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THE EFFECT OF CONCRETE QUALITY AND SUBGRADE CBR ON CRACK WIDTH IN RIGID PAVEMENT: AN EMPIRICAL MODEL APPROACH

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In rigid pavement work especialy for rural areas, two factors that often-become problems are the quality of the concrete and the compactness of the subgrade soil, especially for the construction using labor-intensive method. Cracks on road pavement always start with a small crack width but could result in more significant damage. Thus, this research was carried out to study the influence of concrete quality and CBR value of subgrade on crack behavior in rigid pavement, as well as to obtain an empirical formula that can be used to predict maximum crack width for various steel stress, concrete quality, and CBR value of subgrade. During the experiment, loading was carried out statically and as line loads, at maximum load of 200 kN. The dimensions of the specimen were L × W × H = 200 × 60 × 20 cm, with a reinforcement ratio of ρ=0.0105 and fy 400 MPa. Designed concrete quality was 10 MPa, 20 MPa, and 30 MPa, and the designed CBR values of the subgrade were 5%, 8.5%, and 12%. Experimental results show that both concrete quality and CBR value of subgrade are in inverse relationship with the maximum crack width, while steel stress has a linear relationship. Eventhough both parameters influence the maximum crack width, but the CBR value of the subgrade has more significant influence on reducing the crack width than concrete quality. The empirical formula that can be used to predict the maximum crack width obtained from this experiment is $w_{max} = 0.023\, f_s \left(\frac{1}{fc'}\right)^{0.304} \left(\frac{1}{C_{BR}}\right)^{0.898}$*. The increase of 50% on CBR value could reduce the maximum crack width up to 30.57%, while the similar increase on concrete quality only reduces the crack width by 11.45%. Hence, the implication of how the variables influenced the crack behavior can be seen from this proposed equation.*

Keywords: concrete quality, CBR, crack width, crack behavior, rigid pavement

1 INTRODUCTION

In the last decade, rigid pavement has become increasingly frequently chosen as rural road infrastructure in Indonesia, considering its ease of implementation and the work's labor intensity. However, the weakness in the implementation carried out so far is that the quality of the concrete has not been paid attention to because of the inconsistent mixing process. Apart from that, the subgrade's compactness is often not considered when carrying out the construction work.

Therefore, these two parameters are important to study to determine their influence on road pavement performance. One parameter that should be investigated is crack behavior. Cracks in rigid pavement can signal the onset of more serious degradation. External vehicle loads are a primary factor contributing to cracks in rigid pavements. Monitoring and maintaining crack widths within the maximum allowable limits is essential to ensure the concrete structure achieves its intended service life.

When a concrete structure is subjected to loading, micro cracks initiate and propagate from the surface toward the reinforcement. Concurrently, micro-cracks emerge within voids, internal imperfections, and at the interface of aggregate and cement paste. These cracks evolve due to the combined effects of applied loads and environmental factors. Cracks are thought to degrade mechanical qualities, dramatically enhance the diffusion of deleterious elements, and can lead to reinforcement corrosion, resulting in a loss in structural performance.

1.1 Literature overview

The quality of the concrete primarily influences the durability of rigid pavements. Concrete quality is defined by its capacity to endure applied loads without sustaining structural damage. Concrete with a compressive strength exceeding 43 MPa at 28 days is classified as high-strength concrete [1]. High-strength concrete possesses several key characteristics, such as a high cement content, a low water-cement ratio, high-quality aggregates, minimal water content in the aggregates, and the incorporation of mineral or chemical additives [2]. Because of the loading, concrete can experience deformation, shrinkage, temperature changes, and bending. The phenomena that occur in concrete quality can become increasingly complex due to challenges in its application. One of the significant obstacles in research on concrete quality is the limited exploration of material properties. Each concrete quality criterion has mechanical characteristics in its brittle behavior. This can affect the long-term performance of full-scale structures. In addition, research on concrete quality faces methodological obstacles, including mathematical modeling. This incident often causes a gap between practical implementation and theoretical modeling.

California bearing ratio (CBR) is a value used to determine the bearing capacity of subgrades on rigid pavement. Soil carrying capacity is in a suitable category with a higher CBR value parameter. The density of the subgrade used as an elastic foundation for rigid pavement influences the CBR value [3]. Also, differences in soil type, density, water content, and compaction methods will affect the soil's bearing capacity. Soil with a low CBR value can cause large deformations in the concrete layer due to the load that occurs. This can cause cracks and decrease the quality of the pavement.

Investigations into variations in CBR on rigid pavement need to be carried out to determine various soil conditions as an elastic foundation [4]. The influence of CBR values on rigid pavement performance is a growing and significant research topic. Low CBR value can result in poor soil stress distribution as a rigid pavement foundation. This can increase the tensile stress in the concrete, which can cause problems because of loading. On the other hand, if the CBR value is high, it will become a strong foundation, thereby minimizing problems that occur. Controlling subgrade quality as a rigid pavement foundation is one parameter that must be considered.

