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Design a No-Fine Concrete Using Epoxy in Pavement

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Abstract

No-fines concrete is an advanced pavement material known for its strong drainage capabilities, making it a widely used rigid road surface. With growing demand for reduced cement content due to industrial advancements, researchers have explored epoxy resin as a partial or total cement replacement. This study examines the mechanical properties of no-fines concrete with varying epoxy replacement levels and applies KENSLAB analysis for pavement thickness design. Seven concrete mixes were prepared with epoxy replacing cement at 100%, 95%, 75%, 55%, 35%, and 15%. Mechanical tests, including compressive strength, flexural strength, modulus of elasticity, bulk density, water absorption, and durability (wet-dry), were conducted after 7 and 28 days of curing. Additionally, the PerviousPave system was used to optimize pavement integrity by adjusting slab thickness, subbase layer thickness, and stormwater management. Results showed that the 55% and 100% epoxy replacement mixes performed best. Compressive strength increased by 2.44% and 33.44%, respectively, at 28 days compared to the reference mix. Flexural strength reached 5.99 MPa for 100% epoxy and 4.69 MPa for 55% epoxy at 28 days. Structural analysis demonstrated that increased slab and subgrade stiffness reduced tensile stresses, improving pavement durability and extending service life. These findings highlight the potential of epoxy-modified no-fines concrete for enhanced pavement performance in traffic and environmental conditions.

Keywords: No-Fine Concrete; Pavement; KENSLAB; Mechanical Properties; Durability Test; Structural Design.

1. Introduction

No-fines concrete, also known as porous concrete, is a specialized type of concrete with open voids that allow water to pass through. It is classified as lightweight concrete due to the absence of sand in its composition, meaning it primarily consists of cement, water, and coarse aggregates [1]. Unlike traditional concrete, no-fines concrete has a void ratio of 15-25%, which enables fluid permeability. This type of concrete is commonly used in pavement structures and parking lots. When carefully designed, it can also serve as a suitable material for country road pavements and as a sub-base layer in both flexible and rigid pavements [2, 3]. The demand for permeable pavements has been increasing steadily in cities across the United States and around the world. In Europe, no-fines concrete is used to reduce road noise, minimize water splashing during wet conditions, and improve surface friction. In China, it plays a crucial role in the sponge city initiative, which aims to mitigate urban flooding and reduce the burden on drainage systems. As the adoption of permeable pavement technology grows, researchers are actively working to overcome its key challenges, including limited strength and durability [4, 5]. Since cement is the primary binding material in concrete, it significantly influences the mechanical strength and durability of the final structure [2, 6]. Numerous environmental organizations worldwide, including the United States Green Building Council and the Environmental Protection Agency (EPA), promote the use of porous or permeable pavements as sustainable alternatives to traditional paving systems [7]. According to ACI 522R [8], no-fine concrete is composed of cement, coarse aggregates, water, and either minimal or no-fine aggregates. As a

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result, its compressive strength ranges from 2.8 to 28 MPa, while its water permeability falls between 0.135 and 1.21 cm/s (equivalent to 81–730 L/min/m²) [8]. Additionally, pervious concrete features pore diameters between 0.15 and 8 mm and typically has a porosity of 15% to 35% [9]. Its density generally varies from 1820 to 2100 kg/m³ [10].

Different substitution materials (SM) are frequently included in no-fine concrete compositions. By partially replacing SM for cement and reducing CO_2 emissions, concrete's overall environmental effect can be greatly decreased. Some SM offer extra advantages for concrete's overall finished qualities [11]. Concrete pavement maintenance is one specific case. The first objective is to minimize the temporary absence of the facilities and the cost of the maintenance. It is aware concrete pavements need to be maintained regularly [12]. Various chemical and mineral additives have been integrated into permeable concrete to improve its strength and durability. Examples include granulated blast furnace slag (GGBS), fly ash (FA), rice husk ash (RHA), and silica fume (SF), as well as a range of nano-materials such as nano-alumina (n-Al_2O_3), nano-titanium dioxide ($n - TiO_2$), and nano-silica ($n - SiO_2$). Additionally, carbon-based nano-materials like carbon nanofibers (CNFs) and carbon nanotubes (CNTs) have been incorporated into no-fine concrete mix designs. These additives help refine the concrete's microstructure while also reducing the demand for raw materials in the mixture [7].

Several studies suggest additional ways to control deteriorated pavements. Albayati et al. [13] studied the use of Engineered Cementitious Composite (ECC) and geotextile fabric as mitigation strategies for reflection cracking in Asphalt Concrete overlays. ECC, known for its tensile ductility and fracture resistance, significantly increased load cycles to failure. Obaidi [14] introduced two innovative pothole repair methods: prefabricated asphalt tiles and bonding layers, and prefabrication of asphalt pellets. These methods offer superior mechanical performance, reduced debris production, and improved work conditions, compared to current techniques, demonstrating their potential for improved road maintenance and operator satisfaction. Hashim et al. [15] highlight the significance of incorporating reclaimed asphalt pavement (RAP), the most widely recycled material globally, in hot mix asphalt. The addition of crumb rubber (CR) further enhances durability, improves resistance to thermal cracking and rutting, reduces stiffness, and minimizes fatigue damage. This study compiles previous research on RAP and CR to assess their impact on the mechanical and physical properties of asphalt pavement, as well as their environmental and economic benefits. The findings confirm that utilizing RAP and CR leads to significant structural improvements and cost savings in pavement construction.

