A Statistical Approach to Evaluating the Influence of Paving Block Thickness and Sand Bedding on Surface Deflection

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Abstract

This study aims to investigate the structural behavior of concrete paving block (CPB) road surfaces. A statistical approach was used to analyze surface deflection using a light weight deflectometer (LWD). To assess the statistical significance of each factor's influence, analysis of variance (ANOVA) was conducted. To analyze the relationships between variables, correlation and linear regression analyses were performed. The results show that increasing the thickness of the CPB and sand bedding significantly reduces deflection, while greater deflection occurs with higher loads. As the thickness of the CPB and sand bedding increased, the measured deflection decreased from 0.446 mm to 0.259 mm. Correlation analysis shows a negative correlation between deflection and thickness or strength, and a positive correlation with load. ANOVA analysis confirms that all of the variables significantly affect deflection. The regression equation that includes all of the variables and uses load as a multiplication factor is the most accurate.

Keywords: deflection, sand bedding, thickness, concrete, road surface

1. Introduction

The traffic loads on concrete paving block (CPB) pavements are dynamic, causing rotational and translational movements within the road surface structure. The three principal components of CPB systems are as follows: vertical interlocking, rotation, and horizontal movement. These aspects must be considered in the design and construction of CPB systems [1-2]. The performance of CPB road surfaces can be predicted based on their vertical deformation and horizontal load behavior [3]. The deformation of flexible pavement systems is attributable to the continuous movement of vehicles. This deformation is a combined response from all pavement components [4]. Surface deflection is a significant indicator for analyzing the condition of pavement structures [5]. Road surface deflection is used to evaluate structural conditions and to determine structural repair decisions [6]. Deflection measurements are used to recalculate the stiffness properties of pavement structures from the base layer to the surface layer [7].

CPB is a type of flexible pavement with a simple production process. The various advantages of CPB are high strength, good durability, and low maintenance costs [8]. The load capacity of CPB pavement differs from that of conventional pavement surfaces [9]. The utilization of CPB parameters in road pavement is adapted to traffic loads, as is customary in conventional

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pavement [10]. Based on previous studies, the use of CPB has certain limitations. Several analyses of the mechanical properties and behavior of CPB structures have indicated that CPB is more suitable for use on low-volume roads [11]. In recent years, CPB has become increasingly popular as an alternative to conventional roads. CPB has been widely used in urban and residential areas because it is modular, easy to maintain, and has potential for sustainable infrastructure development.

Several studies on CPB pavement deflection have been conducted. The main parameters that affect CPB deflection are shape, pattern, and thickness [12]. Another parameter that affects CPB performance is sand bedding. The performance of sand bedding is influenced by layer thickness, gradation, slope angle, moisture content, and mineralogy [13]. Joint sand is also important for transferring loads between CPBs and distributing them to the underlying layers [14]. Filling the gaps with sand joints creates a stronger interlocking by reducing rotation [15]. Additionally, pavement layer thickness significantly affects pavement performance on deformation [16]. Thickness variations in cube-shaped samples are more consistent and better suited for testing standards, making them ideal for identifying CPB characteristics [17-19]. The characteristics of porous paving blocks also show the effect of thickness [20]. In terms of structure, deflection in thicker CPB results in lower values than thinner CPB [12].

Previous studies have conducted structural analyses of CPB. Deflection analysis under load (D_0) is the most significant parameter for evaluating CPB performance [21]. An analysis of various CPB shapes shows that the hexagonal shape produces the lowest deformation compared to rectangular and octagonal shapes [22]. Other studies show that CPB with a uniform shape produces lower deflection than zigzag and rectangular shapes [23]. Other parameters indicate that CPB thickness affects its structural performance. According to the deflection prediction model, increasing the thickness of CPB reduces rut depth by 25% [24]. Meanwhile, the 120-mm-thick CPB exhibited elastic behavior upon deformation [5]. Sand bedding is an essential foundation for CPB unit installation. Several studies show that sand bedding thickness can affect CPB interlocking [25]. The high shear strength of the sand bedding layer indicates its ability to distribute loads more effectively [26]. Analysis of different sand bedding thicknesses shows that a thickness of 5 cm provides the highest potential for interlocking [14, 25].

