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Original Article

Optimization of Rigid Pavement Design: Effects of L/B Ratio, and Load Transfer Mechanisms

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Abstract:
This study explores how slab geometry, specifically the length-to-breadth (L/B) ratio, interacts with thermal gradients, load-induced stresses, and support conditions in determining the performance of rigid concrete pavements. Variations in slab width, compounded by the presence of tied shoulders, significantly influence stress distribution and the pavement's structural behavior. The research emphasizes the critical role of load transfer devices like dowel bars at transverse joints and deformed tie bars at longitudinal joints in mitigating faulting and joint separation. By analyzing the combined effects of geometric proportions and reinforcement strategies, the study offers insights into enhancing pavement durability, reducing bottom-up cracking under downward curling, and extending service life through optimized design. This research investigates how variations in slab geometry specifically length to breadth (L/B) ratios impact stress distributions and durability in rigid pavements. Rigid pavement performance is sensitive to geometric proportions, foundation support, and thermal gradients, which induce warping and curling stresses, especially under negative temperature differentials. Wider slabs, particularly those integrated with tied paved shoulders, exhibit altered stress concentration patterns and are more prone to longitudinal as well as transverse cracking. he study further underscores the importance of load transfer mechanisms: dowel bars installed at transverse joints and deformed tie bars at longitudinal joints are essential for transferring loads, minimizing joint deflection, faulting, and slab separation through analysis of stress response and reinforcement demands across varying L/B ratios, the findings suggest that appropriate geometric and reinforcement design can significantly enhance pavement resilience and lifespan. These insights are critical for informing design strategies that mitigate cracking and structural deterioration in rigid pavements.

Key Words: Rigid pavement, Dowel Bar, Tie Bar, structural evaluation

• Introduction:

The structural performance and longevity of rigid concrete pavements are governed by a complex interplay of geometric design, support conditions, thermal behavior, and load transfer mechanisms. Specifically, the width of the slab in relation to its length expressed through the length-to-breadth (L/B) ratio plays a pivotal role in determining how stresses are distributed across the pavement under varying environmental and traffic conditions. Thermal gradients across slab depth induce curling and warping stresses, particularly under negative temperature differentials, exacerbating the risk of bottom-up cracking and joint. These thermally-driven stresses are further compounded by load-induced stresses, which emerge during curling when vehicular loads are applied under constrained support. Effective load transfer across joints is essential for mitigating structural distress. Dowel bars, installed at transverse joints, serve to transfer shear loads and minimize joint deflections. Their effectiveness depends on appropriate dimensions typically around 25 mm in diameter, 500 mm in length, and spaced 250–300 mm apart, depending on slab thickness. Tie bars, located at longitudinal joints, function to tie adjacent slabs together and resist tensile stresses due to slab separation, they must be designed according to bond stress and tension requirements, with spacing and length proportional to slab width and concrete properties. This investigation systematically analyzes the stress response of rigid pavement slabs across a range of L/B ratios, considering support from tied shoulders. It further evaluates the longitudinal and lateral reinforcement needs such as dowel and tie bar dimensions, placement, and spacing, to enhance durability under thermal stress and repeated loading. By targeting both geometric and reinforcement strategies, the study aims to optimize rigid pavement design for improved performance, reduced cracking, and extended service life

Objectives of the study

The primary objective of this study is to optimize the structural design of rigid concrete pavements by systematically investigating the influence of slab geometry specifically the length-to-breadth (L/B) ratio, thermal gradients, and load transfer mechanisms on pavement performance. The research aims to evaluate how varying L/B ratios affect stress distribution and cracking potential under both environmental and traffic-induced loading conditions.

Additionally, the study seeks to quantify the impact of temperature-induced curling and warping stresses, particularly under negative thermal differentials, and their interaction with vehicular loads. A critical component of the investigation focuses on the role of load transfer devices, including dowel bars and tie bars, in minimizing joint deflections and enhancing structural continuity. By analyzing different configurations and placements of these reinforcement elements, the study strives to develop optimized design guidelines that improve pavement durability, reduce maintenance needs, and extend service life under diverse climatic and loading scenarios.