Cracks in concrete serve as indicators of potential serviceability issues before significant structural damage occurs. Cracking is a common problem in concrete structures, frequently weakening mechanical properties of the material and greatly enhancing its permeability to harmful substances [5]. Cracks form when the tensile strength of concrete in a flexural structure is exceeded. As the applied load grows, the tensile strength of the concrete hits its critical limit, causing cracks to occur. One aspect that can be reviewed and controlled in this phenomenon is the prediction of crack widths that occur due to loading [6]. This is important for examining crack problems and predicting their characteristics. Concrete on rigid pavement is a highly stiff road structure [7]. However, there are still many research gaps in the cracking of rigid pavement concrete according to characteristics that cannot be predicted. A comprehensive analysis needs to be carried out to determine and indicate the nature of cracks that occur due to loading from rigid pavement.

Cracking in primary beams occurs as the tensile strength of concrete is reached at varying intervals because of applied loads [8]. These cracks propagate further under cyclic loading, reducing the stress on the surface below the tensile strength of the concrete [9]. Additionally, this leads to a significant decrease in stress and strain within the concrete, ultimately reducing the elasticity of the concrete surrounding the reinforcement. Large cracks appear near surface, particularly close to neutral axis, where crack width approaches zero. Adhesion forces introduce variability in tensile testing approaches for cracked concrete beams [10]. The identified research gap lies in the interaction between concrete and other materials, which significantly impacts crack formation in the tensile fibers of concrete. Studies investigating adhesion forces in concrete indicate that maximum tensile stress predominantly occurs in steel reinforcement [11].

Strengthening one-way reinforced concrete slabs is crucial for effective crack control [12]. Concrete will almost certainly crack because of its poor tensile strength [13]. In reinforced concrete, tensile forces are typically resisted by the steel reinforcement. However, excessive loading can result in larger cracks, which may compromise the integrity of the reinforcement and increase its susceptibility to corrosion and water ingress. Guidelines suggest acceptable crack widths in reinforced concrete under service loads range between 0.10 and 0.41 mm [14]. Therefore, reinforced concrete structures of design must account for the maximum allowable crack width, as excessive crack widths can impact user perceptions of structural safety and lead to significant deflections [15]. Furthermore, deflection is directly influenced by factors such as the magnitude of steel stress and the reinforcement ratio in rigid pavement structures [16].

There are two categories of causes for cracks: external load factors and other factors, such as temperature differences and shrinkage [17]. Furthermore, cracks occur when the elastic area becomes a plastic area, so the concrete exceeds the critical stress, and the crack width increases. In compressed areas of concrete composites, steel reinforcement will maintain tensile stress to a specific limit, thereby reducing crack width. An increase in steel stress causes a corresponding relationship to the rise in the crack width [18]. This creates a research gap in reinforcement factors and repeated loads to understand cracks in concrete structures. The impact of crack width can endanger the reinforcement condition because it is susceptible to corrosion, reducing the tensile capacity. This gap has not been resolved comprehensively because of mathematical modeling and methodology, especially in concrete and soil as supporting media in rigid pavement structures.

Apart from the influence on loading, the structural characteristics of reinforced concrete also influence the behavior of crack width. The stability of rigid pavement is influenced by several variables, such as slab thickness, distance between reinforcement, concrete quality, and steel quality [19]. This variation can cause differences in the width of cracks that occur. In several previous studies, there were still limitations in studying crack width. This requires a more in-depth analysis to produce a rigid pavement design that is more durable and crack-resistant. In addition, there are still opportunities to investigate the impact of specific variables comprehensively.

Moreover, experimental studies on cracked concrete beams have offered more profound insights into tensile stress distribution, revealing a circular pattern between adjacent flexural cracks [20]. Additionally, investigations into the dynamic effects of loading on concrete cracking introduce further complexity. Laboratory scale structural testing with visual crack monitoring and dynamic load variation demonstrates that dynamic loading induces more intricate and rapidly propagating cracks than those formed under static loading conditions [21].

Overall, research on crack behavior in reinforced concrete slabs still has much room for exploration. The combination of load factors, concrete quality, and CBR value as an elastic foundation significantly influences cracks' pattern, distribution, and width. Further numerical and experimental approaches are needed to identify the interaction of these factors. Based on the literature review, it is necessary to research the influence of concrete quality and CBR value as an elastic foundation on the crack width behavior of rigid pavement. This will contribute to developing concrete pavement designs that are more reliable and resistant to cracking, especially in rigid pavement structures.

2 MATERIALS AND METHODS

The materials used to design rigid pavement plate specimens come from Malang, East Java, Indonesia. Fine aggregate in black sand comes from Lumajang, coarse aggregate from crushed stone machines, and Portland Composite Cement (PCC). Based on the tensile test, the reinforcing steel used demonstrated a yield strength of fy 580 MPa, with a reinforcement ratio of ρ = 0.0105, equivalent to 5-D16 bars. Based on the compression test of the cylinders, the concrete quality obtained was 9.13 MPa, 20.23 MPa, and 35.06 MPa. Those should represent three ranges of concrete qualities.

Subgrade soil parameters used as specimen support were carried out using an approach based on the results of the laboratory CBR test. Laboratory CBR testing uses the ASTM-D698-12-2021 standard. Soil compaction was tested using samples passing filter number 4 and a standard proctor load of 2.54 kg. Laboratory CBR testing is a reference for soil conditioning in molds. Test results are presented in Table 1.