Previous studies have investigated the mechanical properties and structural behavior of CPB pavements, mainly focusing on material strength and surface performance. However, these studies have not analyzed in detail the relationship between structural parameters such as CPB thickness and sand bedding thickness, compressive strength, and load on surface deflection behavior. Additionally, structural testing with the Lightweight Deflectometer (LWD) tool is limited to field measurements and does not evaluate statistical approaches to explain the effects of various variables. This study presents a statistical equation that quantifies the effects of CPB, sand bedding thickness, compressive strength, and load on surface deflection. This approach combines experimental and analytical methods to evaluate the structural response of CPB road surfaces.

This paper aims to investigate the structural behavior of CPB using a statistical approach. The analysis focuses on the behavior of flexible pavement structures incorporating CPB layers. Understanding the characteristics of CPB, such as its thickness, strength, and load influence, is key to optimizing its structural performance. This research is expected to address the current limitations in CPB pavement performance and contribute to improving its design and application.

2. Materials and Methods

This study uses a statistical approach to evaluate the effect of sand bedding and CPB thickness on deflection behavior. The objective of this study was to manufacture a CPB structure measuring 1.4 m×1.4 m. This study uses a light weight deflectometer (LWD) to analyze surface deflection. The test results were analyzed using statistical approaches such as correlation analysis, analysis of variance (ANOVA), and linear regression. The overall research methodology is illustrated in Fig. 1.

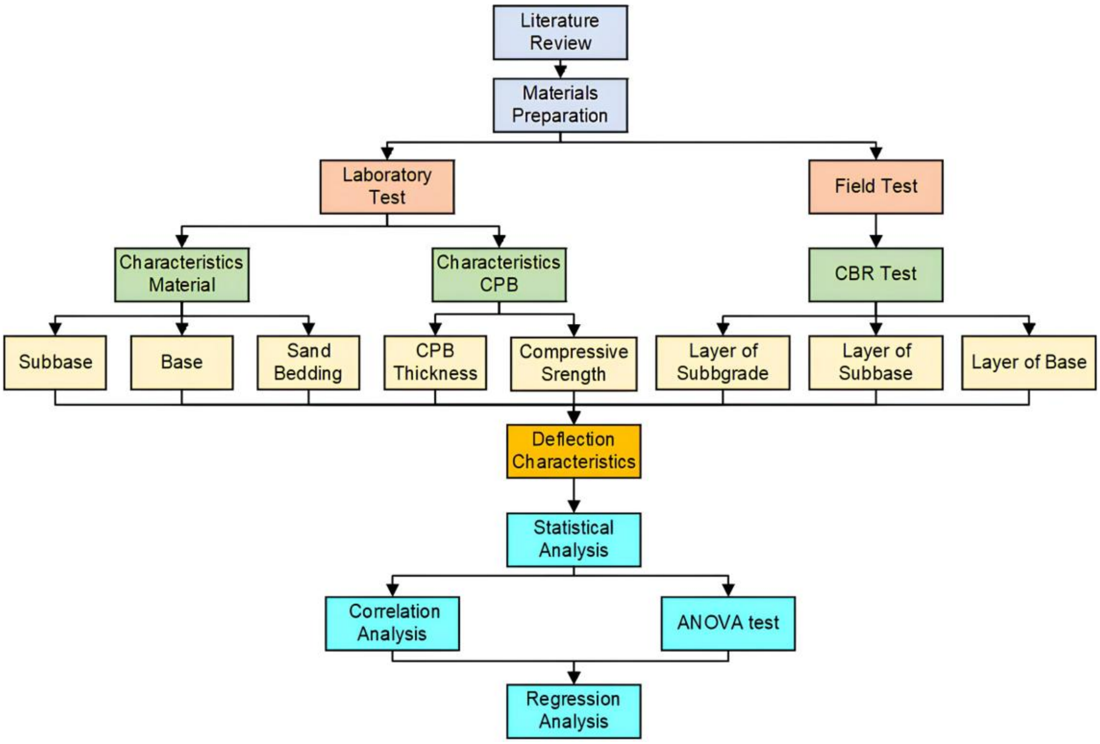

Fig. 1 Research flowchart

Fig. 2 shows the gradation composition of each aggregate material. The gradation analysis was conducted to determine the proportion of various particle sizes in each aggregate type. The results showed that the subbase material exhibited a particle size range from 37.5 mm to 0.075 mm. The base course material consists of aggregates ranging from 25 mm to 0.075 mm. Meanwhile, the sand bedding material exhibits a particle size range of 5 mm to 0.075 mm.

