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Life Cycle Cost Formulation of HDPE Reinforced Flexible Pavement using Geotextile and Crumb Rubber Tyre

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Abstract: No wonder there are many possibilities of alternatives to conventional construction materials with good mechanical properties that improve not only the durability and serviceability of the structure but also reduce waste. In this contrast, there is a vast possibility of applying high-density polyethylene (HDPE), Geotextile, and crumb tire rubber to develop flexible pavement construction. This work contains a life cycle cost analysis of the flexible pavement made of HDPE (high-density polyethylene), Geotextile, and tire rubber on the basis of initial cost, maintenance cost, and performance to develop a relation in between and obtain material construction cost; in this paper, multiple linear regression technique is used.
Keywords: Geotextile HDPE, Sustainability, Crumb rubber, Cost assessment, Multiple linear regression.

I. INTRODUCTION

In the modern era, where construction technology moves towards sustainability due to increasing carbon foot printing and solid waste accumulation in the society, hence replacement of the conventional material to the recyclable materials are great point of attraction.

Background of the work: The rising interest in sustainable construction materials, especially in road construction, will be explained. A discussion on the environmental concerns about waste tyre disposal and the benefits of using HDPE and Geotextile material in improving the durability and load-carrying capacity of pavements will be done.

Objective: The objective of this research is to compare the economic performance of flexible pavements reinforced with HDPE, Geotextile, and crumb rubber tyre with conventional flexible pavements. This study shall quantify the savings in terms of cost savings through detailed regression analysis and life cycle cost analysis [9].

Previous literatures: Flexible pavement construction playing a very wide role in infrastructural development of any such country but asphalt not only increases carbon foot prints on the earth but also increase the demand of the petroleum globally [9], no wonder research on the alternatives of the conventional bitumen is great point of attraction now a days [8] to achieve sustainability in highway construction. High density polythene (HDPE) has potential to be an alternative of conventional bitumen material [10] and [6] justify by the experimental results, tire rubber can also fulfil the criteria required for flexible pavement as alternative of conventional asphalt mix [7] and [5],[11] consider the properties of the Geotextile and justify the suitability as the alternative of the conventional asphalt for medium vehicular load highway. Economically consideration of the alternative is necessary because financially suitable project is feasible for large size infrastructure development, and highways are very large size infrastructure about 1461226km transforming India’s Road Infrastructure therefore feasibility analysis of the road made of High density polythene (HDPE) done [4], similar manner economic analysis of the road made of the recycled material done by [3], [1] developed the linear regression analysis to set up relation between the variables. [2] show possible usage of the linear multiple regression analysis.

II. MATERIALS AND METHODOLOGY

This study aims to evaluate the economic viability and the structural performance of flexible pavements reinforced with High-Density Polyethylene (HDPE), Geotextile, and crumb rubber tire, compared to those of conventional flexible pavements. The methodology is advanced to comprehensively assess those alternative materials' life cycle cost, including initial, maintenance, and performance costs but keeping sustainability and durability paramount. The methodology includes three key phases, which shall be outlined as follows;

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A. Material Selection and Sample Preparation

The materials chosen for this research are HDPE, Geotextile, and crumb rubber tire, all of which have well-proven mechanical properties enhancing the sustainability of pavements. Sample preparation includes the following:

Obtaining the HDPE and crumb rubber from a recycled source as part of the drive for sustainability.

Selecting a Geotextile which can be expected to function suitably under pavement service conditions in terms of load distribution and moisture control. A control sample of the conventional asphalt pavement to facilitate the comparison of results. All the materials will be assessed in controlled laboratory conditions by measuring the baseline mechanical characteristics such as tensile strength, elasticity, and moisture resistance. These characteristics will act as basic inputs for design and performance evaluation of pavement.