- **Need of the study**

The performance of rigid pavements is highly sensitive to slab geometry, load transfer mechanisms, and reinforcement detailing. Variations in length-to-breadth (L/B) ratios significantly affect stress distribution, curling, and warping behaviour, particularly under negative temperature gradients that induce bottom-up cracking. The effectiveness of dowel bars at transverse joints and tie bars at longitudinal joints is crucial for controlling joint separation and faulting, thereby enhancing pavement durability. However, existing design practices often adopt generalized reinforcement provisions without adequately accounting for slab geometry variations and reinforcement bar dimensions. Hence, there is a strong need to evaluate the influence of slab proportions on dowel and tie bar requirements, with an emphasis on optimizing bar diameter, length, and spacing. This study aims to bridge this gap by analysing the structural efficiency of different reinforcement configurations to ensure durability and economy in rigid pavement design.

- **Literature related to Influence of Slab Geometry and Reinforcement Design on the Performance of Rigid Concrete**

The rigid pavement performance has extensively explored the influence of geometric configurations, thermal effects, and load transfer mechanisms on structural integrity and service life. Studies have shown that the length-to-breadth (L/B) ratio of pavement slabs significantly affects stress concentration patterns, particularly at slab corners and edges, where cracking is most likely to initiate. High L/B ratios tend to increase curling and warping deformations due to thermal gradients, especially under negative temperature differentials, leading to bottom-up cracking and reduced load-carrying capacity. Research on thermal behavior in rigid pavements highlights the critical role of temperature-induced curling stresses and their interaction with traffic loads. These stresses are most severe when the slab is curled upward and subjected to axle loads, often resulting in increased tensile stresses at the bottom of the slab. To mitigate these effects, load transfer mechanisms, particularly dowel bars at transverse joints, have been studied for their ability to reduce joint deflection and distribute wheel loads effectively. Dowel bar effectiveness has been linked to parameters such as diameter, length, spacing, and alignment. Similarly, tie bars at longitudinal joints have been analyzed for their contribution to slab continuity and resistance against joint separation due to shrinkage and thermal movement. Optimal sizing and spacing of tie bars are found to be critical for minimizing tensile stresses and preventing faulting. While individual aspects slab geometry, thermal behavior, and joint reinforcement have been well documented, there is limited integrated research that evaluates these factors collectively for design optimization. The literature underscores the need for a comprehensive approach that simultaneously considers geometric design, environmental effects, and reinforcement strategies to enhance the structural performance and longevity of rigid pavements.

CP Tech. (2023) quantified how curling and warping create significant stress gradients through slab depth and shows that tied paved shoulders generally reduce edge restraint and lower stress concentrations at slab edges. The report also notes interactions between load-transfer devices (dowels) and curling behavior — dowels improve load transfer but can increase local stresses at joint faces under certain curling conditions.

Ceylan et al. (2020) studied Using analytical models and charts based on slab geometry and relative stiffness, this work relates slab length/width and boundary conditions to curling-induced stresses and deflections. It highlights that wider slabs (larger breadth for a given length) and the presence or absence of tied shoulders change the slab's radius of relative stiffness, thereby modifying curling stresses and risk of both top-down and bottom-up cracking.

Setiawan et al. (2020) This mechanistic study demonstrates that temperature gradients (top cooler than bottom or vice-versa), combined with subgrade support variability, control magnitude and sign of curling moments. The authors show that L/B ratio and shoulder restraint significantly change predicted stress fields and that bottom-up cracking risk increases when tensile stresses concentrate near the slab base under negative gradients. Their work supports coupling geometric (slab width/L-B) and boundary (tied shoulder) conditions in design checks.

Mallela et al. (2009) proposed mechanistic-empirical methods for sizing deformed tie bars for longitudinal joints. It finds that tie bars are primarily effective for maintaining alignment and restricting lateral separation, with limited influence on curling-induced vertical stresses — therefore tie bar requirements vary more with joint restraint and traffic-induced shear than with thermal curling. The work recommends treating dowel (transverse) and tie-bar (longitudinal) design as complementary: dowels for vertical load transfer under curling; ties for longitudinal continuity.

- **Methodology**

The methodology consisted of four major stages: data collection, model development, calibration, and validation. Data were collected on vehicle volume, routing, speed, and composition at the Bus Stand Junction Fountain. The VISSIM model was developed for the four-legged roundabout, followed by calibration of key driving behaviour parameters such as standstill distance, minimum look-ahead distance, and saturation flow. Validation was performed by comparing simulated data with field observations using statistical techniques.

