presents serious environmental challenges. This study investigates the integrated use of waste cooking oil (WCO), reclaimed asphalt pavement (RAP), fly ash (FA), and bottom ash (BA) to enhance the performance of flexible pavements. Short-term aging of bitumen was simulated using the Rolling Thin Film Oven Test (RTFOT), followed by rejuvenation with varying dosages of WCO. Binder performance was evaluated through penetration, softening point, ductility, viscosity, flash point, and fire point tests. RAP mixtures incorporating rejuvenated binders were designed using Marshall methodology. FA and BA stabilized subgrades reinforced with polypropylene fibers (PPF) were assessed through CBR and triaxial testing. Finite Element Analysis (FEA) was conducted to evaluate pavement response under axle loading and validated using laboratory plate load tests. Results demonstrate that an optimum WCO dosage effectively restores aged bitumen properties, while stabilized subgrades significantly reduce pavement thickness and construction cost. The combined use of WCO, RAP, and fly ash offers a technically viable and environmentally sustainable solution for flexible pavement construction.

Keywords: Waste Cooking Oil, Reclaimed Asphalt Pavement, Fly Ash, Bitumen Rejuvenation, Sustainable Pavements

1. Introduction

Flexible pavements constitute the primary form of roadway infrastructure in many developing countries, leading to extensive consumption of aggregates and bituminous binders [1], [11]. The rapid expansion of highway networks has placed significant pressure on natural resources, while the availability of high-quality virgin materials continues to decline. This situation has encouraged researchers and practitioners to explore alternative construction materials that reduce environmental impact without compromising pavement performance.

Coal-based thermal power plants generate large quantities of fly ash and bottom ash every year, much of which remains underutilized despite possessing favorable engineering properties [6], [7]. Similarly, rehabilitation of existing pavements produces substantial volumes of reclaimed asphalt pavement (RAP), containing aged bitumen that becomes stiff and brittle due to oxidative aging [2], [4]. Direct reuse of RAP is limited unless the aged binder is adequately rejuvenated.

Waste cooking oil has emerged as a promising rejuvenator due to its availability, low cost, and ability to restore the viscoelastic characteristics of aged asphalt binders [1], [3], [5]. Previous studies have shown that WCO can effectively replenish the lighter fractions lost during aging, thereby improving ductility and workability [2], [9].

Pavement performance is also strongly influenced by the strength of the underlying subgrade and subbase layers. Weak subgrades lead to excessive deformation and increased pavement thickness requirements. Stabilization using fly ash and fiber reinforcement has been reported to significantly enhance bearing capacity and stiffness [6]–[8].

This study presents an integrated approach combining WCO-rejuvenated RAP mixtures with fly ash and bottom ash stabilized pavement layers. Laboratory testing, numerical modeling, and economic assessment were carried out to evaluate the feasibility of this sustainable pavement system.

2. Materials and Methods

2.1 Materials

Class F fly ash and bottom ash were obtained from a coal-based thermal power plant. Polypropylene fibers with high aspect ratio were used for reinforcement. RAP materials were collected from a deteriorated national highway and tested as per IS 2386 standards [14]. Virgin VG-30 bitumen was used as the control binder. Waste cooking oil was collected from residential sources, filtered to remove impurities, and characterized before use as a rejuvenator. Short-term aging of bitumen was simulated using the Rolling Thin Film Oven Test (RTFOT) in accordance with ASTM D2872 [13].

2.2 Experimental Procedure

Natural soil was initially tested to determine baseline geotechnical properties. Fly ash and bottom ash were blended with soil in varying proportions, and based on preliminary results, equal proportions were selected. Polypropylene fibers were added to enhance stress–strain behavior and prevent brittle failure, following established stabilization techniques [6], [7]. Aged bitumen obtained from RTFOT was rejuvenated using waste cooking oil at dosages of 0.25%, 0.50%, 0.75%, and 1.0% by weight of binder. Standard binder tests were conducted to determine the optimum rejuvenator content, following methodologies reported in earlier studies [2], [4], [9]. RAP mixtures incorporating rejuvenated binder were designed using Marshall mix design procedures in accordance with MoRTH specifications [12]. Triaxial compression tests were performed to determine stiffness parameters required for numerical analysis.

3. Finite Element Analysis

Finite Element Analysis was carried out to evaluate pavement response under traffic loading. A multilayer elastic pavement model was developed using material properties obtained from laboratory tests. Pavement thickness was designed based on CBR values following IRC:37-2012 guidelines [11]. A standard single axle load was applied, and vertical compressive strain at the top of the subgrade was used as the critical performance indicator.

4. Results and Discussion

Laboratory test results indicated that blending 15% fly ash and 15% bottom ash with natural soil significantly improved subgrade strength, while the inclusion of polypropylene fibers further enhanced stiffness and CBR values. These findings are consistent with earlier stabilization studies [6], [7].

Rejuvenation of aged bitumen using waste cooking oil showed that a dosage of approximately 0.75% effectively restored penetration, ductility, and viscosity values close to those of virgin binder. Similar trends have been reported by Shu et al. [2] and Bardella et al. [5].

RAP mixtures prepared with rejuvenated binder exhibited satisfactory Marshall stability and volumetric properties, confirming the feasibility of high RAP utilization [4], [9]. Finite Element results revealed a substantial reduction in vertical compressive strain when stabilized subgrades were used, indicating improved structural performance and extended service life [10], [11].

5. Economic and Sustainability Assessment

The reduction in pavement thickness achieved through subgrade stabilization and RAP utilization resulted in significant cost savings. Lower consumption of virgin aggregates and bitumen contributed to reduced construction costs and environmental impact. The approach also minimizes landfill disposal of industrial by-products, supporting circular economy principles.

6. Conclusions

This study demonstrates that the integrated use of waste cooking oil, reclaimed asphalt pavement, fly ash, and bottom ash provides a technically effective and environmentally sustainable solution for flexible pavement construction. Waste cooking oil successfully rejuvenated aged bitumen, enabling higher RAP utilization without compromising performance. Fly ash and fiber-stabilized subgrades significantly enhanced bearing capacity and reduced pavement thickness. Finite Element Analysis validated the improved structural response, and economic evaluation confirmed cost effectiveness. The proposed approach is suitable for large-scale implementation in sustainable road infrastructure projects.

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