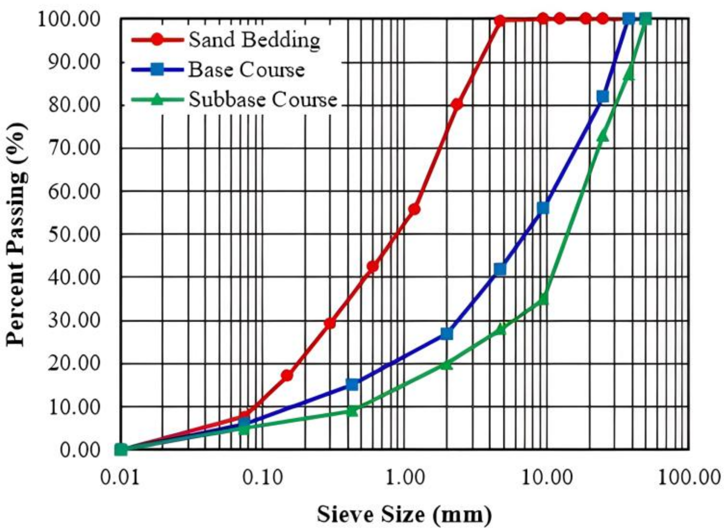

Fig. 2 Results of material gradation analysis for each layer

2.1. Pavement layer characteristics

The California Bearing Ratio (CBR) test is a widely used method for evaluating the potential bearing capacity of subgrade soil in flexible pavement construction [27]. The CBR testing apparatus consisted of a cylindrical penetration plunger with a diameter of 50 millimeters and a length of 102 millimeters. It also included an additional steel loading plate with a diameter of 254 millimeters and a central hole with a diameter of 50.8 millimeters [28]. Table 1 presents the CBR values for each layer in the constructed pavement structure.

Table 1 Comparison of CBR values in the pavement structure

Layer Type	CBR Test Results (%)
Base Course	61.29
Subbase Course	30.68
Subbgrade	12.53

2.2. Subbgrade

The present study used clayey silt for the subgrade layer. This category of material is classified as A-7-5. This layer is located beneath the subbase layer. The CBR testing points were strategically positioned at the center and along both edges of the specimen. These points were selected to represent the compaction characteristics of the entire subgrade layer. Based on these tests, the average CBR value of the subgrade soil layer is 12.53%. The characteristics of the soil are presented in Table 2.

Table 2 Properties of soil in the subgrade layer

No	Soil Properties	Result	Standard testing used
1	Specific Gravity	2.65	ASTM D854
2	Liquid Limit %	86.01	ASTM D4318
3	Plasticity Limit %	53.41	ASTM D4318
4	Plastic Index %	32.6	ASTM D4318
5	AAHSTO Soil Classification	A-7-5	AASHTO M145

2.3. Subbase Course

The subbase layer consists of aggregates with particle sizes ranging from 37.5 mm to 0.075 mm. According to the Indonesian Pavement Manual, the subbase layer uses class B aggregate material, consisting of particles ranging from 37.5 to 0.075 millimeters. The Indonesian Pavement Manual states that the minimum required thickness for the subbase layer in a flexible pavement structure is 150 millimeters. Subbase compaction is carried out in several stages. Each stage is compacted to a thickness of 50 millimeters to achieve optimal density. The thickness of the subbase layer is determined by marking elevation points. These points are located at the edge of the pavement structure. CBR test results indicate an average CBR value of 30.68% for the subbase layer.

2.4. Base Course

The subbase layer is aggregate material with particle sizes ranging from 25 mm to 0.075 mm. The base course layer is located above the subbase layer. This layer is stronger than the layers below it. According to the Indonesian Pavement Manual, the minimum thickness required for the subbase layer in a flexible pavement structure is 200 millimeters. This layer is compacted using a hand stamper to produce optimal density. The CBR test results indicate that the average CBR value of the base course layer is 61.29%.