Researchers have developed new techniques to maintain the rehabilitation of deteriorated pavements to increase the life cycle of pavement structures. No-fine Concrete pavement is one of these techniques used to enhance various mechanical properties and durability. Moreover, the usage of epoxy with it can decrease the load-soaking effect on the existing pavement structure by increasing the bonding between the two pavements [16]. Using epoxy as a partial replacement of cement, rehabilitation projects aim to improve the environmental performance of concrete while maintaining the strength and durability of concrete [17, 18]. Therefore, epoxy-reinforced systems are a secure repair method for highway pavement structures but not widely used globally. They offer flexibility and reduce downtime by allowing construction in sections. However, these systems have disadvantages like discontinuous structures, rapid damage, and reduced bearing capacity. Epoxy-modified concrete can address these issues by providing excellent resistance to cracks, heat, and low temperatures and performing well under various stress conditions, enhancing the overall performance of pavement structures [18, 19]. Previous studies have examined the modification effect of epoxy adhesive in concrete, revealing its advantages in various engineering applications. However, their widespread use in civil engineering has been limited due to high costs. Studies have found that high contents or large distribution volumes of epoxy materials can improve concrete's ductility, toughness, and durability. Large amounts of epoxy or polymer mortars are often discussed for surface concrete repair, but this is not a design requirement. Just a water resistance demand. A small amount of epoxy as a partial replacement for cement is more likely to be accepted in the construction industry [20-22].

No-fines concrete has certain drawbacks, including low compressive, flexural, and tensile strength, primarily due to its high void content [6]. A promising alternative is composite pavement, which incorporates a polymer-based binder. One widely used polymer in engineering applications is epoxy. Researchers have shown growing interest in enhancing concrete by adding epoxy, as highlighted in previous studies [11]. Polymer concrete is a composite material consisting of a polymer binder and aggregates, offering several advantages over conventional concrete. These benefits include a significantly higher strength-to-weight ratio, improved durability, and greater resistance to chemical deterioration [23]. Among the various polymers used, epoxy resin stands out as a key component for enhancing concrete performance. Due to its unique cross-linking network and specific functional groups, epoxy-based materials used in pavement applications offer excellent thermal stability, mechanical properties, adhesive strength, corrosion resistance, and chemical durability [24]. These characteristics make epoxy an effective alternative binder for improving the performance of concrete.

Epoxy concrete is produced by partially or fully replacing cement with epoxy resin as the binding agent, which is then mixed with aggregates. This combination integrates the strengths of both epoxy resin and concrete, resulting in enhanced bond strength, exceptional water resistance, superior chemical durability, and excellent weather resistance [24]. Typically, epoxy formulations are supplied as two-component systems: a resin (Component A) and a hardener

(Component B). In some cases, a third component, a filler, is included to further modify its properties [25]. By leveraging these advantages, epoxy-modified concrete addresses the limitations of traditional no-fines concrete, providing a more durable and high-performance alternative for pavement applications.

Al-Sallami et al. [26] conducted an experiment using different mixtures of porous concrete with varying gravel-to-cement ratios of 6%, 8%, and 10%, while maintaining a constant water-to-powder ratio of 0.45. In some mixtures, cement was fully used as the binder, whereas in others, 40% of the cement was replaced with epoxy based on its weight. The results indicated that incorporating epoxy significantly improved compressive strength, density, flexural strength, and modulus of elasticity across all mixes and curing ages. This improvement was attributed to the strong adhesive bond between the cement paste or mortar and the gravel. The best performance was observed in the mixture with a 6% gravel-to-cement ratio, achieving a compressive strength of 7.91 MPa, flexural strength of 0.84 MPa, modulus of elasticity of 2.55 GPa, and density of 1954 kg/m³ after 28 days of curing. Abbas et al. [27] investigated the effect of using epoxy resin as an admixture in concrete, incorporating it at proportions of 4% and 8%. Mechanical tests, including compressive strength and flexural strength, were conducted to evaluate its impact. The results showed that the compressive strength of concrete specimens ranged from 10 MPa at 4% epoxy to 30.5 MPa at 8% epoxy. This represented an increase of approximately 89.64% and 73.87%, respectively, compared to concrete without epoxy. Similarly, flexural strength ranged from 3.74 MPa to 4.51 MPa for the 4% and 8% epoxy mixtures. The study concluded that adding epoxy resin significantly enhances the compressive strength of concrete.

Jokhio et al. [20] investigated replacing cement with epoxy in a mixture of concrete that comprised cement and silica sand, coarse aggregate, and water. The cement was replaced with epoxy at ratios of 10%, 20%, and 30%. The result showed a decrease in compressive strength of 75%, 79%, and 31%, respectively, in comparison to the reference mixture at 28 days. The study's conclusion was that the inclusion of epoxy resin has a negative influence on the efficacy of cement as a binder, and the limited quantity of epoxy does not generate a sufficient binding effect on its own. At higher proportions, the rise in compressive strength can be ascribed to epoxy resin. The tendency indicates that increased amounts of epoxy resin will lead to enhanced strength of the concrete. The splitting tensile strength results showed lowering to 43% and 47%, respectively, for 10% and 20% of epoxy, but an increase of 4% for a proportion of 30% of epoxy compared with the reference mixture. Nadali et al. [28] investigated the effects of crumb rubber, recycled plastic, and epoxy additives on the mechanical and permeability properties of porous concrete for urban infrastructure and water management. Using kriging and artificial neural network (ANN) models, they analyzed porosity, compressive strength, and permeability. The study found that crumb rubber significantly improved compressive strength (Delta 1.72), while recycled plastic had a smaller effect (Delta 0.26). Permeability decreased with higher crumb rubber and plastic content but increased with epoxy due to pore occlusion. Sensitivity analysis highlighted epoxy content as the most influential factor in failure probability, emphasizing the need for optimized material selection.

