UDC 624
DOI: 10.15587/1729-4061.2024.298680

EFFECT OF VARIATIONS IN CONCRETE QUALITY ON THE CRACK WIDTH IN RIGID PAVEMENT

Wisnumurti
Associate Professor*
Agoes Soehardjono
Professor*
Roland Martin Simatupang
Corresponding author
Doctoral Program Student*
E-mail: martin.smtpng@student.ub.ac.id
*Department of Civil Engineering
Brawijaya University
MT. Haryono str., 167, Malang, Indonesia, 65145

Cracks pose a significant issue in rigid pavement, leading to substantial damage. The manual mixing and casting of road pavement concrete underscore the importance of concrete quality as a critical parameter. This study investigates crack behavior by varying concrete quality. Loading is performed statically using line loads, shedding light on the impact of concrete quality on crack development. The concrete to be used has a quality fc′ of 15 MPa, 25 MPa, and 35 MPa. The fine aggregate used in this study was Lumajang black sand, while the coarse aggregate used was machine crushed stone, and Portland Composite Cement (PCC) was used in all concrete mixes. The reinforcing steel used had a quality fy of 480 MPa, with a reinforcement ratio of ρ = 0.010, which was converted to 5-D16 reinforcement. The subgrade density used to support the specimens had a CBR value of 10 %. Specimen dimensions were 2×0.6×0.2 m for length, width, and thickness. Pavement plates, 30 cm thick, were placed on leveled subgrade soil in a steel box set to achieve a 6 % CBR reading. Hydraulic jacks, monitored by a load cell, applied monotonic static loading with 2 kN intervals, reaching a maximum load of 200 kN. Steel tension and plate settlement were measured using a tension sensor and Linear Variable Differential Transformer (LVDT), respectively. A data logger recorded readings, and crack widths were captured by a digital microscope with 0.01 mm accuracy. Experimental results show that low concrete compressive strength values result in larger crack widths, and vice versa. Cracks also occur at earlier loading of concrete quality fc′ 15 MPa. In addition, experiments show that the reinforcement stress value has a significant influence on crack width in specimens with low concrete quality

***Keywords:** concrete grades, crack width, crack behavior, rigid pavement, concrete quality*

Received date 15.11.2023
Accepted date 01.02.2024
Published date 28.02.2024

***How to Cite:** Wisnumurti, Soehardjono, A., Simatupang, R. M. (2024). ffect of variations in concrete quality on the crack width in rigid pavement. Eastern-European Journal of Enterprise Technologies, 1 (1 (127)), 33–40. doi: https://doi.org/10.15587/1729-4061.2024.298680*

1. Introduction

Rigid pavements are a vital element of road infrastructure, and an in-depth understanding of crack behavior is essential to ensure the reliability and durability of these structures. This issue is becoming increasingly crucial as traffic loads increase and the need for durable pavements increases. In this context, research on crack width is particularly relevant as it can provide insight into the structural response of pavements to variations in concrete quality. In analyzing crack width, aspects of concrete quality are the main focus, as differences in concrete composition and characteristics can have a significant impact on crack formation and development. Therefore, this research not only contributes to the scientific understanding of cracking phenomena in rigid pavements, but also has practical implications that can be used in the planning, construction and maintenance of road infrastructure.

Road infrastructure is a major part of a country's development, and reinforced concrete is an alternative structure used as pavement due to its rigidity and ease of material acquisition. The strength of concrete itself is influenced by its characteristic compressive strength. In addition, the composite work between concrete and reinforcement also affects the ability of the structure to accept loads. However, the brittle nature of concrete can lead to cracking, and is one of the most common defects in rigid pavement slabs. The occurrence of cracks in rigid pavements can be the beginning of greater damage. One of the causes of cracks in rigid pavements is external loads from vehicles. To ensure that the concrete structure can reach its planned life, one of the parameters that must be considered is that the crack width does not exceed the maximum allowable crack width [1]. Therefore, research aimed at analyzing the crack width of various concrete grades is relevant.

Research on concrete crack width has been widely proposed by several researchers, including when a concrete structure is loaded, macro cracks will appear and propagate from the outer surface of the concrete to the reinforcement. In addition, micro cracks also occur in voids, internal defects, and transition zones at the interface between aggregate and cement paste in concrete [2]. Over time, cracks tend to develop due to the influence of load and environmental factors. Cracks are believed to reduce mechanical properties and significantly increase the diffusion of harmful materials [3].

A number of previous studies have critically investigated the phenomenon of crack width in concrete structures; however, to date, no study has investigated the relationship between crack width and concrete quality with a specific focus on the applied load. Therefore, this research was initiated to fill this knowledge gap and present a substantial contribution to the scientific literature. By concentrating attention on the complex interaction between crack width and concrete grade, particularly in the context of applied loads, this research is expected to provide deep insight into the factors that influence the structural response of concrete to external loads. This approach will enrich our understanding of crack width-related mechanisms and, in turn, provide a foundation for improved planning and construction methods that are more contextualized and effective.