2.5. Sand Bedding and Jointing Sand

Sand bedding and jointing sand are materials employed for the purpose of leveling layers and filling gaps between CPB. The utilization of these materials in the composition of the bottom layer of CPB has been demonstrated to enhance stability, improve interlocking, and facilitate the installation process. Sand bedding and jointing sand utilize stone ash material with a size range of 5 mm to 0.075 mm. The present study utilized sand bedding thicknesses of 3 cm, 5 cm, and 7 cm.

2.6. Concrete Paving Block

This study used CPB samples from the PT Master Block, located in Gunung Sindur, Bogor Regency. The thickness variations of CPB are 6 cm, 8 cm, and 10 cm. The present study utilizes identical shape and pattern parameters to achieve a consistent structural response. The herringbone pattern has been shown to have certain advantages over alternative patterns in terms of reducing surface deflection [24]. Meanwhile, the utilization of stone ash in the filling of the joints serves to ensure the uniform distribution of load between adjacent blocks during testing.

Table 3 Characteristics of CPB

Variation of CPB Thickness	Compressive strength of CPB cube 1	Compressive strength of CPB cube 2	Compressive strength of CPB cube 3
6 cm	22.07 MPa	24.30 MPa	27.04 MPa
8 cm	22.12 MPa	24.35 MPa	27.30 MPa
10 cm	22.21 MPa	24.87 MPa	27.55 MPa

The compressive strength of CPB is evaluated using block and cube specimens. Based on previous studies, cube specimens provide more realistic and consistent strength values [17-19]. The length-to-height ratio of a block-shaped specimens are not ideal for direct compression testing. This phenomenon can be attributed to the application of load, which gives rise to a shear effect, local bending, and stress concentration on the sides. Conversely, cube-shaped samples possess symmetrical proportions, thereby ensuring that the compressive force is more uniformly distributed across the concrete volume. These results are more realistic and follow the recommendation (SNI 03-0691) that CPB testing must use cube samples. The conversion factor for the compressive strength of CPB cubes to blocks ranges from 0.74 for a thickness of 6 cm, 0.84 for a beam thickness of 8 cm, and 0.94 for a thickness of 10 cm. Table 3 presents the compressive strength values of CPB.

2.7. LWD Test

The LWD test is a non-destructive technique that is frequently employed in the evaluation of road surfaces. The test method utilizes loads ranging from approximately 15 kN, employing load plates with a diameter of 100 to 300 millimeters [29]. The present study used load variations of 6.9 kN, 8.6 kN, and 10.1 kN. These variations are intended to represent realistic service conditions and to prevent structural damage during repeated measurements. Despite the fact that the road surface design meets an equivalent single axle load (ESAL) of approximately 81 kN, the measured deflection data can be normalized to the applied stress level. This allows for a regression prediction model for higher design loads, assuming a linear elastic response.

2.8. Analysis Method

This study utilizes a statistical approach to data analysis. The initial step in this process is to utilize statistical correlation analysis. The calculation of the correlation value can be performed using the following Eq. (1).

$$r = \frac{\sum_{i=1}^{n}(Xi-\overline{X})(Yi-\overline{Y})}{\sqrt{\sum_{i}^{n}(Xi-\overline{X})^2\sum_{i}^{n}(Yi-\overline{Y})^2}} \tag{1}$$

where, X_i and Y_i are the values in each variable, $\overline{X}$ and $\overline{Y}$ are the average of the X and Y values, n is the number of data, and r represents the correlation coefficient. The subsequent step in this process is analysis of variance (ANOVA). This analysis is employed to ascertain the significance of the relationships between independent and dependent variables. The objective of the ANOVA test is to identify the independent variables that contribute to the observed deflection. In the final stage, multiple linear regression statistical analysis is used. This analysis is used to explain the relationship between independent variables and dependent variables. The regression formula is presented in Eq. (2).

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + ... \alpha_n X_n + \in \tag{2}$$

where Y is the predicted dependent variable. X_1 and X_n (n=2, …,n) are explanatory variables employed in predicting the dependent variable, α_0 and α_i (i = 1, ..., n) are coefficients of the unit change affected by X. Meanwhile, $\in$ is the estimated error term in the equation.