No-fine concrete is an advanced pavement material designed primarily for stormwater management by facilitating water infiltration through its porous structure. Although its primary function is hydrological, the structural design of no-fine concrete pavements must be carefully addressed to ensure they can withstand traffic loads and environmental stresses over time. In the PerviousPave system, the slab thickness determined by the structural design algorithm serves as a direct input for the hydrological design. To meet stormwater management requirements, the thickness of the subbase or reservoir layer is adjusted (increased) as needed. This integrated approach ensures that both the structural integrity and hydrological performance of the pavement are optimized for the project [29]. Similar to conventional concrete pavements, the structural design of no-fine concrete primarily focuses on fatigue failure, which arises from repetitive traffic loading. However, field studies have shown minimal fatigue cracking in no-fine concrete pavements, suggesting that other modes of deterioration, such as raveling (surface degradation) and clogging (loss of permeability), may be more critical. Unlike traditional pavements, erosion is less significant due to the use of a stable granular base layer beneath the no-fine concrete [29, 30]. The pavement thickness is determined based on traffic loading, mechanical properties, and the foundation's support. Vancura et al. [30] and AlShareedah & Nassiri [31] have developed thickness design methodologies specifically for no-fine concrete pavements. They used an approach that incorporates realistic mechanical properties and traffic categories, recommending thicknesses ranging from 150 to 250 mm to accommodate varying load levels while maintaining structural integrity. Key mechanical properties, such as flexural strength and elastic modulus, play a vital role in the pavement's ability to resist traffic-induced stresses and environmental impacts. These properties influence the load-carrying capacity and overall durability of the pavement. The modulus of subgrade reaction (k-value) reflects the stiffness of the foundation and is a critical parameter for stress distribution within the pavement structure. Additionally, the average daily truck traffic (ADTT) and vehicle types significantly influence the required pavement thickness to ensure adequate performance over its design life [31, 32].

Previous studies have primarily focused on the effect of epoxy as a partial replacement for cement in no-fines concrete, with a maximum replacement level of 50%. However, no research has explored the impact of using epoxy beyond this limit, particularly in pavement applications. This study aims to investigate the mechanical properties of no-fines concrete by incorporating epoxy resin in varying proportions, reaching up to 100% replacement. Additionally, it seeks to develop a dedicated design approach for the wearing surface of no-fines concrete pavement by integrating epoxy, utilizing structural pavement analysis through KENSLAB. To achieve this, the article is structured as follows:

1. Introduction and Literature Review – Discusses the background of no-fines concrete, previous studies on epoxy-modified concrete, and the significance of exploring higher epoxy replacement levels in pavement applications.
2. Materials and Methods – Describes the materials used, mix design, and experimental setup for evaluating the mechanical and physical properties of epoxy-modified no-fines concrete.
3. Experimental Work – Details the conducted tests, including compressive strength, flexural strength, modulus of elasticity, bulk density, water absorption, and durability assessments.
4. Results and Discussion – Presents and analyzes the findings, highlighting the effects of epoxy on the mechanical performance and permeability of no-fines concrete.
5. Structural Analysis Using KENSLAB for Pavement Design – Examines the impact of epoxy replacement on pavement performances by assessing slab and subgrade stiffness, durability, and service life.

By integrating experimental analysis and structural modeling, this study aims to enhance the understanding of epoxy-modified no-fines concrete, optimizing its application for durable and sustainable pavement solutions.

2. Material and Methods

Figure 1 presents significant details regarding the process of the methodology during this workflow.

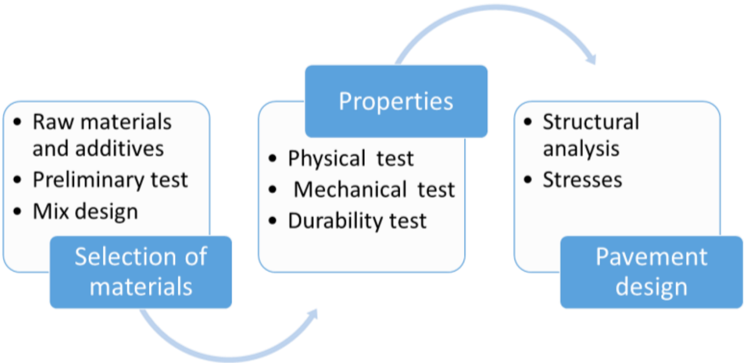

Figure 1. Chart of workflow

2.1. Cement

In this study, Ordinary Portland Cement Type I was used, which was supplied by the Mass Iraq Company for the cement industry and produced by the United Cement Company. This cement, known in the local market as Mass Bazian, is presented in Table 1. It conforms to the Iraqi specification limits I.O.S.5 [33].

Table 1. Chemical composition of cement

Oxides	Mass Cement	Iraqi specification limits I.O.S. 5/1984 [33]
CaO	61.61	-
SiO_2	20.54	-
Fe_2O_3	3.28	-
Al_2O_3	4.88	-
MgO	1.93	< 5
SO_3	1.87	< 2.8
L.S.F	0.89	0.66 - 1.02
L.O.I	2.31	< 4
I.R	0.58	< 1.5
C_3S	51.903	-
C_2S	19.794	-
C_3A	7.389	-
C_4AF	9.981	-

2.2. Coarse Aggregate

Coarse aggregate (gravel) was used in this study with specific gravities of 2.65, absorption % of 1.6, and SO_3 of 0.04. The maximum size of the used gravel is 10 mm (Figure 2). It is in conformity with ACI 522R-10 [8] and also conforms to SCRB/R9 [34].