- **Methodology**

The study began with the identification and collection of key parameters influencing the structural performance of rigid concrete pavements. These included slab length (L), breadth (B), thickness, length-to-breadth (L/B) ratios, and reinforcement configurations involving dowel and tie bars. Three reinforcement combinations were considered for analysis: 32 mm dowel bars paired with 10 mm tie bars, 36 mm dowel bars with 12 mm tie bars, and 38 mm dowel bars with 16 mm tie bars. To assess the impact of slab geometry, pavement slabs of constant length (4.5 meters) were modeled with varying widths ranging from 3.20 to 4.50 meters, resulting in L/B ratios from 1.0 to 1.4. The thermal and load-induced stress behavior of these slabs was evaluated under different geometric conditions. For reinforcement detailing, the required lengths and spacing of dowel bars were determined for each diameter based on load transfer efficiency, while tie bar dimensions were calculated according to bond stress and tensile capacity criteria to ensure joint stability and reduce cracking potential. A comparative evaluation was conducted by plotting the variations in tie bar spacing with changes in L/B ratio across different diameters, alongside an analysis of dowel bar spacing relative to their diameters to determine effectiveness. Results were interpreted using graphical tools such as scatter plots, bar charts, and pie charts to visualize performance trends. Finally, recommendations were developed for optimal reinforcement configurations that strike a balance between structural performance and cost-effectiveness.

- **Data Collection and Analysis**

To accurately assess the impact of vehicular loading on rigid pavement performance, axle load data was collected from relevant traffic studies and weigh-in-motion (WIM) stations along representative highway corridors. The data included classifications of axle types single, tandem, and tridem along with their corresponding frequency of occurrence and load magnitudes. An axle load spectrum was developed by categorizing the collected data into standard load bins, allowing for a comprehensive understanding of the distribution and intensity of loads applied to the pavement over time. This spectrum enabled the identification of critical loading scenarios that significantly influence stress responses, particularly during slab curling or under non-uniform support conditions. The collected axle data was then used to simulate realistic traffic loading conditions in the pavement model, ensuring that both typical and extreme loading cases were considered in the structural analysis. The analysis accounted for cumulative load repetitions, which are vital for evaluating long-term fatigue performance and crack propagation potential. This data-driven approach provided a robust foundation for evaluating the adequacy of various reinforcement strategies and geometric configurations under real-world traffic loading conditions. Axle load spectrum used for the structural evaluation of rigid pavement has been shown in table 01.

Table: 01

Axle load spectrum

RSA			RTaA			RTrA		
265-275	0	0.00	540-560	0	0.00	770-800	0	0.00
255-265	0	0.00	520-540	0	0.00	740-770	0	0.00
245-255	0	0.00	500-520	0	0.00	710-740	0	0.00
235-245	0	0.00	480-500	0	0.00	680-710	0	0.00
225-235	0	0.00	460-480	0	0.00	650-680	0	0.00
215-225	0	0.00	440-460	0	0.00	620-650	0	0.00
205-215	0	0.00	420-440	0	0.00	590-620	0	0.00

RSA			RTaA			RTrA		
195-205	0	0.00	400-420	0	0.00	560-590	0	0.00
185-195	1	0.43	380 - 400	0	0.00	530-560	0	0.00
175-185	1	0.43	360 - 380	0	0.00	500-530	0	0.00
165-175	2	0.86	340 - 360	0	0.00	470-500	0	0.00
155-165	0	0.00	320 - 340	0	0.00	440-470	0	0.00
145-155	4	1.72	300 - 320	1	1.11	410-440	2	28.57
135-145	2	0.86	280 - 300	4	4.44	380-410	0	0.00
125-135	5	2.15	260 - 280	5	5.56	350-380	1	14.29
115-125	4	1.72	240 - 260	14	15.56	320-350	0	0.00
105-115	12	5.15	220 - 240	11	12.22	290-320	0	0.00
95-105	5	2.15	200 - 220	10	11.11	260-290	0	0.00
85-95	15	6.44	180 - 200	3	3.33	230-260	0	0.00
< 85	182	78.11	< 180	42	46.67	< 230	4	57.14

Cement Concrete pavements have different types of Joints as below:

- Contraction Joint
- Expansion Joint
- Construction Joint
- Longitudinal Joint

Contraction joints are transverse joints which relieve the tensile stresses in concrete pavement. Expansion joints are transverse joints to allow expansion of concrete slab due to rise in slab temperature during summer months. Construction joints should be as far as possible is placed at location of Contraction joints.