Building on the understanding of previous literature that has highlighted the complexity of the interaction between crack width and concrete quality, this research aims to systematically and in-depth explore the impact of external loads on the crack width phenomenon. Therefore, this research seeks to make a significant contribution to filling the related knowledge gap and, furthermore, to develop a more comprehensive insight into the structural response of concrete in the context of varying load conditions.

Therefore, research aimed at the development of rigid pavement structures, as a critical element of road infrastructure, is relevant for current conditions.

2. Literature review and problem statement

High-strength concrete, defined as concrete with a compressive strength exceeding 43 MPa at 28 days [4], is a type of heterogeneous composite material composed of cement paste, aggregates, contact zones between aggregates and paste, and voids. The mechanical properties of concrete are influenced by its constituent elements [5]. The basic materials used for high-strength concrete are essentially the same as those used for normal concrete.

In the case of high-strength concrete, the characteristics include high cement content, low water cement ratio, use of high quality aggregates, low aggregate water content, and use of mineral or chemical additives [6]. In the context of loads acting on the structure, such as shrinkage loads and temperature changes, bending and deformation of structural elements occur. In beams, bending occurs due to strains arising from external loads [7]. Loads acting on structures, such as shrinkage loads and temperature changes, can cause bending and deformation of structural elements. However, there are still some issues that have not been fully explored in high-strength concrete research. Such as research on the dynamic properties of concrete, especially for high-strength concrete, is still a big challenge for many researchers. Some of the reasons why these parts have not been studied are due to methodological and mathematical difficulties, as well as challenges in implementing in full-scale structures.

When the tensile strength of concrete in flexural structures is exceeded and the load continues to increase, the tensile strength of the concrete will reach its limit. At this point, cracks begin to appear as the tensile force spreads upwards, approaching the Neutral line. This Neutral line will shift upwards, followed by the propagation of cracks [8]. Flexural cracking can occur vertically or parallel to the acting force [9].

According to [10], changes in the load on the beam cause the tensile strength of the concrete to be reached at the beam surface at different intervals, which is referred to as primary cracking. These cracks will develop with increasing moment, form a pattern similar to a wedge shape, and vary in width from the beam edge to zero at the Neutral line. These cracks result in a drastic reduction in concrete stress and strain, causing a loss of elasticity in the concrete region around the reinforcement. However, the adhesion of the reinforcement bars at the beam surface provides protection, and the concrete region around the reinforcement receives most of the stress and strain, with the intensity decreasing closer to the reinforcement.

Research conducted on the effect of reinforcement number and repetitive load on crack width in one-way concrete slabs is an important contribution to the understanding of cracks in concrete structures [11]. According to the study, cracks in concrete are difficult to avoid because concrete is weak against tensile strain [12]. In the context of reinforced concrete, the tensile strength due to external loads is carried by steel reinforcement, but if the tensile force caused by the load exceeds the critical stress of the concrete, the cracks will grow larger.

Significant crack width can jeopardize the state of the steel reinforcement as it can leave it exposed and prone to corrosion, reducing its stress capacity. Therefore, the planning of reinforced concrete structures must consider maximum crack width limitations that involve not only technical aspects, but also aesthetics, as a large enough crack width can affect the perception of strength for users and cause large deflections [13].

Determining the maximum crack width depends on several factors such as crack position, crack length, and crack surface texture [14]. Aesthetically, acceptable crack widths range from 0.25 mm to 0.38 mm, while crack widths related to corrosion rates depend on the environment surrounding the concrete structure [15].

The causes of cracks in reinforced concrete can be classified into two categories, namely cracks caused by external loads and cracks caused by other factors, such as shrinkage or temperature differences [16]. Flexural cracking and shear cracking are types of cracking caused by external loads, where flexural cracking occurs in tensile areas with sharp shapes, while shear cracking occurs in thin body plates [17].

In the context of flexural cracking, research notes that cracks begin to form as the tensile stress of concrete exceeds its critical stress. As the elastic to plastic region transitions, the crack width increases. However, in the region around the steel reinforcement, the bond between steel and concrete keeps the stress and strain fixed to some extent, reducing the crack width compared to the concrete surface without reinforcement [18]. However, there are still some issues that have not been fully explored in this research. There are several problems, including the number of restraints and repeated loads affecting the width of cracks in one-way concrete slabs, which is an important contribution to the understanding of cracks in concrete structures. Additionally, research into how significant crack widths can compromise the confining state of steel as it can leave it exposed and susceptible to corrosion, reducing its tensile capacity. Some reasons why these sections have not been studied may include methodological and mathematical difficulties, as well as challenges in determining the maximum crack width, which depends on several factors such as crack position, crack length, and crack surface texture.

Flexural cracking develops at regular intervals in each moment region of the beam, but in the constant moment region, flexural cracking develops at discrete intervals depending on the distribution of concrete weakness. The exact location of constant moment cracks is difficult to predict, but the maximum and minimum spacing of adjacent cracks and the maximum crack width can be predicted fairly accurately through analysis of the increased concrete stress in the tensile region [19].

Research involving tests on concrete cylinders with uniaxial tensile forces provides insight into concrete tensile stresses and the resulting crack widths. This approach involves analyzing the tensile axial stress distribution at the bond transfer between the steel reinforcement attachment and the concrete. In addition, an experimental approach with concrete beams having cracks provided further understanding of the tensile stress distribution in the circular shape between adjacent flexural cracks [20].