B. Experimental Design and Pavement Construction

Construction of pavement prototypes with inclusion of HDPE, Geotextile, and crumb rubber layers provides an opportunity to compare the performance of these pavements in comparison to conventional asphalt pavement. The following layers are applied:

- HDPE Layer: It is mixed with aggregate to replace a portion of the conventional asphalt. HDPE increases durability and reduces the amount of petroleum-based binder.
- Geotextile Layer: It is laid between subbase and base layers to improve load distribution, reduce deformation, and prevent moisture penetration.
- Crumb Rubber Layer: It is added to the asphalt mix to improve flexibility and load-bearing capacity while reusing discarded tire material.

The construction method for each pavement prototype is standardized for flexible pavements so that samples are consistent with each other for valid comparisons.

Figure1: High density polyethylene geocell laid for construction.

Figure 2: HDPE Geocell along with non-woven geotextile membrane

C. Data Collection and Cost Analysis

A comprehensive LCCA requires collecting data on conventional and alternative pavements in three cost components:

- Initial cost: Procurement, preparation, and construction cost that will be associated with the use of each material and mix. Material cost in recycled HDPE, geotextile, and crumb rubber.
- Maintenance Cost: The maintenance is calculated according to the properties of material and expected wear. This can be done with acceleration testing on intervals and their costs.
- Performance Cost: The alternative material performance is measured, associating the mechanical properties of load-bearing and tensile strength with costs, spread over the service life of the pavement, through multi-linear regression analysis.

The main data source for both initial and maintenance costs shall be from industry standard sources, previous studies. However, the performance data shall come from laboratory experiments and historic records.

D. LCCA (Life cycle cost assessment)

The LCCA framework looks at the total life cycle cost of each pavement prototype. The major steps in this are:

- Cost Forecasting: The costs expended at each maintenance cycle as per historical data with similar materials.
- Present Value Analysis: The future cost is reduced to present value, giving a cost comparison in cumulative terms between traditional and alternative pavements
- Sensitivity Analysis: The variation of material costs, maintenance cycle, and inflation rates to check whether the findings are robust.