- **Design of Dowel Bar**

Load transfer to relieve part of load stresses in edge and corner regions of pavement slab at transverse joints is provided by means of mild steel round dowel bars. The dowel bars are designed based on the PQC slab thickness proposed in accordance with Table 5 of IRC 58-2015. Recommended diameter and length of the dowel bar is as per the **Error! Reference source not found.** below.

Table: 02

Recommended Dimensions of Dowel bars

Slab Thickness (mm)	Dowel Bar Details		
	Diameter (mm)	Length (mm)	Spacing (mm)
200	25	360	300
230	30	400	300
250	32	450	300
280	36	450	300
300	38	500	300
350	38	500	300

Based on the slab thickness and axle load data, the size of dowel bars is calculated as follows:

Bearing stress in the concrete that is responsible for the performance of dowel bars at the joints. Maximum bearing stress Fbmax between the concrete and dowel bar is obtained from equation below:

Fbmax = Kmds Pt (2+βZ)/ (4β3 EI)………………… Equation 1

Where,

β = relative stiffness of the bar embedded in concrete in mm = √(Kmds bd / 4EI)

Kmds = modulus of dowel support, MPa/m = 415000 MPa/m

b = diameter of the dowel, mm

z = joint width (5mm for contraction joint and 20mm for expansion joint) in mm

E = modulus of Elasticity of the dowel bar, MPa = 200000 MPa

I = Moment of Inertial of Dowel, mm4

Pt = Load transferred by design dowel bar, kN

The Allowable Bearing stress in concrete Fb is given by

Fb = (101.6-bd) fck/95.25…………………………..... Equation 2

Where, fck = grade of concrete, 40MPa

The design check for bearing stress is as follows:

Table: 03
Design check for Dowel Bar

S. No	Design Parameter	Contraction Joint	Expansion Joint
1	Slab Thickness, h (m)	0.300	0.300
2	Joint Width, z (mm)	5	20
3	Modulus of Subgrade Reaction, k (MPa/m)	55	55
4	Radius of relative Stiffness, l (m)	1.08	1.08
5	Modulus of elasticity for Dowel Bar (MPa)	200000	200000
6	Modulus of Dowel Support (MPa/m)	415000	415000
7	Maximum Single Axle load (kN)	170	170
8	Maximum Single Wheel Load (kN)	85	85
9	% of Load transfer across the joint through Dowel bar (%)	50	50
10	Wheel load to be considered for Dowel bar Design (kN)	85	85
11	Factor of Safety	1	1
12	Grade of Concrete (MPa)	40	40
13	Diameter of the dowel bar (mm)	32	32
14	Spacing between the Dowel bar (m)	0.30	0.24
15	Length of Dowel bar (m)	0.5	0.5
16	No of Dowel bar Participating in Load transfer	4	5
17	No of Spacings	3	4
18	Total Load transfer by Dowel bar System	2.341	2.788
19	Load transferred by outer dowel bar, Pt (kN)	18.156	15.245
20	Moment of Inertia, mm4	51445.76	51445.76
21	Relative Stiffness of Dowel bar, β	0.024	0.024
22	Allowable Bearing stress in Concrete, Fb (MPa)	29.228	29.228
23	Bearing stress between Concrete and Dowel bar, Fbmax	28.656	28.121

S. No	Design Parameter	Contraction Joint	Expansion Joint
24	Design Check, Fb > Fbmax	29.228 > 28.656 Safe	29.228 > 28.121 Safe

- **Design of Tie Bar**

Tie bars shall be provided in longitudinal joints in accordance with IRC 58-2015 and IRC 15-2017.
The area of steel required for metre length of the joint is given by:
As = b x f x W /Sst ……………………………………….Equation-3
where,
As – Area of steel in mm2, required per metre length of joint
B - Lane width in metres
f - Coefficient of friction between pavement and sub base/ base (usually taken as 1.5)
W – Weight of slab in kN/m2
Sst – Allowable Working stress of steel in MPa.
The length of Tie bar is given by:
L = 2 x Sst x Acs / Bw x Pptb …………………………..Equation-4
Where,
L – Length of Tie bar (mm)
Sst – Allowable Working Stress in Steel (MPa)
Acs – Cross Sectional Area of one tie bar (mm2)
Pptb – Perimeter of the Tie bar (mm) and
Bw – Permissible Bond Stress of Concrete (i) for deformed tie bars = 2.46 MPa and (ii) for plain tie bars = 1.75 Mpa