Meanwhile, research exploring the impact of dynamic loading on concrete cracks adds another dimension of complexity to the understanding of cracks. Laboratory-scale structural tests with dynamic load variations and visual monitoring of cracks show that dynamic loads can produce more complex and faster-developing cracks compared to static loads [21].

Furthermore, research focusing on the statistical analysis of load versus crack mouth plots provided additional insights. Through statistical analysis methods, this research highlighted the load distribution at specific points during crack development, providing a deeper understanding of concrete crack dynamics [22].

3. The aim and objectives of the study

The aim of the study is to determine the effect of concrete quality on crack width in rigid pavement.

To achieve the aim, the following objectives were accomplished:

– to investigate the relationship between concrete quality and crack width;

– to assess the impact of load variations on crack development.

4. Materials and methods

Concrete quality planning for specimens was carried out using materials around Malang, East Java, Indonesia. Concrete is planned to use *fc′* qualities of 15 MPa, 25 MPa and 35 MPa. The fine aggregate used in this research was Lumajang black sand, and the coarse aggregate used was machine crushed stone, and Portland Composite Cement (PCC) cement was used for all concrete mixtures.

The reinforcing steel used has a quality of *fy* 480 MPa, with a reinforcement ratio of $\rho=0.010$, which is converted into 5-D16 reinforcement. The density of the subgrade used as a support for the specimen has a CBR value of 10 %. The dimensions of the specimens used in this research were $2\times0.6\times0.2$ m respectively for length, width and thickness. Specimen dimensions and details of rigid pavement plate reinforcement are as shown in Fig. 1.

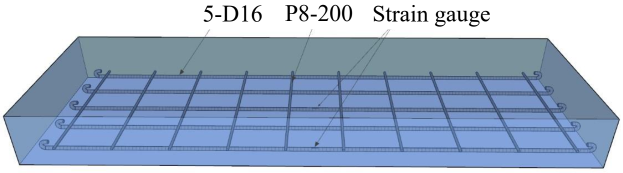


Fig. 1. Placement of concrete reinforcement bar and strain-gauge sensors

The next step is for the pavement plate to be placed on the subgrade soil with a thickness of 30 cm, which has been leveled in a steel box. Thus, the plate specimen is assumed to rest on an elastic support. The subgrade was set to obtain a CBR reading of 6 % as part of the study limits. The placement of the specimen on the elastic support can be seen in Fig. 2.

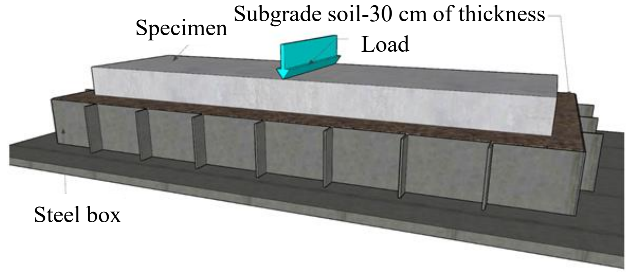


Fig. 2. Placement of the specimen on the subgrade soil support

Loading is carried out with a hydraulic jack, which is read through the load cell. The loading method is monotonic static, with load addition intervals of 2 kN and the maximum load is up to 200 kN. Steel strain measurements are carried out through strain-gauge readings, and plate settlement measurements are carried out by reading using a Linear Variable Differential Transformer (LVDT).

The load cell, strain gauges and LVDTs are connected to a data logger, which functions to record readings during the loading process. Visual observations then were made on both sides of the specimen, to determine when the first crack occurred. When the initial crack has occurred, the crack width is photographed using a digital microscope, which has an accuracy of up to 0.01 mm. Fig. 3 shows the loading setup, and the equipment test setup can be seen in Fig. 4.

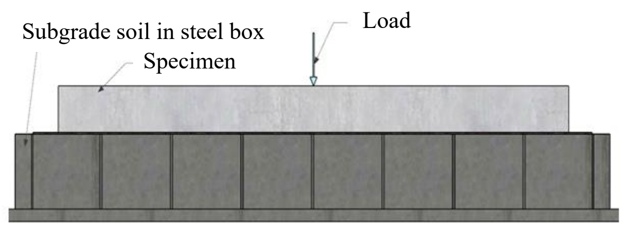


Fig. 3. Loading position

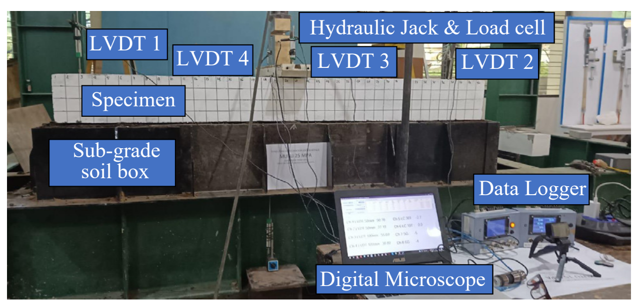


Fig. 4. Experimental setup

Testing of plate specimens was carried out on the test frame as shown in Fig. 3. The stages of this research process include:

1. Preparing the subgrade soil that has been tested for CBR as an elastic support in the soil box on the test frame.

2. Placing the specimen using a forklift on top of the subgrade that has been set on the test frame.

3. Modeling the line load using steel plate and sand. Sand media to facilitate load transfer from the load cell. Sand thickness is about 1–2 cm evenly.