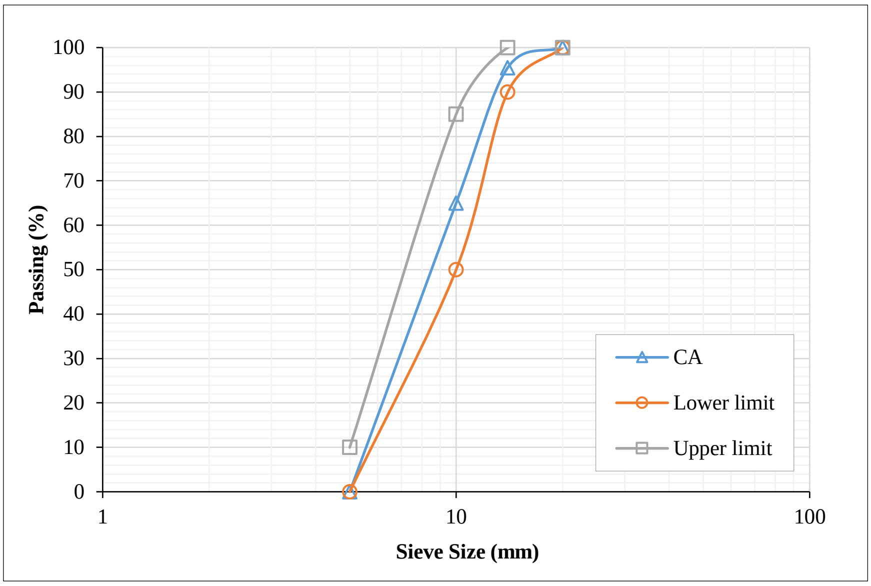

Figure 2. Granulation curve of coarse aggregate (Gravel)

2.3. Epoxy

An epoxy material with high compressive resistance and non-absorption was used as a binder partial replacement of ordinary Portland cement under the trade name Sika 42-LP. The properties of epoxy are shown in Table 2.

Table 2. Properties of epoxy

Product Data	Properties of Sikadur 42-LP		
Type	Epoxy risen		
Form	Grey component A: B: C		
Shelf Life	24 months for minimum from protection data		
Mixing Ratio	Comp A: B: C = 2:1:12 part by weight by weight. Solid/ Liquid= 4:1 by weight		
Density	2 kg/l (mixed material)		
Pot Life	The pot life of resin and hardener is determined by the mixed amount, with shorter pot life at high temperatures and longer at low temperatures. Divided adhesives or chilling components can improve workability.		
Mechanical Strength	***Curing Time (day)***	***Compressive strength (MPa)***	***Tensile strength in flexure (MPa)***
	1	45	30
	3	67	34
	7	77	39
	14	83	41
	28	85	42

2.4. Water

Tap water was used throughout this work in mixing concrete without any additives.

2.5. Experimental Setup

In this paper, the mixes were blended using the weight-based approach. The coarse aggregate/cement ratio was 4.5 for each mixture. The water/cement ratio was 0.4, fixed for all mixtures. Furthermore, the percentage of partial replacement of cement with epoxy was 5, 25, 45, 65, 85, and 100% by weight of cement. The amounts of cement, coarse aggregate, and water were about 320, 1440, and 128 kg/m³, respectively. Table 3 exhibits the mix design of this study for 1 m³.

Table 3. Mix design of no-fine concrete pavement

Mix No.	Cement	Epoxy	w/c	Gravel
R	100%	0	0.4	
1	95%	5%	0.4	
2	75%	25%	0.4	
3	55%	45%	0.4	With fixed amount of coarse aggregate
4	35%	65%	0.4	
5	15%	85%	0.4	
6	0	100%	0	

The preparation of no-fine concrete pavement mixtures was dependent on previous studies and the design mentioned in the specification ACI 522R-10 [8]. The objective design strength of the reference mixture was 14 MPa. The mixing method was done according to the procedure mentioned in ASTM C192 [35]. Coarse aggregates were mixed with cement after adding the water to it. Epoxy resin (C) and hardener (A+B) were mixed for 2 min before being added to the concrete mix. After that, the molds were wrapped inside with thermal nylon to prevent the adhesion of the mixture to the surface of them. Then, the final mixture was added inside the mold until a homogenous mixture was completely formed after compaction (Figure 3). All samples were cured at 7 and 28 days in water for all series. Cubic molds with dimensions of 100×100×100 mm were prepared for conducting the tests of compressive strength, bulk density, absorption, and durability tests (wetting in water and drying in air). Prism molds with dimensions of 380 × 80 × 80 mm were prepared for flexural testing. Cylindrical molds with dimensions of 150×300 mm were prepared for the modulus of elasticity test.

Figure 3. The process of samples preparation

2.6. Specimens Testing

The bulk density of the no-fine concrete cubic samples was determined by B.S. 12390: Part 7 [36]. The water absorption was carried out by B.S. 1881: Part 122 [37]. The compressive strength test was carried out using the E.L.E. International-2007/UK/A.D.R.-2000-standard machine instrument. It was performed according to B.S. 1881: Part 116 [38]. The flexural strength was applied according to ASTM C78-84 [39]. Furthermore, the static modulus of elasticity was performed according to ASTM C469 [40].

The durability process (wetting and drying) cycles started at 28 days. Cubical samples were employed. The cycles began after the samples had been submerged in water for 48 hours. Concrete samples exposed to rapid wetting and drying cycles were tested for durability using ASTM D559 [41] and based on Bui et al. [42] and Fwa [43]. Immersion in water at 20°C for 24 hours and drying in air for 24 hours were the two stages of this process. Figure 4 illustrates some of the samples with different tests.