Table 1. Laboratory CBR test result

Blow Number	Penetration		Dry Unit Weight
	2.54 mm (%)	5.08 mm (%)	gr/cm3
10	3.10	5.34	1.07
25	4.51	8.04	1.15
56	7.18	12.95	1.25

From the results of laboratory CBR tests, it was planned to use subgrade CBR values of 5%, 8.5%, and 12% to represent three ranges of soil compactness. The compaction in the steel box was carried out in layers with Optimum Moisture Content conditions (OMC). The first layer has a planned height of 5 cm with a soil volume of 73.500 cm3. For subgrade with a laboratory CBR value of 5% (10 blows) and a dry unit weight of 1.07 gr/cm3, converted to the soil weight and resulted in a total soil weight of 78.68 kg for 5 cm thickness of the layer. This soil was then compacted in a box using a concrete cylinder weighing 12.5 kg according to the planned height of 5 cm, which was assumed to be a roller in compacting soil in an actual field. This was done repeatedly until the height of the soil reached 30 cm. A similar approach was used for the other target CBR values. Final CBR value of the subgrade was then obtained using the field CBR test instrument. The test result showed the CBR values obtained were 5.73%, 8.07%, and 11.81%, which are already similar to the designed CBR values.

The dimensions of the test objects used in this research were 200 × 60 × 20 cm in length, width, and thickness, respectively. Figure 1 illustrates the specimen dimensions and reinforcement details.

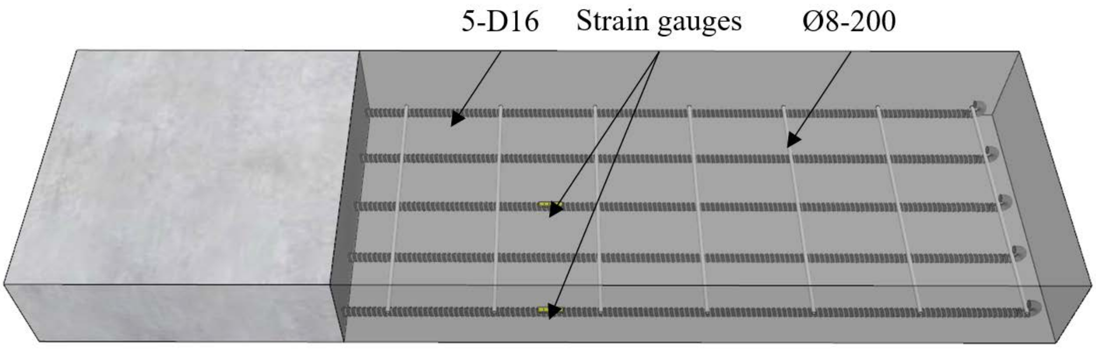

Fig. 1. Placement of reinforcement bars and strain gauges

Loading was carried out with a hydraulic jack using a monotonic static loading method. This research was carried out with a load interval of 2 kN and a maximum load of up to 200 kN. The steel strain was measured through strain gauge readings, and specimen settlement was measured using a Linear Variable Differential Transformer (LVDT). All research data were connected directly to a data logger to capture readings during the loading process. Visual inspections were performed on both sides of the specimen to detect the occurrence of the first crack. Once the initial crack formed, its width was measured and documented using a digital microscope with an accuracy of up to 0.01 mm. Position of loading is illustrated in Figure 2, and the testing equipment set-up is presented in Figure 3.