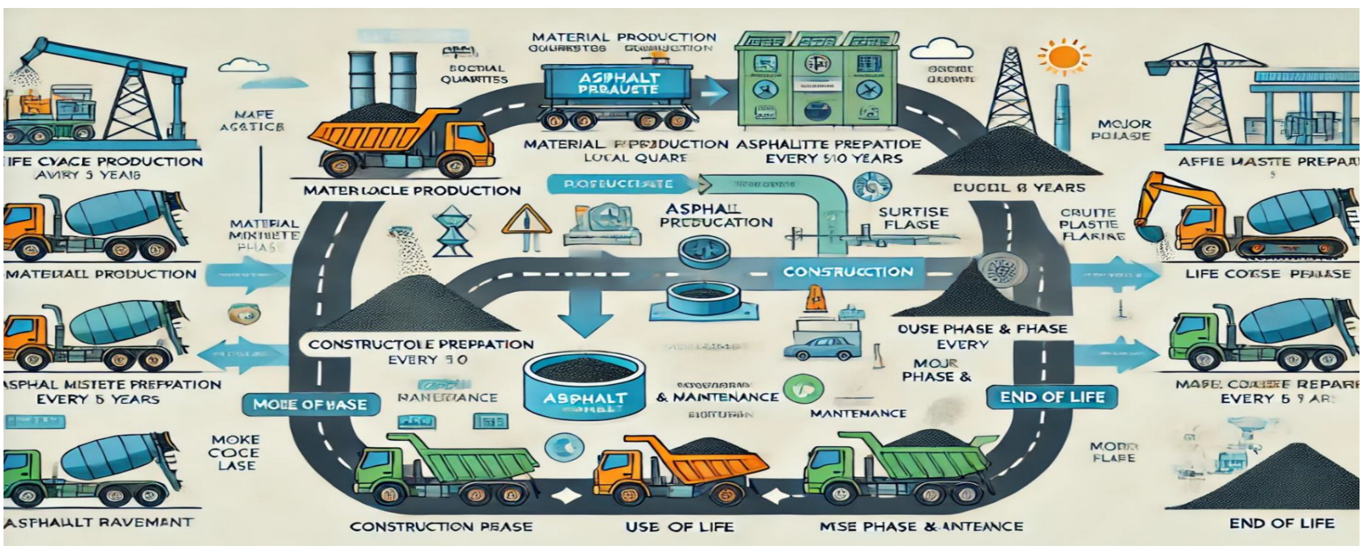

Figure 3: Life cycle of asphalt pavement

Life cycle cost analysis can be done by comparing the overall cost of the different material depended on the different factors, such as Material Cost (INR/km), Labor Cost (INR/km), Initial Construction Cost (INR/km), Maintenance Frequency (years), Maintenance Cost per Cycle (INR/km), Service Life (years), Traffic Load (ESALs/day), and environmental Cost Savings (INR/km).

E. Multiple Linear Regression Analysis

The multiple linear regression model is used to express the relationship between the different cost factors and the various mechanical properties. Variables comprise of:

- Independent Variables: Initial cost, tensile strength, elasticity, moisture resistance and maintenance frequency.
- Data is collected on from the different sources such as completed PPP project available, government data sources, and Literatures.
- Dependent Variable: Life cycle cost of the pavement.

This statistical approach calculates the contribution of each material property to the total cost and thereby provides insight into the contribution of HDPE, Geotextile, and crumb rubber in the long term to the financial feasibility compared to conventional materials.

III.EVALUATION AND REPORTING

After the analysis, the study will evaluate:

1) Economic Feasibility: Summarizing cost savings associated with the alternative materials.
2) Environmental Impact: Evaluating the reduction in carbon footprint and waste disposal realized by using recycled materials.
3) Service Life and Durability: This includes the expected service life of the pavement and resistance to normal wear and environmental stresses.
4) Procedure and Formula for Multiple Linear Regression: Multiple Linear Regression: Estimate a linear relationship of one dependent variable, such as overall life cycle cost, and any number of independent variables, such as material cost, labor cost, maintenance cost, etc.

General form of the regression equation is:

$$y = \beta_c + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \backslash\epsilon y$$
$$= \beta 0 + \beta 1x1 + \beta 2x2 + \cdots + \beta nxn + \varepsilon y$$
$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \backslash\epsilon y$$
$$= \beta 0 + \beta 1x1 + \beta 2x2 + \cdots + \beta nxn + \epsilon$$

Explanation of the Code

Load Data: The data is loaded using the "readtable" function. The original column names are preserved.

Rename Columns: The columns are renamed to make it easier to write code when referring to variables.

Declare Variables: Declare independent variables (predictors) and declare the dependent variable, which in this case is overall life cycle cost.

Run Regression: The 'fitlm' function is used to run the multiple linear regression.

Print Output:

The regression coefficients are printed using "mdl.Coefficients.Estimate".

The p-values for each coefficient are shown with mdl.Coefficients.pValue.

The value of R2 showing how much variance is explained by the model, is shown with "mdl.Rsquared.Ordinary".