The cycles of wet-dry were repeated every 7 days during 30 days. The durability properties of exposed samples were evaluated using a bulk density test according to the following Equation:

$$\gamma\% = \frac{\gamma_{word} - \gamma_i}{\gamma_i} \times 100\% \tag{1}$$

where $\gamma\%$ is the bulk density change after exposure to wet-dry cycles, in % γw or d, the bulk density of sample after wetting or drying, in kg; and, γ_i, the initial bulk density of sample before exposing the wet-dry cycles, in kg.

Compressive Strength Flexural Strength Modulus of elasticity

Figure 4. Some of the samples with different tests

3. Results and Discussion

3.1. Impact of Epoxy on the Compressive Strength and Bulk Density on no-fine Concrete Mixes

Figure 5 presents the correlation between compressive strength and bulk density of samples with different proportions of epoxy after 7 and 28 days. Generally, there is a variation in the density distribution values with the compressive strength values for different proportions of adding epoxy instead of cement to produce no-fine concrete.

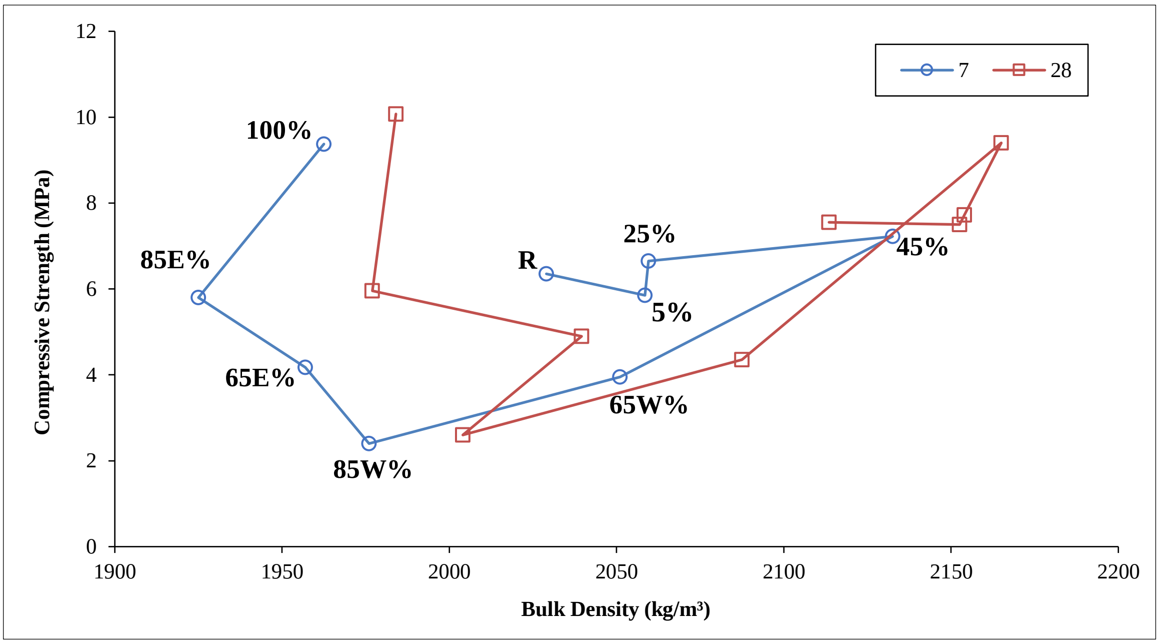

Figure 5. Effect of compressive strength and bulk density of no-fine concrete

The results show that replacing 100% of cement with epoxy yields the highest values in both bulk density and compressive strength, reaching approximately 1962.5 and 1984 kg/m³, and 9.375 and 10.075 MPa after 7 and 28 days, respectively. When compared to the reference concrete, the 100% epoxy mix demonstrated a compressive strength increase of 47.64% after 7 days and 33.44% after 28 days. Additionally, this mix can be classified as more lightweight than the reference mix, with a weight reduction of about 6.13% after 28 days. Figure 6 illustrates the sample with 100%

epoxy resin used in the compressive strength test. These results are consistent with the findings of Li et al. [44], confirming that increasing the epoxy resin-to-aggregate ratio significantly improves the compressive strength of permeable concrete containing crushed stone aggregate. This enhancement is mainly attributed to the characteristics of the aggregate and the strong bond formed between the epoxy resin binder and the aggregates.

Figure 6. The cubical sample with 100% epoxy

For the mixture containing 45% epoxy, an increase in compressive strength of approximately 13.78% and 24.5% was observed after 7 and 28 days, respectively, despite a reduction in density by about 5.10% and 2.44% compared to the reference mix. In the case of the 5% epoxy mixture, no clear trend was observed, with a slight decrease in both strength and density relative to the reference mix. Conversely, the 25% epoxy mix showed improvements in both strength and density at both 7 and 28 days. It is important to note that water was added to all mixtures except the 100% epoxy mix. The mixtures performed well with epoxy replacement levels up to 45%. However, when water was added in combination with higher epoxy replacement levels (65% and 85%), a significant decrease in compressive strength—approximately 37.80% and 42.38%—was observed after 7 and 28 days, respectively. Although there was a slight increase in density by 1.08% at 7 days, it decreased by about 1.25% at 28 days.

These results suggest that the addition of water, when combined with high epoxy replacement levels, negatively impacts performance by reducing cement content and promoting segregation within the mixture, as shown in Figure 7. This observation aligns with the findings of Awodiji and Sule [45], who noted that the presence of water in epoxy-modified concrete mixes can lead to a loss in compressive strength. Therefore, water may not be necessary beyond a certain level, depending on the water-to-cement ratio used in the mix design.