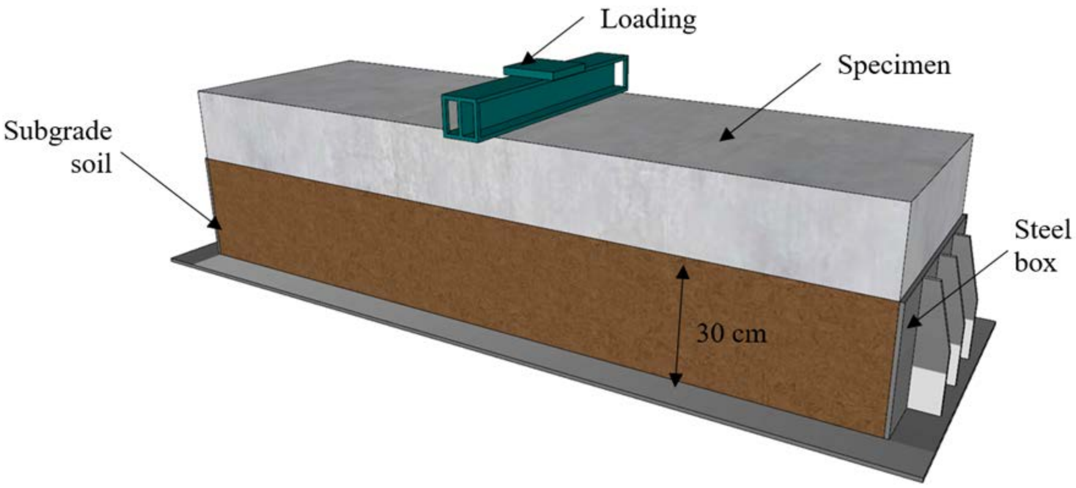

Fig. 2. Specimen on the subgrade as an elastic support

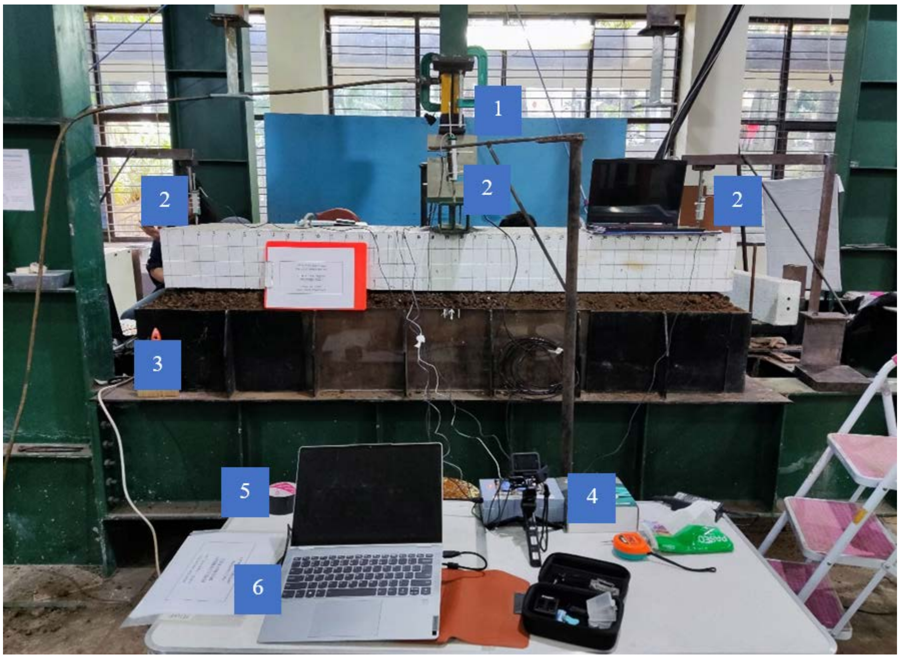

Fig. 3. Testing equipment setup

Where 1 – hydraulic jack and load cell; 2 – LVDTs; 3 – steel box; 4 – data logger; 5 – digital crack microscope; 6 – laptop

The experimental sequences are explained below:

1. Preparing and compacting of subgrade soil as an elastic support for the specimen.
2. Reading the CBR values of the prepared soil.
3. The rigid pavement plate specimen was placed on the subgrade on the test frame using a forklift.
4. Setting the H-beams as spreader beams to model the line load.
5. Connecting the strain gauge to the data logger.
6. Setting the LVDT at the mid-span and both ends and connecting all measurement instruments to the data logger.
7. Apply the load using a hydraulic jack at certain intervals and observe the first cracks appear.
8. Capturing the photo of the first crack using a digital crack microscope and photographing the crack every 2 kN loading interval until the maximum loading of 200 kN.
9. Repeat all processes for the other CBR values.

3 RESULTS

3.1 Relationship between crack width (w) and steel stress (fs)

Steel stress (fs) affects the resulting crack width. The occurrence of load (p) will influence steel stress, and a more significant load will result in more tremendous steel stress. In approaching the relationship according to the influence of variation in concrete quality and CBR of subgrade, a separate experimental study was carried out according to the control variables. The variations in concrete quality are 9.13 MPa, 20.23 MPa, and 35.06 MPa, with a CBR value of 8.07%. Meanwhile, variations in CBR values of subgrade are 5.73%, 8.07%, and 11.81%, with a concrete quality of 20.23 MPa. The steel stress value obtained is based on the reinforcing steel strain gauge sensor. The relationship between steel stress and load that occurs according to variation in concrete quality and CBR value of subgrade can be seen in figures 4 and 5.