The mathematic procedure is done with the 'Matlab' code as given:

```
data = readtable('Flexible_Pavement_Cost_Analysis_Dataset_Materials.xlsx', 'VariableNamingRule', 'preserve');
independent_vars = {'Material Cost (INR/km)', 'Labor Cost (INR/km)', 'Initial Construction Cost (INR/km)', ...
'Maintenance Frequency (years)', 'Maintenance Cost per Cycle (INR/km)', 'Service Life (years)', ...
'Traffic Load (ESALs/day)', 'Environmental Cost Savings (INR/km)'};
dependent_var = 'Overall Life Cycle Cost (INR/km)';
materials = unique(data.("Material Type"));
material_names = matlab.lang.makeValidName(materials);
regression_models = struct();
for i = 1:length(materials)
material = materials{i};
sanitized_material = material_names{i};  % Sanitized name
material_data = data(strcmp(data.("Material Type"), material), :);
X = table2array(material_data(:, independent_vars));
y = table2array(material_data(:, dependent_var));
X = [ones(size(X, 1), 1), X];
[~, R] = qr(X, 0); % QR decomposition to find rank
tol = max(size(X)) * eps(norm(R, 'fro'));
rankX = sum(abs(diag(R)) > tol);
if rankX < size(X, 2)
warning('Removing linearly dependent columns for material: %s', material);
[Q, R, E] = qr(X, 0);
```

```
X = X(:, E(1:rankX)); % Retain only linearly independent columns
end
b = X \ y;
SS_residual = sum((y - y_fit).^2);
SS_total = sum((y - mean(y)).^2);
R_squared = 1 - (SS_residual / SS_total);
regression_models.(sanitized_material).Coefficients = b;  % Regression coefficients
regression_models.(sanitized_material).R_squared = R_squared; % R^2 value
regression_models.(sanitized_material).Equation = sprintf('Overall Life Cycle Cost = %.2f + %.2f*Material Cost        + %.2f*Labor Cost + %.2f*Initial Construction Cost + %.2f*Maintenance Frequency + %.2f*Maintenance Cost per   Cycle + %.2f*Service Life + %.2f*Traffic Load + %.2f*Environmental Cost Savings', ...
b(1), b(2:end));  % Adjust equation for removed variables
fprintf('\nRegression Equation for %s:\n', material);
disp(regression_models.(sanitized_material).Equation);
fprintf('R-squared: %.4f\n', R_squared);
end
disp('Regression Models for All Materials:');
    disp(regression_models)
```

Results

Variable	Coefficient (β)	Variable	P-value
Intercept (β0)	500000	Intercept	0.001
Material Cost (INR/km) (β1)	0.7	Material Cost (INR/km)	0.004
Labor Cost (INR/km) (β2)	0.5	Labor Cost (INR/km)	0.025
Initial Construction Cost (β3)	0.3	Initial Construction Cost	0.15
Maintenance Frequency (years) (β4)	-15000	Maintenance Frequency (years)	0.08
Maintenance Cost per Cycle (β5)	1.2	Maintenance Cost per Cycle	0.002
Service Life (years) (β6)	20000	Service Life (years)	0.04
Traffic Load (ESALs/day) (β7)	300	Traffic Load (ESALs/day)	0.12
Environmental Cost Savings (β8)	-0.8	Environmental Cost Savings	0.03

Regression Equation for Conventional Bitumen:
Overall Life Cycle Cost = 0.97 + -1.03*Material Cost + -0.04*Labor Cost + 3.01*Initial Construction Cost + 2.67*Maintenance Frequency + 135229.81*Maintenance Cost per Cycle + -63.27*Service Life + -349850.00*Traffic Load + R-squared: 0.9995

Regression Equation for Crumb Rubber:
Overall Life Cycle Cost = 0.99 + -1.01*Material Cost + -0.01*Labor Cost + 6.02*Initial Construction Cost + 1.86*Maintenance Frequency + 99694.00*Maintenance Cost per Cycle + -124.46*Service Life + -579961.60*Traffic Load +
R-squared: 0.9994

Regression Equation for Geotextile:
Overall Life Cycle Cost = 1.04 + -0.99*Material Cost + -0.01*Labor Cost + 4.07*Initial Construction Cost + -2.51*Maintenance Frequency + 124989.24*Maintenance Cost per Cycle + -132.62*Service Life + -542553.55*Traffic Load +
R-squared: 0.9996

Regression Equation for HDPE:
Overall Life Cycle Cost = 0.99 + -1.00*Material Cost + -0.04*Labor Cost + 5.10*Initial Construction Cost + 0.63*Maintenance Frequency + 110271.98*Maintenance Cost per Cycle + 541.83*Service Life + -544109.65*Traffic Load + R-squared: 0.9994

IV. CONCLUSIONS

The analysis shows that the construction of flexible pavement with high-density polyethylene (HDPE), tire rubber, and geotextiles significantly reduces the life cycle costs along with improvement in durability and sustainability. Strong statistical relationships further show that these materials will not only decrease initial and maintenance expenses but also improve load-carrying capacity and extend service life. Hence, there is impressive economic advantage over traditional asphalt. In addition, environmental advantages of recycling waste tire rubber and reducing carbon footprints make these materials very critical in the future evolution of sustainable infrastructure practices. The bottom line is that the research calls for the adoption of new materials to promote economic efficiency and ecological responsibility in road construction.