65% with water and epoxy 85% with water and epoxy

Figure 7. Water Effect on mixtures 65% and 85%

To evaluate performance without the influence of water, additional tests were conducted using epoxy mixed only with cement, excluding water. In this case, the samples exhibited a reduction in bulk density—indicating lighter concrete—and a notable improvement in compressive strength.

For the 65% epoxy mix (65E%) compared to its water-based counterpart (65W%), compressive strength increased by approximately 5.7% and 12.64%, while bulk density decreased by about 4.58% and 2.3% after 7 and 28 days, respectively. An even more significant improvement was observed in the 85% epoxy mix (85E%) compared to 85W%, with compressive strength increasing by around 141.67% and 129.23%, and a slight reduction in density by 2.58% and 1.35% over the same periods. Due to their poor performance, the 65W% and 85W% mixes were excluded from further analysis.

Epoxy is incorporated into no-fines concrete to enhance bonding between aggregates, increase tensile strength, and improve overall durability. It contributes to better resistance against chemical attacks, moisture penetration, and physical wear. However, the interaction between epoxy and no-fines concrete may lead to varied cracking and failure patterns, which are influenced by factors such as curing conditions, the composition of the epoxy, and the type of aggregate used. Figure 8 shows the observed crack and failure patterns across all tested samples.

Figure 8 illustrates the condition of the samples before, during, and after loading, where the dominant failure mode was brittle fracture. In general, the epoxy-modified samples exhibited more pronounced failure compared to the reference mix. Specifically, the 65W and 85W samples experienced complete collapse, likely due to weak bonding at the interface between the epoxy and concrete, along with noticeable segregation in the mix, as previously shown in Figure 7. In contrast, the samples with 100% epoxy replacement underwent only partial collapse, indicating a stronger adhesion between the epoxy and the aggregates.

In summary, increasing the epoxy content while simultaneously reducing the cement ratio in the presence of water significantly compromised the structural integrity of the concrete. This led to increased brittleness and sudden failure, possibly due to mismatches in thermal or moisture expansion coefficients between epoxy and cementitious materials. The variability in failure patterns underscores the necessity for further investigation to determine the optimal epoxy-to-cement ratio.

On the other hand, the 100% epoxy mixture demonstrated a unique failure behavior, suggesting improved bonding performance—likely due to the coarse aggregates' rough surface texture. The epoxy effectively filled the voids between aggregates, enhancing the concrete's resistance to mechanical loads and water infiltration. However, it is important to note that epoxy lacks certain beneficial characteristics of cement paste, such as flexibility and compressibility, which may still make it susceptible to failure under specific loading conditions.

Figure 8. Crack and failure patterns of the samples

3.2. Impact of Epoxy on Water Absorption on no-Fine Concrete Mixes

The water absorption of the test samples at 7 and 28 days of curing was measured for various epoxy content levels, and the results are presented in Figures 9 and 10. As shown, no-fines concrete containing 100% epoxy exhibited the lowest water absorption among all mixtures, with absorption decreasing further as curing time increased. This can be attributed to the waterproof nature of epoxy.

These findings are consistent with those reported by Sedeeq and Shaheen [46], who highlighted the critical role of waterproofing in protecting concrete structures from the damaging effects of moisture infiltration. Their study investigated the use of a tar-epoxy blend to reduce water absorption in concrete. When a 1:1 ratio of tar to epoxy was applied to concrete surfaces, it rendered them fully waterproof. Experimental results demonstrated that concrete specimens coated with this mixture showed significantly less deterioration when exposed to acidic environments compared to uncoated samples.