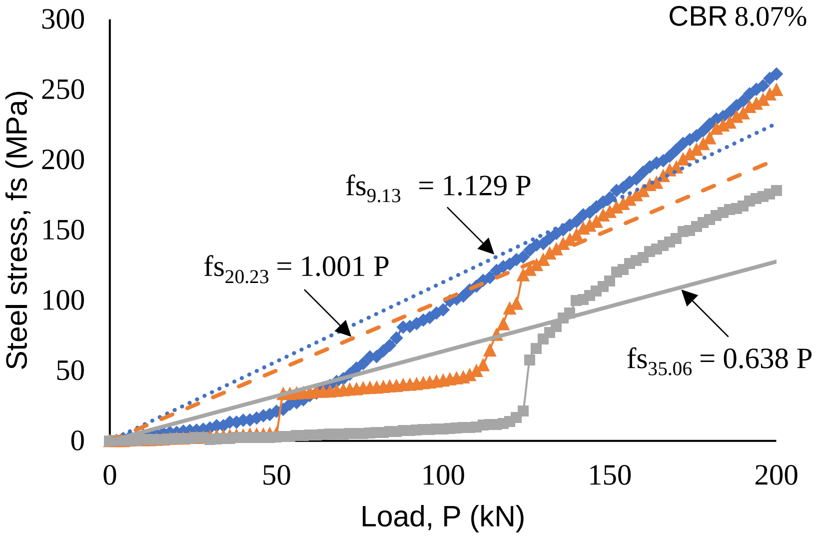

Fig. 4. Relationship of steel stress vs load at CBR 8.07%

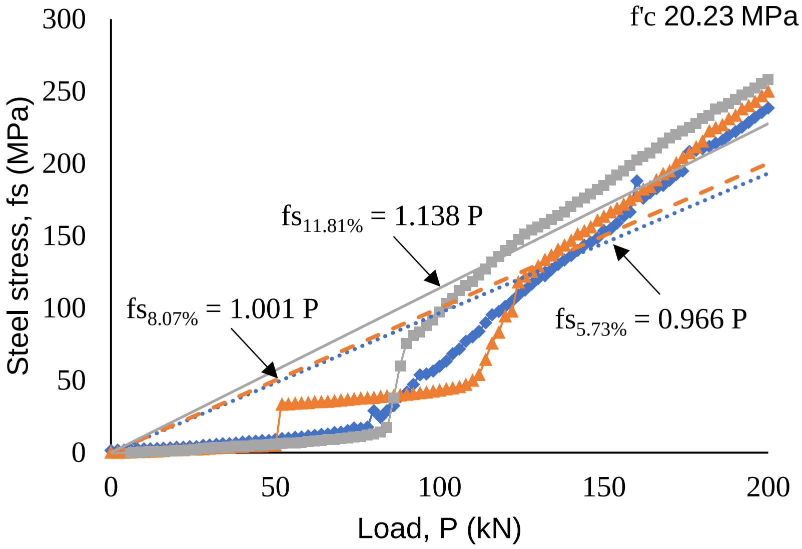

Fig. 5. Relationship of steel stress vs load at fc' 20.23 MPa

Figure 4 shows that variation in concrete quality on rigid pavement slabs has a relationship, the higher the concrete quality, the smaller the steel stress when loading occurs. Meanwhile, figure 5 shows that variations in the CBR value of subgrade have a relationship. The higher the CBR value of the subgrade, the greater the steel stress. This is because the higher the CBR value of the subgrade, the higher the soil density, so the soil density will also influence the external forces that occur apart from the load.

A digital crack microscope was used to measure crack width in rigid pavement slabs. According to the variation, figures 6 and 7 show the relationship between crack width and steel stress.

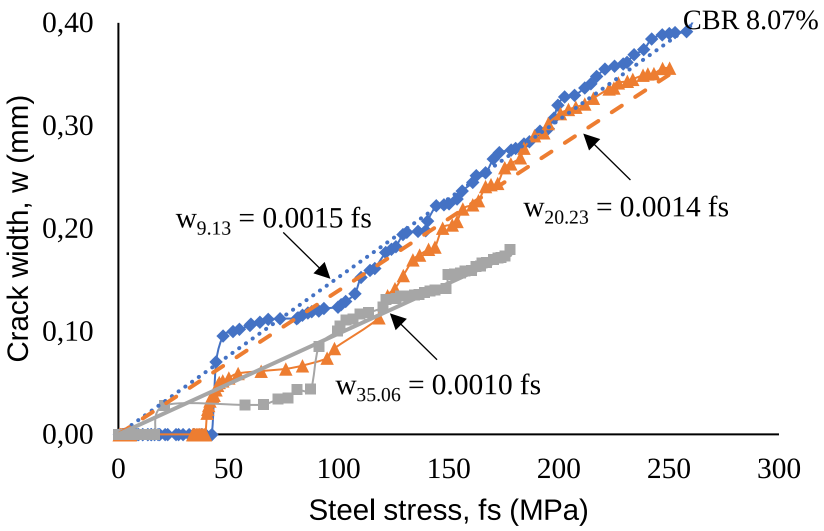

Fig. 6. Relationship of crack width vs steel stress at CBR 8.07%

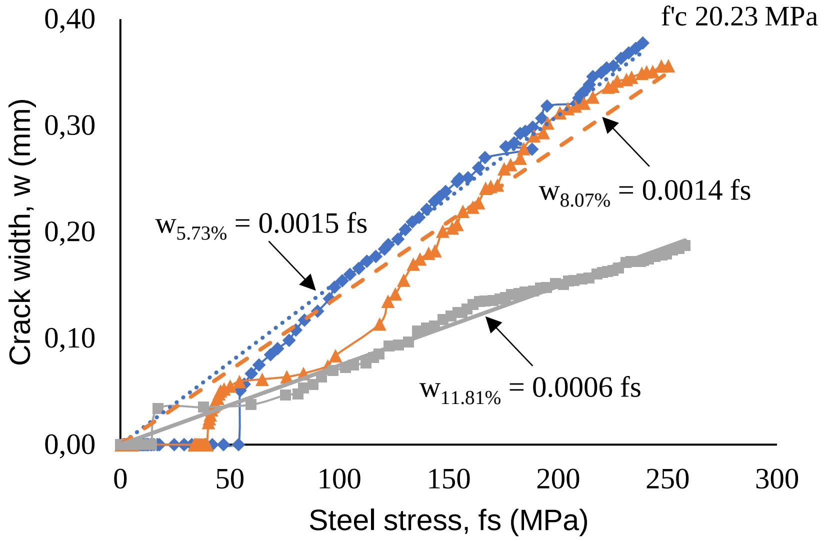

Fig. 7. Relationship of crack width vs steel stress at fc' 20.23 MPa

Figures 6 and 7 show the differences in crack width due to the steel stress in each variation. The largest crack width occurred in rigid pavement slabs with a concrete quality of 9.13 MPa and a CBR value of 5.73%. Furthermore, the initial crack that occurs in each variation is different. In a variation of concrete quality, an initial crack appears in the lowest concrete quality, fc' 9.13 MPa. While for variation in the CBR value of subgrade, the initial crack occurred in the highest CBR value of 11.81%. The concrete material and soil compactness as an elastic foundation on a rigid pavement slab influenced this.