3. Results and Discussion

This section presents and discusses the experimental and statistical results obtained from light weight deflectometer (LWD) testing. The present analysis focuses on the deflection behavior of the CPB surface under variations in CPB thickness, sand bedding thickness, compressive strength, and applied load. The ensuing results are organized in a specific manner. Initially, the observed deflection characteristics are described. This is followed by an examination of the relationships between variables, the influence of parameter groups, and deflection predictions based on various variables.

3.1. Analysis of CPB Deflection Characteristics

The present study evaluates the characteristics of CPB structures with variations in CPB thickness and sand bedding thickness. The results of the analysis indicated that the thickness of the CPB and sand bedding influences the deflection value. The analysis results indicate that an increase in CPB thickness and sand bedding causes a decrease in deflection values. These results indicate that thicker structures demonstrate greater resistance than thinner CPB and sand bedding, as shown in Fig. 3.

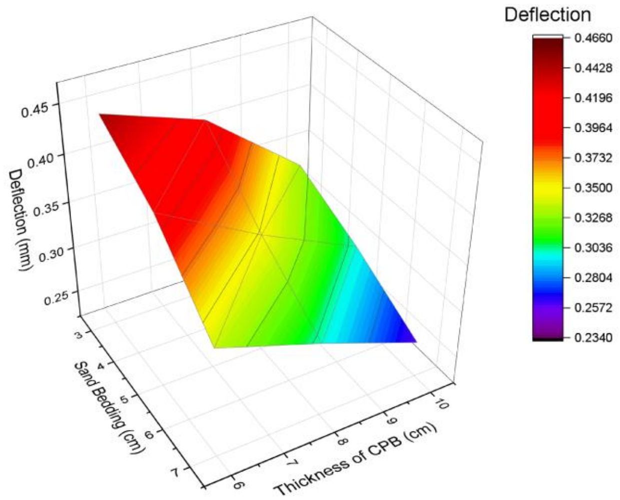

Fig. 3 Deflection characteristics based on sand bedding and CPB thicknesses

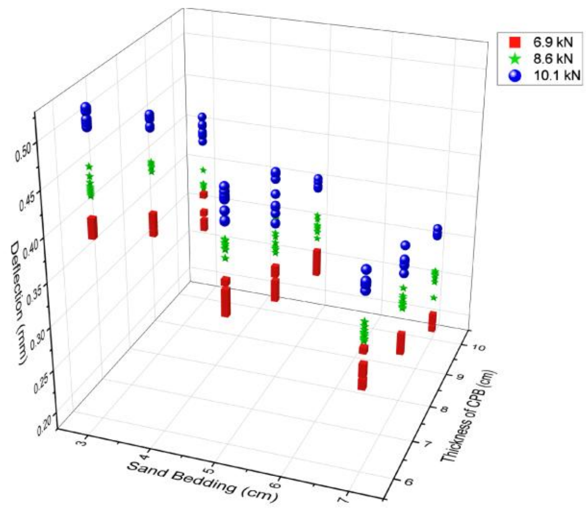

Fig. 4 Comparison of deflections under different loads

Furthermore, this study varied the load by 6.9 kN, 8.6 kN, and 10.1 kN on the thickness of the CPB and sand bedding. The results showed similar findings, namely that an increase in the thickness of the CPB and sand bedding resulted in lower deflection values, as depicted in Fig. 4. The increased thickness of the CPB results in a more rigid surface layer, thereby ensuring the uniform distribution of loads. The utilization of thick sand bedding has been demonstrated to facilitate the distribution of load to the lower layers of the pavement. Meanwhile, increased loads on variations in CPB thickness and sand bedding resulted in greater deflection values. This result is consistent with the basic principle of elasticity, where deformation is directly proportional to the applied force (load).

3.2. Relationship Between Dependent Variables and Independent Variables

This study uses correlation analysis to evaluate the relationship between dependent variables and independent variables. The objective of this analysis was to measure the relationship between deflection (Y) and independent variables. Additionally, this analysis evaluated the relationship between independent variables. The results of the correlation analysis are presented in Tables 4 and 5.