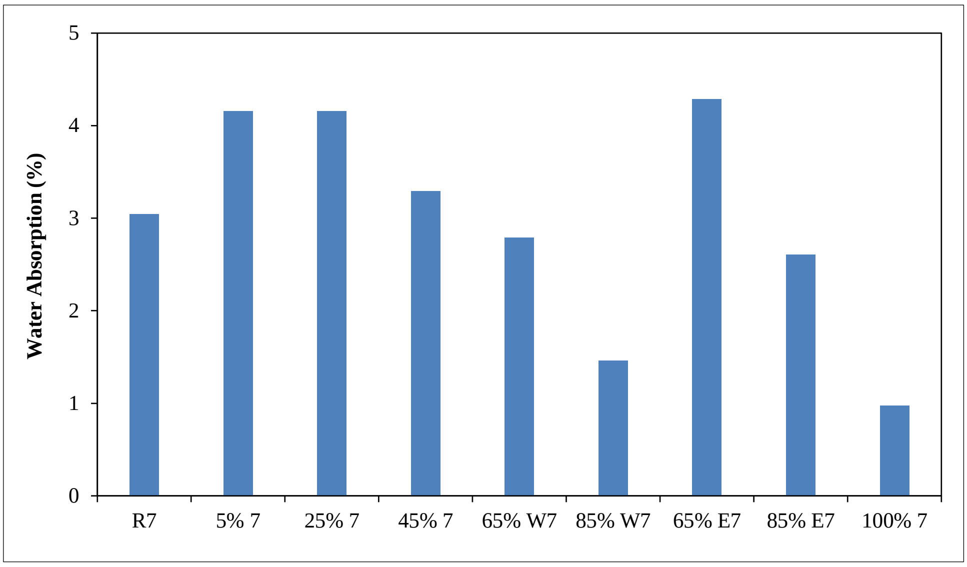

Figure 9. Effect of water absorption of no-fine concrete mixes at 7 days

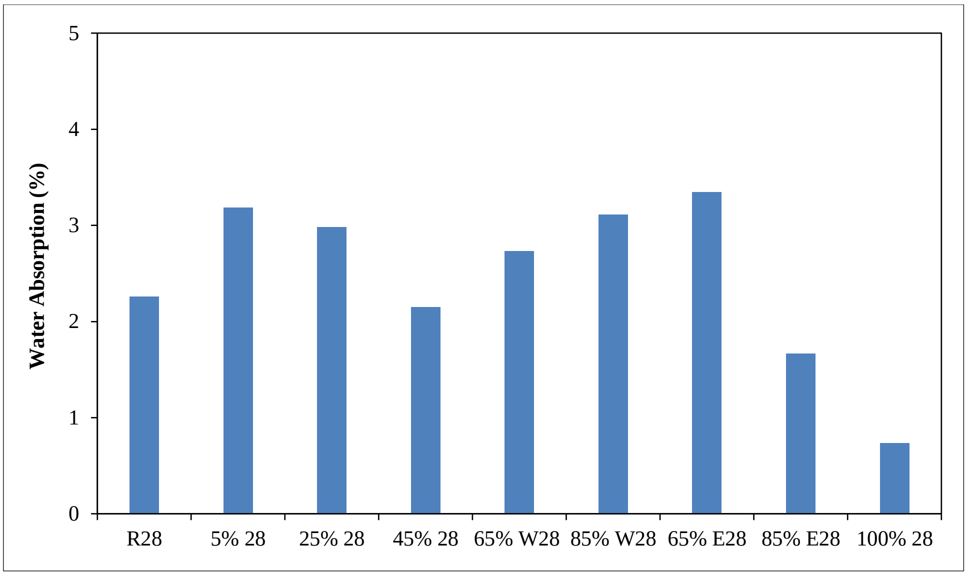

Figure 10. Effect of water absorption of no-fine concrete mixes at 28 days

The absorption of 5% and 25% epoxy had the highest values with curing time compared with others. The increment percentage was about 36.67%, 40.80% of 5% and 36.54%, 31.83% compared to the reference mix at 28 days of curing. In contrast, the absorption decreased by about 4.82% at 45% epoxy compared to the reference mix at 28 days. 65W% and 85W% had an absorption of 2.734 and 3.114% at 28 days. This can be explained by the fact that 65% and 85% reductions in workability lead to more water, although epoxy material mixed with cement was a waterproof material. These findings confirm that the use of epoxy as a partial replacement for cement resulted in a reduction in physical and mechanical properties.

3.3. Impact of Epoxy on the Flexural Strength on No-Fine Concrete Mixes

In general, the flexural strength of no-fines concrete tends to follow a pattern similar to that of compressive strength, a trend that was also observed in this study.

As shown in Table 4, the flexural strength of the 25%, 45%, and 100% epoxy mixes showed identical values, each demonstrating an increase of 17.08% after 7 days compared to the reference mix. In contrast, the 5% and 65E% mixes exhibited a reduction in flexural strength, with decreases of 12.08% and 52.08%, respectively, at 7 days relative to the reference mix.

Table 4. The results of flexures strength of no-fine concrete mixes

Mix	Flexural Strength (MPa)	
	7 days	28 days
R	2.40	3.25
5%	2.11	3.87
25%	2.81	4.49
45%	2.81	4.69
65E%	1.15	1.41
85E%	2.40	3.27
100%	2.81	5.99

It was observed that the mixes containing 100% and 45% epoxy as a replacement for cement achieved the highest flexural strengths, reaching 5.99 MPa and 4.69 MPa, respectively, after 28 days. In contrast, the mixes with 65E% to 85E% epoxy showed the lowest flexural strength values at the same curing age. These results highlight the importance of carefully controlling the water-to-cement ratio when designing epoxy-modified concrete, as increasing the epoxy resin content can significantly enhance strength. Additionally, the 5% and 25% epoxy mixes also showed improvements in flexural strength, with increases of approximately 19.08% and 38.15%, respectively, after 28 days compared to the reference mix. As indicated in Table 4, there is a general trend suggesting that higher epoxy resin content leads to stronger concrete. However, the flexural strength at both 7 and 28 days varied depending on the proportion of binder replacement, underscoring the need for further research involving different filler materials and a wider range of replacement ratios. Notably, the mix with 100% epoxy replacement outperformed the control sample in terms of flexural strength, suggesting that higher epoxy content may enhance the overall mechanical performance of the concrete. Nevertheless, this assumption warrants further study to confirm its long-term durability and practical applicability in real-world construction scenarios.

3.4. Impact of Durability (Wet-Dry Cycles) on No-Fine Concrete Mixes

In this study, the durability of no-fines concrete was evaluated using a wetting-in-water and drying-in-air test over five cycles. As shown in Figure 11, the mix containing 100% epoxy exhibited the highest increase in bulk density after undergoing the wetting and drying cycles, outperforming all other mixes. This behavior can be attributed to the stronger internal bonding within the concrete matrix, resulting from the higher concentration of epoxy. In contrast, the bulk density of the other mixes generally decreased after exposure to repeated wetting and drying, indicating a lower resistance to such environmental stresses.