The relationship between crack width and steel stress that occurs in each variation will be analyzed by regression, thus obtaining the approximate formula in these following equations:

$w = 0.0015\ fs$ for fc' 9.13 MPa (1)

$w = 0.0014\ fs$ for fc' 20.23 MPa (2)

$w = 0.0010fs$ for fc' 35.06 MPa (3)

$w = 0.0015\ fs$ for CBR 5.73% (4)

$w = 0.0014\ fs$ for CBR 8.07% (5)

$w = 0.0006\ fs$ for CBR 11.81% (6)

The formula for crack width and steel stress that occurs is a linear equation. Hence, this approach formula could predict crack width with specific steel stress on a rigid pavement slab.

3.2 Relationship between crack width and concrete quality

In the experimental results, crack width measurements in rigid pavement slabs were carried out up to the load of 200 kn. This was due to capacity factors of the loading equipment and will affect the steel stress results. To represent all data subjected to a 200 kn load, figures 4 and 5 show the use of a 160 MPa steel stress. The relationship between crack width and concrete quality at fs 160 MPa is shown in figure 8.

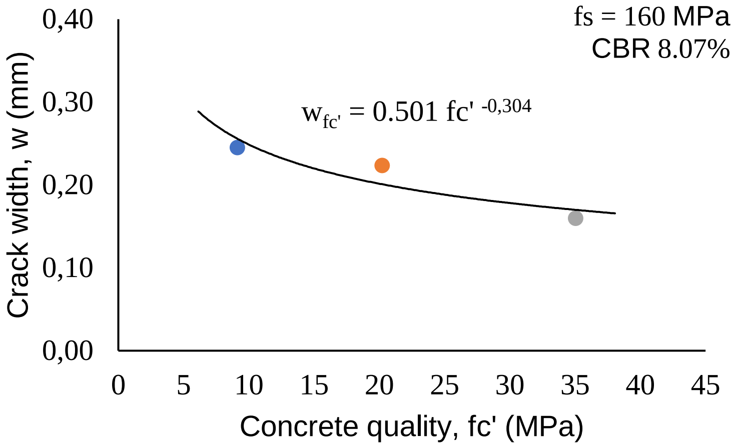

Fig. 8. Relationship between crack width (w) and concrete quality (fc') at fs = 160 MPa

Figure 8 shows that concrete quality influences the crack width behavior. The higher the concrete quality, the smaller the crack width will be. By using regression analysis, a formula for approximating maximum crack width with variation in concrete quality can be obtained as equation (7).

$$w_{max} = 0.501 \left(\frac{1}{fc'}\right)^{0.304} \tag{7}$$

This formula can predict the maximum crack width in certain concrete qualities with a CBR value of 8.07% and fs 160 MPa.

The relationship between crack width and CBR value of subgrade at fs 160 MPa is shown in figure 9.

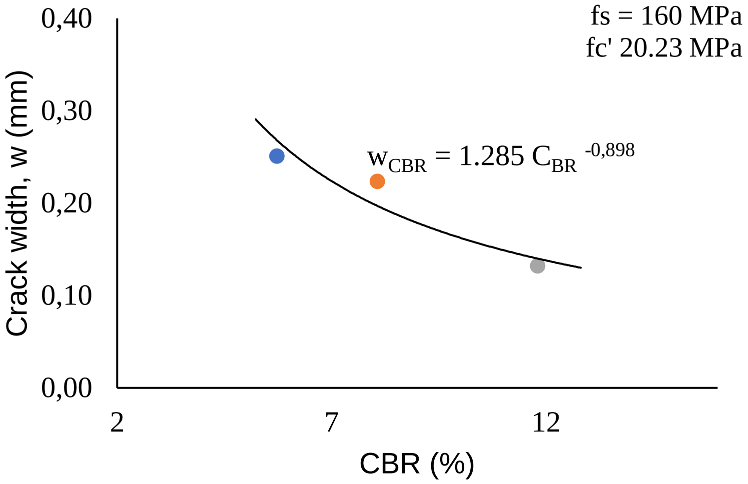

Fig. 9. Relationship between crack width (w) and CBR values (CBR) at fs = 160 MPa

Figure 9 shows that the CBR value of the subgrade influences the crack width behavior. The higher CBR value of the subgrade will result in a smaller crack width. By using regression analysis, an approximate formula for maximum crack width is obtained with variation in the CBR value of subgrade as equation (8).

$$w_{max} = 1.285 \left(\frac{1}{C_{BR}}\right)^{0.898} \tag{8}$$

This formula can predict the maximum crack width at specific basic soil CBR values with the f'c of 20.23 MPa and fs 160 MPa.