4. Setting-up all tools that support research ranging from load cells, hydraulic jacks, LVDTs to strain gauge cables

mounted on data loggers. Setting-up tools on the test frame can be seen in Fig. 4.

5. Giving load using a hydraulic pump with a certain multiple while seeing the first crack point appears.

6. After the first crack is visible, the crack detector is immediately operated at the first crack point to photograph the crack.

7. The loading is continued with every certain multiple and then photographed using a crack detector at the point where the first crack appears. At each test, a video will be taken, which will show the load readings and data logger. In addition, the data logger can be connected to a laptop to directly get the data.

8. Observation of the crack pattern is done visually where the observer is next to the specimen.

9. Strain gauge readings for reinforcement can be seen in the data logger. This is intended to determine whether the reinforcement has melted or not. Strain gauges were installed on the tensile reinforcement in the center and at the edge.

10. Observations continue to be made with increasing load multiples until the limit strength of the plate specimen is obtained.

5. Results of research on crack width with variations in concrete quality in rigid pavement

5. 1. Relationship between crack width and concrete quality

Fig. 5 shows the relationship between load (P) and crack width (w) that occurs in rigid pavement plates with variations in concrete quality. Observation results show that the pavement plate experiences initial cracking at loads of 64 kN, 88 kN, and 118 kN for grades 15 MPa, 25 MPa, and 35 MPa, respectively. The crack width value that is visually visible at the initial crack ranges from 0.054 mm to 0.062 mm.

For the load of 80 kN, specimens with a quality of fc' 15 MPa experienced a crack width of 0.102 mm, while other specimens with larger concrete strength did not show visual cracks.

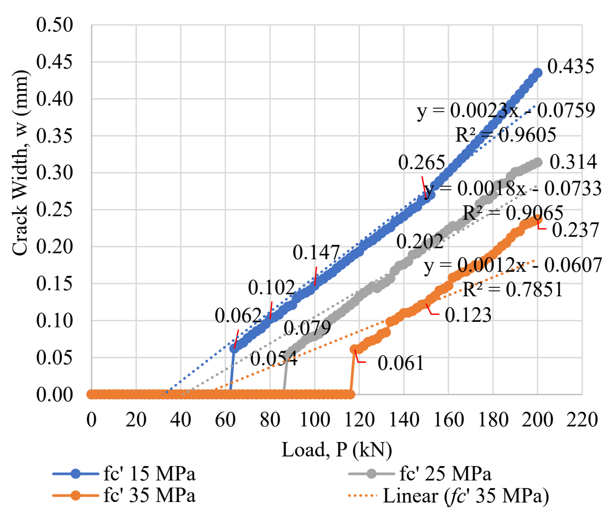


Fig. 5. Relationship between load (P) and crack width (w) due to variations in concrete grades (fc')

Measurements of crack widths that occurred at a load of 100 kN showed values of 0.147 mm and 0.079 mm for specimens with a quality of fc' 15 MPa and 25 MPa, respectively. While the specimen with a quality of fc' 35 MPa did not experience cracks at this load.

At the load of 150 kN, the crack widths that occurred were 0.265 mm, 0.202 mm, and 0.123 mm for specimens with concrete compressive strengths of 15 MPa, 25 MPa, and 25 MPa, respectively.

Loading for fc' 25 MPa and 35 MPa quality specimens was stopped at a load of 200 kN, with crack width measurements of 0.314 mm and 0.237 mm, respectively. Meanwhile, specimens with a quality of fc' 15 MPa do not provide load readings after exceeding a load of 152 kN, however, based on the behavior in the graph, this plate will experience a larger crack width compared to specimens of quality fc' 25 MPa and fc' 35 MPa at a load of 200 kN.

The relationship between crack width and concrete quality at load values is shown in Fig. 6.

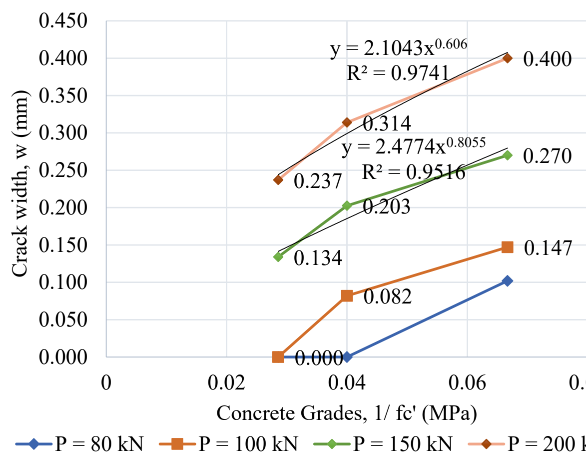


Fig. 6. Relationship between crack width and concrete quality at load values P=80 kN to P=200 kN

Fig. 6 shows that the crack width behavior is identical for the various concrete grades used. A crack width of 0.3 mm will occur when the concrete grade used $fc' \leq 25$ MPa, at a load of P=200 kN. Fig. 5 shows that the relationship between crack width and load for each concrete grade used in the experiment can be seen. By using linear regression, the following relationship formulas were obtained:

$$w = 0.0024P - 0.0921 \text{ for concrete grade } fc' \text{ 15 MPa,} \quad (1)$$

$$w = 0.0025P - 0.1877 \text{ for concrete grade } fc' \text{ 25 MPa,} \quad (2)$$

$$w = 0.0024P - 0.2339 \text{ for concrete grade } fc' \text{ 35 MPa.} \quad (3)$$

We can then predict the crack width at certain load values for each compressive strength value.