Table: 04
Design Check for Tie Bar

Design Parameters	
Slab Thickness, m	0.300
Slab Width b, m	4.375
Coefficient of friction, f	1.5
Density of Concrete, kN/m3	24
Allowable Tensile Stress in deformed bars, MPa	200
Allowable Bond Stress in deformed bars,	2.46
Design of Deformed Bars	
Diameter of Tie bar, m	0.012
Area of Steel required per meter width (mm2/m) as per Eq. 1	244.125
Cross section area of tie bar, A (mm2)	113.04
Perimeter of Tie Bar, P (mm)	37.68
Spacing of Tie Bar (mm)	463.04 say 460
Length of Tie bar, L (mm) as per Equation 2	487.80
Required Length of Tie Bar L (mm) (100mm for Bondage loss and 50mm for inaccuracy)	637.80 say 640

- **Results and Discussion**

An analytical comparison was conducted to assess the effect of dowel bar diameter on dowel spacing in rigid pavement slabs, considering slab geometries with varying length-to-breadth (L/B) ratios ranging from 1.0 to 1.4. The dowel diameters evaluated were 32 mm, 36 mm, and 38 mm, with corresponding constant dowel bar lengths of 500 mm for all cases. Other parameters, such as slab thickness (310 mm), tie bar dimensions, and spacing were kept consistent within each group to isolate the effect of dowel diameter.

The results, as illustrated in the bar chart, indicate a direct correlation between dowel diameter and allowable spacing. For 32 mm diameter dowels, the spacing was maintained at 250 mm. When the dowel diameter increased to 36 mm, the spacing increased to 330 mm, and for 38 mm diameter dowels, the spacing further increased to 360 mm. This demonstrates that larger dowel diameters facilitate greater spacing between dowels without compromising load transfer efficiency at transverse joints The requirement of Dowel and Tie bar for different L/B ratio has been shown below.

Table: 05
32 mm dowel bar & 10 mm Tie bar

Sl No	Slab Size			Dowel bar details			Tie bar details			L/B ratio
	L	B	Thk of Slab	dia	length	spacing	dia	length	spacing	
1	4.5	4.50	310	32	500	250	10	560	315	1.0
2	4.5	4.25	310	32	500	250	10	560	330	1.1
3	4.5	4.00	310	32	500	250	10	560	350	1.1
4	4.5	3.75	310	32	500	250	10	560	375	1.2
5	4.5	3.50	310	32	500	250	10	560	400	1.3
6	4.5	3.20	310	32	500	250	10	560	440	1.4

Table: 06
36 mm dowel bar & 12 mm Tie bar

Sl No	Slab Size			Dowel bar details			Tie bar details			L/B ratio
	L	B	Thk of Slab	dia	length	spacing	dia	length	spacing	
1	4.5	4.50	310	36	500	330	12	640	450	1.0
2	4.5	4.25	310	36	500	330	12	640	480	1.1
3	4.5	4.00	310	36	500	330	12	640	510	1.1
4	4.5	3.75	310	36	500	330	12	640	540	1.2
5	4.5	3.50	310	36	500	330	12	640	580	1.3
6	4.5	3.20	310	36	500	330	12	640	635	1.4

Table: 07
38 mm dowel bar & 16 mm Tie bar

Sl No	Slab Size			Dowel bar details			Tie bar details			L/B ratio
	L	B	Thk of Slab	dia	length	spacing	dia	length	spacing	
1	4.5	4.50	310	38	500	360	16	810	800	1.0
2	4.5	4.25	310	38	500	360	16	810	850	1.1
3	4.5	4.00	310	38	500	360	16	810	900	1.1
4	4.5	3.75	310	38	500	360	16	810	960	1.2
5	4.5	3.50	310	38	500	360	16	810	1030	1.3
6	4.5	3.20	310	38	500	360	16	810	1125	1.4

- **Findings of the Study:**

Furthermore, the dowel spacing remained unchanged across all L/B ratios within each diameter group, indicating that dowel spacing is predominantly governed by dowel diameter rather than slab geometry in the configurations studied. This observation suggests that the use of larger diameter dowels can lead to a reduction in the total number of dowels required per joint, potentially optimizing material usage and installation efforts, albeit at the cost of using larger individual dowels. In summary, the findings confirm that increasing dowel diameter results in a proportional increase in dowel spacing, offering potential structural and economic advantages in rigid pavement design. Variation of dowel bar and tie bar spacing has been shown in figure below.