Table 4 Correlation analysis results between dependent and independent variables

Varible	y	X_1	X_2	X_3	X_4
	(Deflection)	(Sand bedding thickness)	(CPB thickness)	(compressive strength of CPB)	(load)
Correlation Value (r)	1,000	-0.485	-0.479	-0.492	0.514

The findings of the present study reveal a negative correlation between deflection and sand bedding thickness (r = -0.485), CPB thickness (r = -0.479), and compressive strength (r = -0.492). This negative correlation suggests that the presence of thicker and stronger structural layers can increase stiffness and minimize vertical displacement. Conversely, the load variable (X4) exhibited a positive correlation with deflection (r = 0.514). In accordance with the fundamental tenets of material mechanics, an increase in load invariably leads to an increase in deflection.

Table 5 Correlation analysis results between independent variables

	X_1 (Sand bedding thickness)	X_2 (CPB thickness)	X_3 (compressive strength of CPB)	X_4 (load)
X_1 (Sand bedding thickness)	1			
X_2 (CPB thickness)	0	1		
X_3 (Compressive strength of CPB)	0	0	1	
X_4 (load)	0	0	0	1

The correlation results between the independent variables (X_1-X_4) demonstrate no significant dependence. These findings suggest that all variables are independent and contribute significantly to structural performance. Additionally, the findings indicate that no variables demonstrate evidence of multicollinearity. The findings of this study ensure the accuracy of regression analysis and confirm that each variable can explain road surface deflection.

3.3. Influence of variable groups of thickness, sand bedding, compressive strength, and load

Subsequently, an analysis of variance (ANOVA) test was performed to evaluate the significance of each variable on surface deflection. The primary function of ANOVA tests is to determine the relationship between two or more groups and to ascertain the significance of that relationship.

Table 6 Summary of F, P, and Fcrit values from ANOVA

Variable 1	Variable 2	F_{value}	P_{value}	F_{crit}
X_1 (Sand bedding thickness)	X_2 (CPB thickness)	55.485	0.000	3.033
X_2 (CPB thickness)	X_1 (Sand bedding thickness)	56.131	0.000	3.033
X_1 (Sand bedding thickness)	X_3 (Compressive strength of CPB)	55.043	0.000	3.033
X_3 (Compressive strength of CPB)	X_1 (Sand bedding thickness)	60.217	0.000	3.033
X_1 (Sand bedding thickness)	X_4 (load)	56.782	0.000	3.033
X_4 (load)	X_1 (Sand bedding thickness)	56.119	0.000	3.033
X_2 (CPB thickness)	X_3 (Compressive strength of CPB)	61.623	0.000	3.033
x3 (Compressive strength of CPB)	X_2 (CPB thickness)	54.275	0.000	3.033
X_2 (CPB thickness)	X_4 (load)	53.018	0.000	3.033
X_4 (load)	X_2 (CPB thickness)	53.812	0.000	3.033
X_3 (Compressive strength of CPB)	x4 (load)	62.414	0.000	3.033
x4 (load)	X_3 (Compressive strength of CPB)	56.973	0.000	3.033

As illustrated in Table 6, the results of the ANOVA show that all independent variables have a significant effect on the dependent variable. The results indicate that F_{value} exceeds F_{crit} and the P value is less than 0.05 in all combinations. Specifically, the relationship between sand bedding thickness (X1), CPB thickness (X2), compressive strength (X3), and load (X4) is significant. These results demonstrate a consistent trend with the findings of the previous correlation analysis. The findings indicate that variables X1, X2, X3, and X4 significantly impact the value of Y, as evidenced by $F_{value} > F_{crit}$ and $P_{value} < 0.05$. Therefore, the ANOVA results suggest that all variables should be used as independent variables in regression analysis. From the perspective of regression analysis in pavement structure analysis, the absence of multicollinearity ensures that each parameter can be used in multiple linear regression analyses. These analyses can produce accurate predictive models.

3.4. Deflection prediction based on various variables

The subsequent section presents four multiple linear regression equations that predict surface deflection (Y) based on sand bedding thickness (X_1), CPB thickness (X_2), compressive strength (X_3), and applied load (X_4). The present study utilizes the load parameter (x4) as a multiplier factor. This parameter shows a direct relationship between load and surface deflection, as illustrated in Table 7.