5. 2. Relationship between crack width and reinforcing steel stress

Crack width measurements were carried out from the first time a crack occurs and documented for each loading interval until the loading ends. A digital microscope with a magnification of up to 220x was used for this observation. Fig. 7–9 show the increase in crack width as the loading progresses.

The initial condition before hydraulic loading shows that the concrete structure has a relatively crack-free surface, with the crack width at zero. As hydraulic loading was applied, there was a significant change in the condition of the structure, characterized by a progressive increase in crack width. The final condition shows wider cracks that are evenly distributed across the surface of the concrete structure, reflecting the impact of hydraulic loading on structural response and crack formation. Fig. 7 shows the crack width of concrete subjected to 15 MPa loading in the initial and final cracking conditions.

Fig. 8 shows the crack width of concrete subjected to 25 MPa loading in the initial and final cracking conditions.

Fig. 9 shows the crack width of concrete subjected to 35 MPa loading in the initial and final cracking conditions.

Fig. 7–9 show the results of measuring the width of the crack when it first occurred and at the end of loading for each test object. Observation results show that initial cracking occurs at a greater load value for test specimens with concrete quality *fc′* 35 MPa, where cracking occurs at a load of 118 kN. For test specimens with *fc′* quality of 25 MPa, and 15 MPa, initial cracking occurred at smaller loads, which were 88 kN and 64 kN, respectively. These results show the influence of the concrete compressive strength value on the occurrence of the first crack.

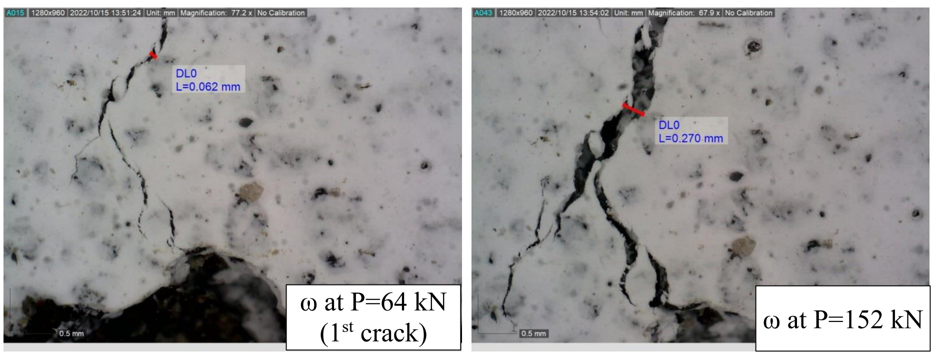
The steel stress value shown in Fig. 10 was obtained from measuring the steel strain value from the strain-gauge sensor, which was recorded during the loading process.

The comparison between the crack width that occurs and the steel reinforcement stress value for each concrete quality can be seen in Fig. 10. The relationship between crack width (w) and steel stress (fs) is then regressed, and the results can be seen in the equation [18], (1)–(3):

$$w = 0.0016 fs \text{ for } fc' \text{ 15 MPa}, \quad (4)$$

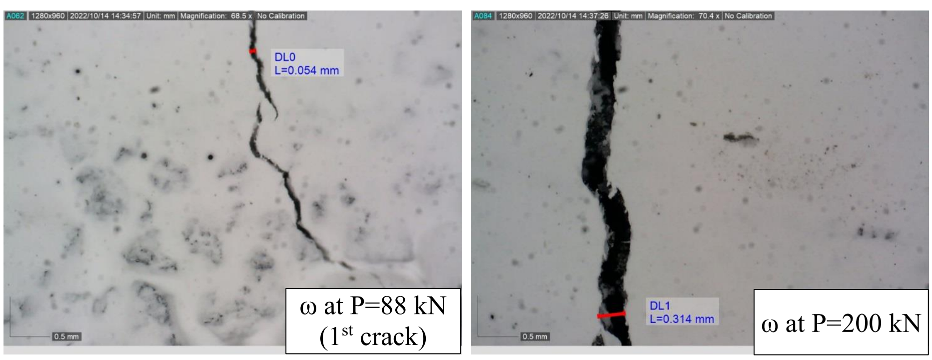
$$w = 0.0012 fs \text{ for } fc' \text{ 25 MPa}, \quad (5)$$