In estimating the crack width of rigid pavement on an elastic foundation based on variation in concrete quality and CBR values of subgrade, it is necessary to create a new formula with the application of steel stress parameters, concrete quality, and CBR values of subgrade. From the results of the empirical formula analysis based on equations (2), (7), and (8), the final formula with experimental findings can be seen in the following equation (9).

$$\mathrm{w_{max}} = 0.023\ \mathrm{f_s}\left(\frac{1}{\mathrm{fc'}}\right)^{0.304}\left(\frac{1}{\mathrm{C_{BR}}}\right)^{0.898} \tag{9}$$

Where wmax is maximum crack width (mm), fs is steel stress (MPa), fc' is concrete quality (MPa), and CBR is CBR values of subgrade (%). This new formula is proposed to predict the maximum crack width using concrete quality and CBR value of subgrade parameters on rigid pavement, in various steel stress value.

4 DISCUSSION

4.1 Relationship between crack width (w) and steel stress (fs)

The relationship between steel stress and load influences the occurrence of crack width. Figures 4 and 5 show each variation's relationship between steel stress and load. In experimental studies, steel stress parameters due to loading directly influence the crack occurrence. The higher the loading and steel stress, the greater the crack width. Relationship between load and steel stress on crack width is an essential parameter in designing and maintaining the rigid pavement structure. Apart from that, the assumptions on beams on elastic foundations and concrete structural mechanics have a dominant influence.

The difference in the influence of steel stress on crack width is influenced by concrete quality and the CBR value of the subgrade in Figure 4 and Figure 5. Rigid pavement slabs with concrete quality of 9.13 MPa and CBR 11.81% show a significant influence of steel stress on the crack width that occurs. Furthermore, a rigid pavement slab made of concrete with a specified quality of 35.06 MPa and a CBR of 5.73% shows a slight influence of steel stress on crack width that occurs, although large crack widths still occur at low variation values. This is because the condition of the elastic foundation as CBR value influences the cracked width. The higher the CBR value of the subgrade, the better the soil compactness. It will affect the steel stress and initial cracks on rigid pavement. For variation in concrete quality of 9.13 MPa, 20.23 MPa, 35.06 MPa, the initial crack occurred first at the lowest concrete quality. Initial crack width for specimens with variation in concrete quality were respectively 0.0706 mm at fs 44 MPa, 0.0206 mm at fs 40 MPa, and 0.0282 mm at fs 21 MPa. Meanwhile, the initial crack firstly occurred at the highest CBR value for the CBR variations of 5.73%, 8.07%, and 11.81%. Initial crack width for specimens in the CBR variations were respectively 0.0509 mm at fs 55 MPa, 0.0206 mm at fs 40 MPa, and 0.0338 mm at fs 17 MPa.

Figure 5 shows that an increase in the CBR subgrade value will increase the steel tension that occurs in reinforcement. This is because the soil which is denser with a higher CBR value has a greater modulus than the soil reaction, thereby reducing the flexibility of the pavement system. With the increasing modulus of the basic reaction, vertical deformation because the load will decrease, but the voltage distribution in the concrete plate becomes more concentrated. As a result, although cracks can be smaller, the tensile stress of reinforcement can increase faster. Besides cracked width is also influenced by K values, where soil with a low reaction modulus will cause a greater deformation on the sidewalk, thereby increasing the possibility of the formation of cracks earlier and broader. The higher the CBR value, the smaller the cracks that occur. This is because the soil with a higher-K value is able to distribute more even loads, thereby reducing the concentration of voltage that can trigger crack formation.

The formula approach with regression analysis can estimate crack widths in identifying problems, especially variations in concrete quality and subgrade CBR value. Figures 6 and 7 show that the widest crack width occurs on rigid pavement with a concrete quality of 9.13 MPa and a CBR of 5.73%. Furthermore, the smallest crack width occurs on rigid pavement with a concrete quality of 35.06 MPa and a CBR of 11.81%. These are influenced by the concrete material and soil compactness as an elastic foundation on a rigid pavement slab.

The crack width behavior on concrete quality and CBR value of the subgrade have a relationship where the higher the concrete quality and CBR value of the subgrade, the smaller the crack width on the rigid pavement. The proposed formula shows the relationship between crack width (w), steel stress (fs), concrete quality (MPa), and CBR value of subgrade (%). This means that every unit increase in steel stress (fs) will increase crack width according to the coefficient of variation, as shown in Figures 6 and 7. In variation concrete quality, equation (1) indicates that crack width tends to increase by 0.0015 mm for every unit of steel stress. Equation (2) indicates that crack width tends to increase by 0.0014 mm for every unit of steel stress. At the same time, equation (3) indicates that crack width tends to increase by 0.0010 mm for every unit of steel stress. Furthermore, with variation in the CBR value of the subgrade, equation (4) indicates that crack width tends to increase by 0.0015 mm for every unit of steel stress. Equation (5) indicates that crack width tends to increase by 0.0014 mm for every unit of steel stress. Equation (6) indicates that crack width tends to increase by 0.0006 mm for every unit of steel stress. These show that high-quality concrete will also produce high crack resistance. Also, subgrade soil with a high CBR (%) value will produce good crack resistance.