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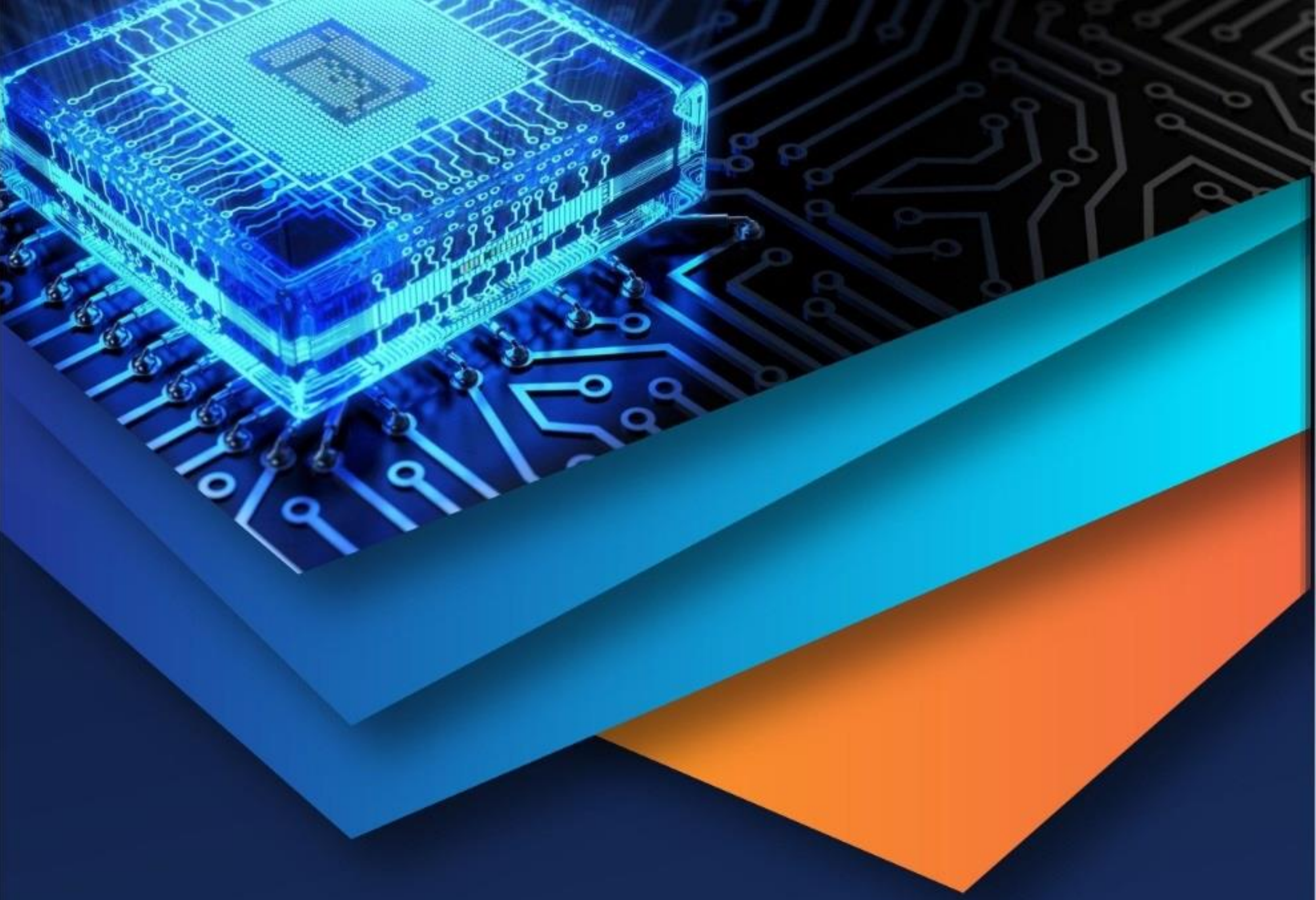

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