$$w = 0.0011 fs \text{ for } fc' \text{ 35 MPa}. \quad (6)$$



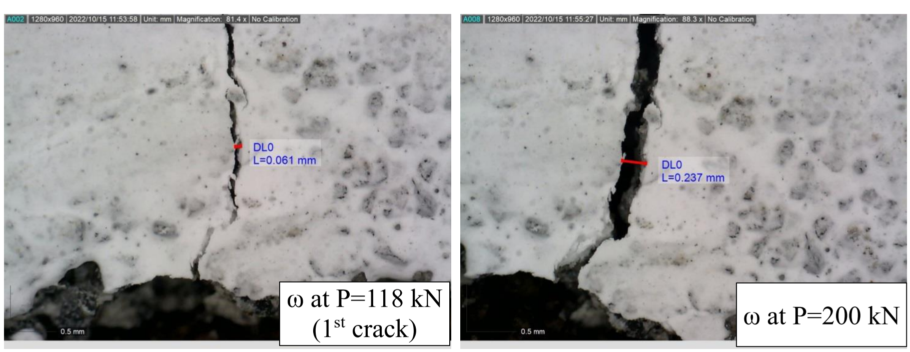
a *b*

Fig. 7. Crack width for specimens *fc′* 15 MPa: *a* — initial crack; *b* — final crack



a *b*

Fig. 8. Crack width for specimens *fc′* 25 MPa: *a* — initial crack; *b* — final crack



a *b*

Fig. 9. Crack width for specimens fc′ 35 MPa: *a* — initial crack; *b* — final crack

Fig. 11 shows that for the same load, the steel stress has a smaller value in the highest concrete quality specimens.

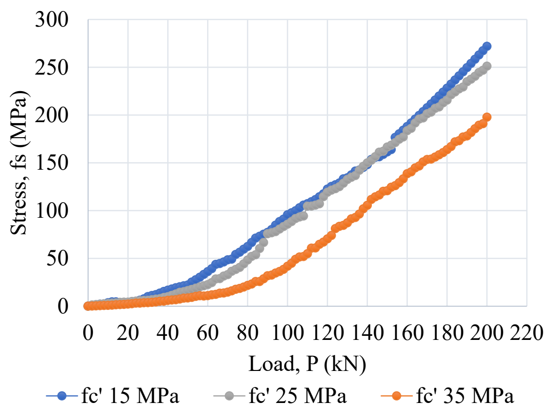


Fig. 10. Relationship between load (P) and steel stress (fs) for varying concrete compressive strength values

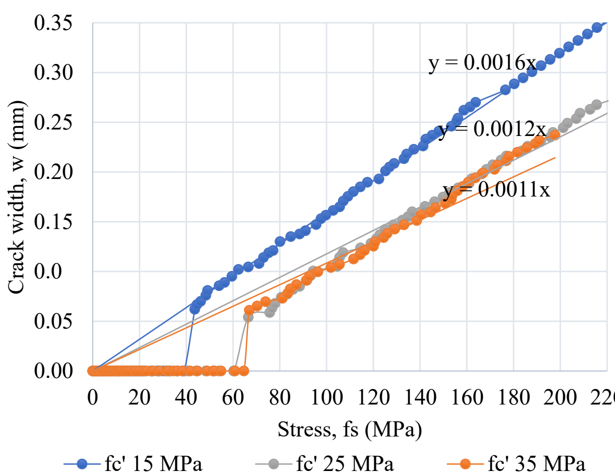


Fig. 11. Relationship between crack width (w) and steel stress (fs) due to variations in concrete grades (fc')

Fig. 11 shows that in specimens with concrete compressive strength fc' 15 MPa, the steel stress value has a significant influence on the width of the crack that occurs. Meanwhile, specimens with concrete compressive strengths of fc' 25 MPa and fc' 35 MPa show an almost identical relationship between reinforcing steel stress and crack width. The higher the quality of the concrete, the smaller the influence of the steel stress value on the crack width of the rigid pavement.

6. Discussion of experimental results of crack width with variations in concrete quality in rigid pavement

Fig. 5, 6 show that the crack width behavior is identical for the various concrete qualities used. Where from the research results we get equations (1)–(3). These equations show the relationship between load (P) and crack width (w) for various concrete qualities. Where for each unit increase in load (P), the crack width will increase by a corresponding coefficient, depending on the quality of the concrete. For example, in equation (1), it is found that for concrete with a quality of fc' 15 MPa, every increase of 1 unit of load will increase the crack width by 0.0024 mm, reduced by 0.0921. Equation (2) also states that for every 1 unit increase in load, the crack width will increase by 0.0025 mm, reduced by 0.1877. And in equation (3) also for every 1 unit increase in load, the crack width will increase by 0.0024 mm, reduced by 0.2339. This shows that concrete of higher quality (fc' 35 MPa) has a slightly lower increase in crack width per unit increase in load compared to concrete of lower quality (fc' 25 MPa). This may indicate that higher quality concrete has better crack resistance.

Fig. 10 shows that there are significant differences in the effect of steel stress on crack width, depending on the concrete grade used. While specimens with concrete strength fc' 15 MPa show a large influence of steel stress on crack width, specimens with concrete grades fc' 25 MPa and fc' 35 MPa show almost identical relationships. In higher concrete grades, the influence of steel stress values on crack width in rigid pavement is lower.