4.2 Relationship between crack width and concrete quality

This study introduces a new proposal for rigid pavement design based on concrete quality and CBR values of subgrade parameters. This research focuses on crack width on concrete quality and CBR under the influence of steel stress and applied loading. Figures 8 and 9 show that the higher the concrete quality and the CBR value of the subgrade, the smaller the crack width will be. This means that concrete quality and CBR value of subgrade have an inverse relationship with crack width. The mechanism for cracking concrete microstructure is closely related to the tensile voltage that functions due to external loads and characteristics of the micro-concrete structure itself. The relationship between steel tension and load affects the incidence of cracked width. In experimental studies, steel voltage parameters due to loading directly affect the incidence of cracks. The higher the loading and steel tension, the greater the cracked width. At the micro level, cracks in the concrete occur when the tensile stress because the load exceeds the concrete tensile capacity itself. Micro concrete structure consisting of cement, aggregate, and interface transition zones has different characteristics in holding the attraction load of the interface transition zone, as a more porous and weak area compared to cement and aggregate paste, this is the main starting point for crack initiation. When the concrete receives a load, the tensile stress distributed in the micro structure causes the microcrophocatet to begin to form, especially around the interface transition zone. The difference in the influence of steel tension on cracks is influenced by the quality of concrete and CBR value from the subgrade.

Based on the empirical formula from equation (9), for a fs value of 160 MPa with fc' 10 MPa and CBR 5%, a predicted crack width of 0.43 mm is obtained. Increasing concrete quality to 20 MPa will reduce crack width to 0.35 mm (18.77%). Furthermore, increasing concrete quality to 30 MPa will reduce the crack width to 0.31 mm (11.45%). It shows a 50% increase in CBR value can reduce the crack width by 30.57%, while an increase in the quality of similar concrete only reduces the crack width by 11.45%. It means that the stiffness and capacity of load retaining from the subgrade, represented by the CBR value, played a more significant role in reducing the formation of cracks compared to concrete power. The physical mechanism that underlies this phenomenon is related to the ability of the soil to distribute and absorb the pressure given by rigid pavement structures. A higher CBR value shows a denser subgrade, which increases the overall stiffness of the pavement system and reduces the concentration of local tension that causes cracks. Higher concrete quality produces lower steel voltage when loading occurs, while a higher CBR value causes an increase in steel tension. This opposite behavior can be associated with the interaction between foundation and sidewalk plates. A more concise subgrade provides better support, reduces differential settlements and increases the efficiency of load transfer, thereby reducing the level of flexible cracks in concrete plates. Meanwhile, a higher quality concrete mixture increases material strength but does not significantly affect the voltage distribution in the foundation. This explains why increasing the CBR value produces a reduction in a more substantial crack width than increasing concrete strength.

However, the predicted crack width remains greater than the maximum allowable limit of 0.30 mm. Furthermore, increasing concrete quality to 40 MPa will reduce the crack width to 0.27 mm (8.27%), where the allowable crack width of 0.30 mm has not been reached. On the other hand, an increase in CBR to 7.5% will reduce crack width to 0.30 mm (30.57%). Increased CBR to 10% will reduce the crack width to 0.23 mm (22.81%). It can be seen that predicted crack width has not reached the allowable crack width of 0.30 mm. Hence, both concrete quality and the CBR value of subgrade influence the crack width, but the latter parameter has a more significant influence.

The proposed empirical formula comes from a combination of steel stress (fs), concrete quality (MPa), and CBR value of subgrade (%) because these parameters are often used in actual conditions in the field. The choice of concrete quality and CBR of subgrade on rigid pavement are parameters that need to be considered, especially elastic foundations, expressed in the the CBR value of subgrade (%). The proposed formula in this research study will provide a solution in choosing the design or maintenance of rigid pavement by understanding the complex interaction between concrete quality and the CBR value of subgrade on crack width.

This research has limitations that do not fully reflect practical conditions in the field. Lack of exploration, the number of controlled variables, and the size of the rigid pavement slab can influence crack width. The influence of environmental factors such as humidity and temperature, which cause shrinkage in reinforced concrete rigid pavements have not been taken into consideration. However, the application of this research study can provide benefits in insight and sustainability in rigid pavement projects, especially in terms of concrete quality and CBR values of subgrade parameters, as well as future research.

5 CONCLUSION

1. The higher the concrete quality (fc') and CBR value of subgrade, the smaller the maximum crack width (wmax) will be on rigid pavement. Based on research results, a 50% increase in concrete quality can reduce crack width (w) by 11.45%. While a 50% increase in CBR value of subgrade can reduce crack width (w) by 30.57%. Therefore, the influence of the CBR value of the subgrade has a more significant effect than concrete quality.
2. The effectiveness of combining the formula with the steel stress (fs), concrete quality (MPa), and CBR value of subgrade (%) produces an empirical formula that is proposed in this study, as explained in the previous chapter. Thus, the innovative findings of this formula can be considered for designing and predicting the maximum crack width of rigid pavement in various steel stress, concrete quality, and CBR value of subgrade.

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