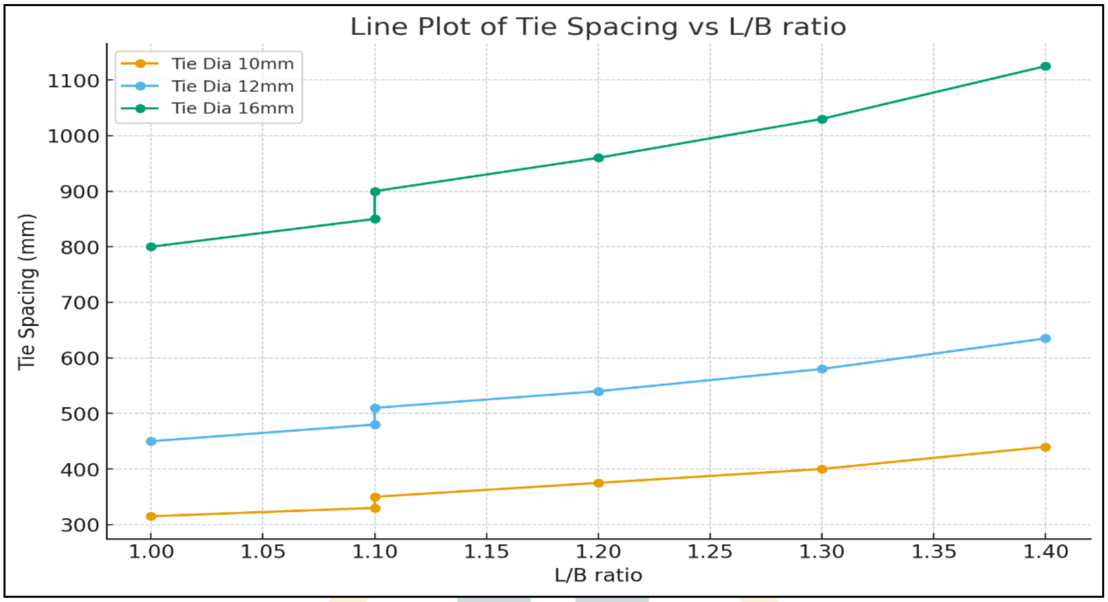

Figure 1, variation of Tie Bar spacing for different L/B ratio

Influence of Dowel Diameter on Spacing:

The study clearly demonstrates that dowel bar spacing increases with an increase in dowel diameter. Specifically, dowel spacing values of 250 mm, 330 mm, and 360 mm were observed for dowel diameters of 32 mm, 36 mm, and 38 mm, respectively.

Constant Dowel Spacing Across Varying L/B Ratios:

Within each dowel diameter group, dowel spacing remained constant despite variations in the length-to-breadth (L/B) ratio of the slab. This indicates that dowel spacing is primarily influenced by dowel diameter, not by the slab aspect ratio, under the studied conditions.

Potential for Material and Cost Optimization:

The ability to increase dowel spacing with larger diameters suggests potential material and labor cost savings. Fewer dowels are required for larger diameters without compromising structural performance at joints, making this a viable design optimization strategy.

Structural Efficiency:

The increase in allowable spacing for larger dowels supports efficient load transfer across transverse joints, which is critical for the long-term performance of rigid pavements. Larger dowels can thus improve both structural integrity and service life of the pavement system.

Design Guidance:

The findings provide empirical support for dowel bar design in rigid pavements, reinforcing the practice of using larger diameter dowels at wider spacing as a means of achieving both structural adequacy and economic efficiency.

The study identifies dowel diameter as a critical parameter influencing dowel spacing in rigid pavement design. It was observed that increasing the dowel diameter from 32 mm to 38 mm allowed for a corresponding increase in spacing from 250 mm to 360 mm. This relationship indicates that larger dowel bars can effectively transfer loads over wider distances, enabling reduced dowel quantities per joint while maintaining structural integrity. Such optimization contributes to both material efficiency and potential cost savings in pavement construction.