The solution proposed in this study provides the benefit of a regression formula that describes the relationship between crack width and steel stress for each concrete grade. The main advantage of this research lies in the in-depth understanding of the complex interaction between crack width and concrete grade. With this regression formula, this research provides the ability to predict the crack width at a given load for any value of concrete compressive strength, enabling wider applications in the planning and design of concrete structures.

The solution obtained through the regression formula approximates the essence of the identified problem, which is the relationship between crack width and concrete grade. The effect of reduced steel stress values at higher concrete grades can be explained by the superior mechanical properties of concrete. This in-depth analysis reveals that at higher concrete grades, the contribution of steel stress to crack width is further reduced.

This research introduces a new method for concrete quality planning in rigid pavement concrete specimens. This study also considers the subgrade density with a CBR value of 10 %. In contrast to previous studies, this research focuses on the complex interaction between crack width and concrete quality, especially in the context of applied loads. The results show that concrete quality affects crack width, with fc' 15 MPa concrete tending to crack at smaller loads compared to fc' 25 MPa and fc' 35 MPa concrete.

Equations (4)–(6) refer to the analysis carried out to compare the width of the cracks that occur and the stress value in the reinforcing steel for each quality of concrete. Equation (4) explains that for every unit increase in stress in the reinforcing steel, the crack width will increase by an appropriate coefficient, depending on the quality of the concrete. For example, for concrete with a quality of fc' 15 MPa, every 1 unit increase in stress in the reinforcing steel will increase the crack width by 0.0016 mm, whereas equations 5 and 6 are 0.0012 mm and 0.0011 mm, respectively.

The positive relationship between stress and crack width in concrete can be explained through the concepts of material mechanics and concrete behavior (Fig. 11). When concrete is subjected to load or stress, cracks or micro cracks can form. As the stress increases, the crack width also tends to increase. Cracks that occur in concrete include longitudinal cracks, transverse cracks, and corner cracks. Relatively large cracks not only damage the aesthetics of concrete structural elements but can also cause structural failure. Apart from that, rigid pavement plates have flexural failure so that the crack pattern that occurs starts with the first crack at the bottom of the plate. The crack pattern in terms of plate thickness variations has a similar pattern. The initial crack width in the plate is 0.04 mm. The thicker the plate, the smaller the crack width at the same load.

Limitations of this study include its experimental nature under laboratory conditions, which may not fully reflect the practical situation in the field. Environmental factors such as temperature and humidity, which can affect concrete behavior, were not fully considered.

Shortcomings of this study include the lack of exploration of additional factors that may affect crack width, such as ambient environmental conditions. The limited sample size may also limit the generalizability of the results.

This research could be extended by considering the influence of additional variables such as temperature and humidity on field conditions. In addition, the application of the research results in practical projects could provide further insight into the sustainability and validity of these findings in real-world situations.

7. Conclusions

1. The higher the concrete quality, the smaller the influence of steel stress on crack width in rigid pavement, it can be seen that the value of steel stress has a significant impact, especially at concrete quality fc' 15 MPa, while at concrete quality fc' 25 MPa and fc' 35 MPa.

2. The relationship between load (P) and crack width (w) in rigid pavement slabs with various concrete grades shows initial cracking at a certain load for each concrete grade. The crack width at the initial stage ranged from 0.054 mm to 0.062 mm. At a load of 80 kN, the 15 MPa fc' specimen experienced a crack width of 0.102 mm, while the higher concrete grades showed no visual cracks.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This research received funding from the Associate Professor Research Grant of the Faculty of Engineering, Universitas Brawijaya, Malang.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

Thank you to the Faculty of Engineering, University of Brawijaya Malang, which has funded this research, and to those who have contributed to the implementation of this research.

References

1. Nassar, R.-U.-D., Soroushian, P., Sufyan-Ud-Din, M. (2021). Long-term field performance of concrete produced with powder waste glass as partial replacement of cement. Case Studies in Construction Materials, 15, e00745. https://doi.org/10.1016/j.cscm.2021.e00745
2. Daneshvar, D., Behnood, A., Robisson, A. (2022). Interfacial bond in concrete-to-concrete composites: A review. Construction and Building Materials, 359, 129195. https://doi.org/10.1016/j.conbuildmat.2022.129195
3. Yasser, N., Abdelrahman, A., Kohail, M., Moustafa, A. (2023). Experimental investigation of durability properties of rubberized concrete. Ain Shams Engineering Journal, 14 (6), 102111. https://doi.org/10.1016/j.asej.2022.102111
4. Aljaberi, M., Elshesheny, A., Mohamed, M., Sheehan, T. (2024). Experimental investigation into the effects of voids on the response of buried flexible pipes subjected to incrementally increasing cyclic loading. Soil Dynamics and Earthquake Engineering, 176, 108268. https://doi.org/10.1016/j.soildyn.2023.108268
5. Awolusi, T. F., Sojobi, A. O., Oguntayo, D. O., Akinkurolere, O. O., Orogbade, B. O. (2021). Effects of calcined clay, sawdust ash and chemical admixtures on Strength and Properties of concrete for pavement and flooring applications using Taguchi approach. Case Studies in Construction Materials, 15, e00568. https://doi.org/10.1016/j.cscm.2021.e00568
6. Kumar, D., Alam, M., Sanjayan, J., Harris, M. (2023). Comparative analysis of form-stable phase change material integrated concrete panels for building envelopes. Case Studies in Construction Materials, 18, e01737. https://doi.org/10.1016/j.cscm.2022.e01737
7. Pongsivasathit, S., Horpibulsuk, S., Piyaphipat, S. (2019). Assessment of mechanical properties of cement stabilized soils. Case Studies in Construction Materials, 11, e00301. https://doi.org/10.1016/j.cscm.2019.e00301
8. Shtayat, A., Moridpour, S., Best, B., Shroff, A., Raol, D. (2020). A review of monitoring systems of pavement condition in paved and unpaved roads. Journal of Traffic and Transportation Engineering (English Edition), 7 (5), 629–638. https://doi.org/10.1016/j.jtte.2020.03.004
9. du Plessis, L., Ulloa-Calderon, A., Harvey, J. T., Coetzee, N. F. (2018). Accelerated pavement testing efforts using the Heavy Vehicle Simulator. International Journal of Pavement Research and Technology, 11 (4), 327–338. https://doi.org/10.1016/j.ijprt.2017.09.016