Eq. (1) considers the thickness parameters (X1 and X2) and load. This equation produces a coefficient of determination of $R^2 = 0.603$. These findings suggest that the equation is applicable in scenarios where compressive strength is considered constant. Eqs. (2) and (3) present the compressive strength parameter (X_3) against the thickness of the sand bedding (X_1) or the thickness of the CPB (X_2). The results of the analysis show that the R^2 values are 0.620 and 0.612, respectively. These results illustrate the impact of compressive strength on enhancing road surface stiffness and decreasing surface deflection. Eq. (4) demonstrated the highest degree of accuracy in the analysis that incorporated all variables ($R^2 = 0.917$). This analysis shows strong agreement with theoretical predictions, wherein the predicted deflection (y) approaches zero as the applied load (x4) approaches zero. Eq. (4) shows that the combined effects of geometry (X_1, X_2), material (X_3), and load (X_4) can be used with a single predictive equation. These results are suitable for practical evaluation and optimization of the CPB pavement system design.

Table 7 Deflection of the CPB structure using a statistical approach.

No.	Variables Involved	Equation	R^2	Variable Definition
1	$y = f(X_1, X_2, X_4)$	$y = X_4*(0.07984 - 0.00299X_1 - 0.00295X_2)$	0.603	X_1 = sand bedding thickness (cm); X_2 = CPB thickness (cm); X_4 = applied load (kN); y = deflection (mm)
2	$y = f(X_1, X_3, X_4)$	$y = X_4*(0.11490 - 0.00299X_1 - 0.00241X_3)$	0.62	X_1 = sand bedding thickness (cm); X_3 = compressive strength (MPa); X_4 = applied load (kN); y = deflection (mm)
3	$y = f(X_2.X_3.X_4)$	$y = X_4*(0.12354 - 0.00295X_2 - 0.00241X_3)$	0.612	X_2 = CPB thickness (cm); X_3 = compressive strength (MPa); X_4 = applied load (kN); y = deflection (mm)
4	$y = f(X_1, X_2.X_3.X_4)$	$y = X_4*(0.13849 - 0.00299X_1 - 0.00295X_2 - 0.00241X_3)$	0.917	X_1 = sand bedding thickness (cm); X_2 = CPB thickness (cm); X_3 = compressive strength (MPa); X_4 = applied load (kN); y = deflection (mm)

4. Conclusions

This study aims to investigate the structural behavior of CPB using a statistical approach to analyze the deflection characteristics of the surface layer. The main conclusions are summarized as follows:

(1) Increasing the thickness of the CPB and sand bedding effectively improves structural stiffness and load distribution in flexible pavements, thereby significantly reducing surface deflection. As the thickness of the CPB and sand bedding increased, the measured deflection decreased from 0.446 mm to 0.259 mm. These results indicate that thicker structures demonstrate greater resistance than thinner CPB and sand bedding.

(2) The parameters of sand bedding thickness (X_1), CPB thickness (X_2), and CPB compressive strength (X_3) contribute to reducing surface deformation. However, the load (X_4) is still the main factor affecting deflection. This parameter describes the relationship between geometry and material interaction, which is critical for controlling the response of the road surface to loads.

(3) The ANOVA results indicated that all independent variables, namely sand bedding thickness (X_1), CPB thickness (X_2), compressive strength (X_3), and load (X_4), have a significant effect on surface deflection at a p-value less than 0.05. The F value showed a consistent increase, exceeding the critical threshold, thereby confirming the strong influence of all variables on deformation behavior. These findings validate the utilization of all variables in regression analysis and indicate the absence of multicollinearity, meaning each variable can contribute to model performance.

(4) Four regression equations were developed, with the most effective equation incorporating all variables (X_1, X_2, X_3, and X_4) and producing an R^2 value of 0.917. This equation can be used to estimate road surface deflection based on material and geometric properties, thereby supporting optimization in the design and performance evaluation of CPB roads.

(5) It is recommended that further research be conducted to validate the equations developed under field conditions. In order to enhance the reliability of predictions, additional parameters must be considered, such as environmental impact.

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Conflicts of Interest

The authors declare no conflict of interest.

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