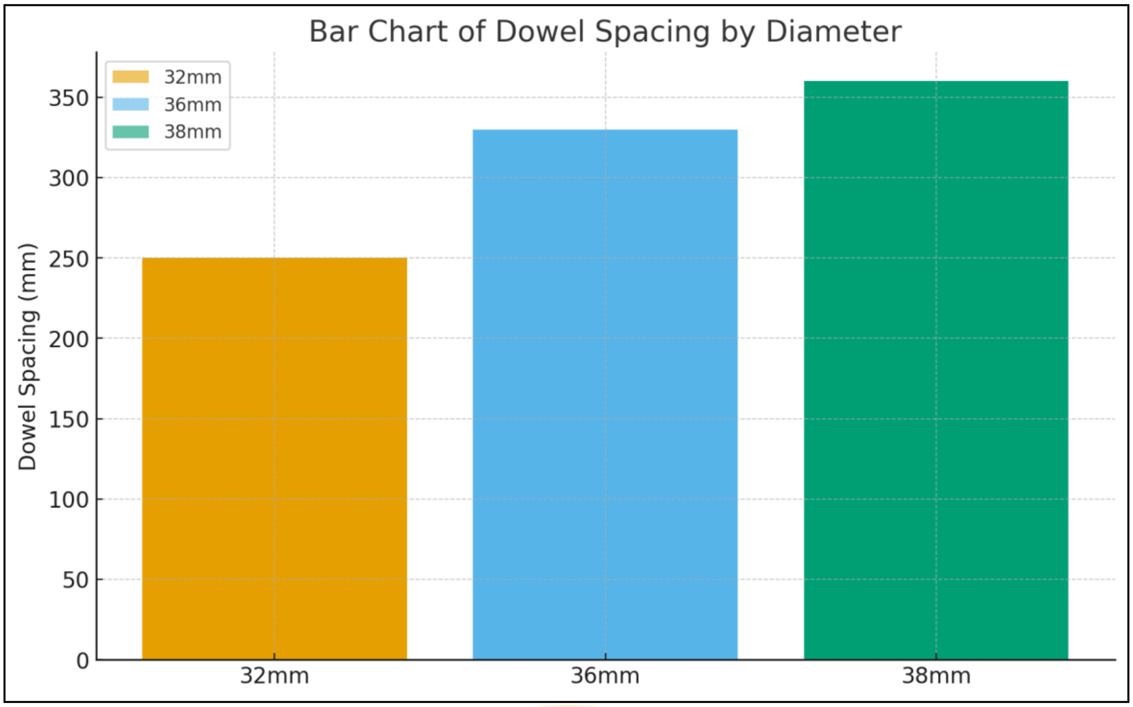

Figure 2, variation of Dowel Bar spacing for different diameter adopted

- **Suggestions**

1. **Optimization of Bar Spacing:** Tie and dowel bar spacing should be selected considering both structural adequacy and economy. Larger bar diameters allow greater spacing, reducing steel consumption and easing construction.
2. **Consideration of L/B Ratio:** For slabs with higher L/B ratios, reinforcement detailing must be carefully optimized to control stresses and prevent cracking. Standardized design charts can be developed for practical use.
3. **Quality Control During Construction:** Proper placement and alignment of dowel and tie bars are essential for effective load transfer and joint performance. Field monitoring should be enforced to avoid misalignment.
4. **Adoption of Mechanized Installation:** Use of dowel bar inserters and automated tie bar placement can enhance construction accuracy and speed.
5. **Integration with Pavement Management Systems (PMS):** Detailing should be aligned with long-term maintenance strategies for sustainable performance.

- **Conclusion**

The graphical representation of slab data highlights the progressive increase in tie bar spacing with higher L/B ratios across all bar diameters, indicating the direct influence of slab geometry on reinforcement requirements. Comparative analysis of tie bars (10 mm, 12 mm, and 16 mm) shows that larger diameters accommodate greater spacing, ensuring structural adequacy while minimizing steel congestion. Similarly, dowel bar spacing increases with diameter, reflecting their role in effective load transfer across joints. The line and scatter charts clearly capture the growth trend, while bar and pie charts provide quick insights into proportional differences. Overall, the analysis confirms that reinforcement detailing must be optimized based on slab size and aspect ratio to achieve both structural performance and economic efficiency.

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