10. Wang, H., Zhang, W., Zhang, Y., Xu, J. (2022). A bibliometric review on stability and reinforcement of special soil subgrade based on CiteSpace. Journal of Traffic and Transportation Engineering (English Edition), 9 (2), 223–243. https://doi.org/10.1016/j.jtte.2021.07.005
11. de Medeiros, W. R. P., de Medeiros Melo Neto, O., Luz, P. M. S. G., Oliveira, R. K. F. de, Guedes, L. R. (2023). Utilizing marble and granite industry waste in asphalt mixtures for enhanced road performance and sustainability. Journal of Engineering Research. https://doi.org/10.1016/j.jer.2023.10.032
12. Akbas, M., Ozaslan, B., Iyisan, R. (2023). Utilization of recycled concrete aggregates for developing high-performance and durable flexible pavements. Construction and Building Materials, 407, 133479. https://doi.org/10.1016/j.conbuildmat.2023.133479
13. Rebelo, F. J. P., Martins, F. F., M.R.D. Silva, H., Oliveira, J. R. M. (2022). Use of data mining techniques to explain the primary factors influencing water sensitivity of asphalt mixtures. Construction and Building Materials, 342, 128039. https://doi.org/10.1016/j.conbuildmat.2022.128039
14. Suryadi, A., Qomariah, Q., Susilo, S. H. (2022). The effect of the use of recycled coarse aggregate on the performance of self-compacting concrete (SCC) and its application. Eastern-European Journal of Enterprise Technologies, 2 (6 (116)), 41–47. https://doi.org/10.15587/1729-4061.2022.255266
15. Klusáček, L., Nečas, R., Požár, M., Pěkník, R., Svoboda, A. (2021). Transverse prestressing and reinforced concrete as the key to restoration of masonry arch bridges. Engineering Structures, 245, 112898. https://doi.org/10.1016/j.engstruct.2021.112898
16. Aghcheghloo, P. D., Larkin, T., Wilson, D., Holleran, G., Amirpour, M., Kim, S. et al. (2023). The effect of an emulator inductive power transfer pad on the temperature of an asphalt pavement. Construction and Building Materials, 392, 131783. https://doi.org/10.1016/j.conbuildmat.2023.131783
17. Bekheet, W. (2014). Short term performance and effect of speed humps on pavement condition of Alexandria Governorate roads. Alexandria Engineering Journal, 53 (4), 855–861. https://doi.org/10.1016/j.aej.2014.09.009
18. Soehardjono, A., Aditya, C. (2021). Analysis of the effect of slab thickness on crack width in rigid pavement slabs. EUREKA: Physics and Engineering, 2, 42–51. https://doi.org/10.21303/2461-4262.2021.001693
19. Rasidi, N. (2015). Maximum Crack Width Prediction in Deck Slab Concrete Structure. IPTEK Journal of Proceedings Series, 1. https://doi.org/10.12962/j23546026.y2014i1.292
20. Cavalli, M. C., Chen, D., Chen, Q., Chen, Y., Cannone Falchetto, A., Fang, M. et al. (2023). Review of advanced road materials, structures, equipment, and detection technologies. Journal of Road Engineering, 3 (4), 370–468. https://doi.org/10.1016/j.jreng.2023.12.001
21. García-Troncoso, N., Hidalgo-Astudillo, S., Tello-Ayala, K., Vanegas-Alman, N., Bompa, D. V. (2023). Preparation and performance of sugarcane bagasse ash pavement repair mortars. Case Studies in Construction Materials, 19, e02563. https://doi.org/10.1016/j.cscm.2023.e02563
22. Wang, W., Wang, M., Li, H., Zhao, H., Wang, K., He, C. et al. (2019). Pavement crack image acquisition methods and crack extraction algorithms: A review. Journal of Traffic and Transportation Engineering (English Edition), 6 (6), 535–556. https://doi.org/10.1016/j.jtte.2019.10.001