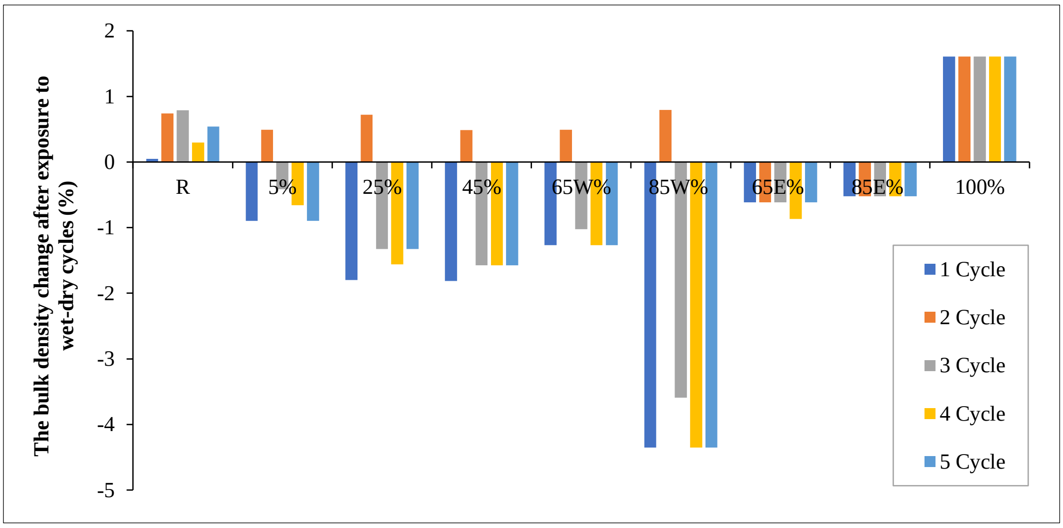

Figure 11. Effect of durability of no-fine concrete mixes

As shown in Figure 11, the 85W% mix exhibited a significant decrease in bulk density after five cycles of wetting and drying, indicating poor durability under these conditions. In contrast, the 5%, 25%, and 45% mixes showed similar patterns in the percentage of change in bulk density, with only slight variations between their responses to the exposure cycles. This consistent behavior can likely be attributed to the higher cement content in these mixes, which contributes to stronger internal bonding and greater resistance to microcracking caused by the drying phase. The improvement in durability due to epoxy use has also been highlighted in the study by El-Hawary and Abdul-Jaleel [19], which supports these findings.

On the other hand, the 65E% and 85E% mixes experienced a slight reduction in bulk density after five cycles of wetting and drying, showing a different trend from the reference mix and suggesting lower resistance to environmental stress at these epoxy replacement levels.

3.5. Impact of Epoxy on the Modulus of Elasticity on No-Fine Concrete Mixes

The modulus of elasticity for no-fines concrete was calculated according to the ACI 318 equation for different additive ratios depending on the results of compressive strength:

$$E = 4700\sqrt{f'c} \tag{2}$$

The results are summarized in Figure 12, which shows the highest stiffness with 100 % replacement, while the lowest stiffness appeared for 65% replacement. These results showed the effect of the epoxy on the no-fine concrete, and it was confirmed by AlShareedah & Nassiri [47].

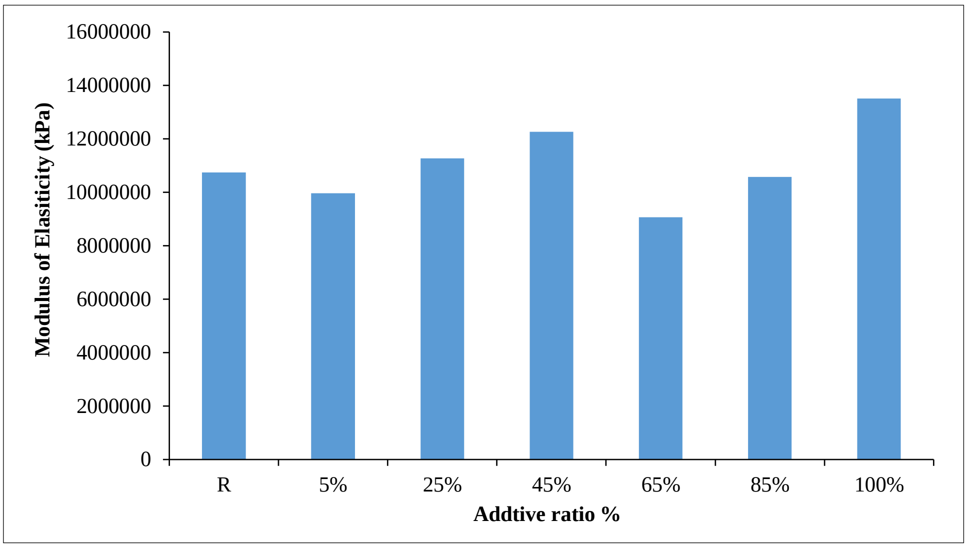

Figure 12. Effect of modulus of elasticity of no-fine concrete mixes

4. KENSLAB Model

The two-dimensional finite-element mesh, based on the example from Huang [48], was utilized for the analysis of the system under a linear elastic assumption. A single wheel load was modeled as a uniform pressure distributed over a rectangular contact area. This load was applied at two critical locations: directly on the edge of the surface and at its midpoint, as these positions typically exhibit the highest stress concentrations. The resulting stress profiles and characteristics were analyzed. Figures 13 and 14 illustrate the case where no-fine concrete layer was considered in the system.

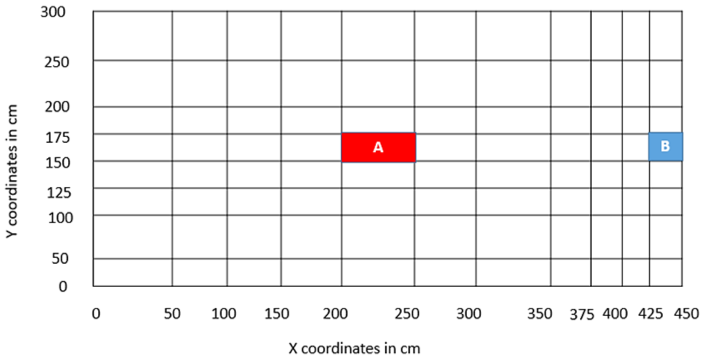

Figure 13. The finite element grid for no-fine concrete pavement with wheel loads in two positions (A and B)

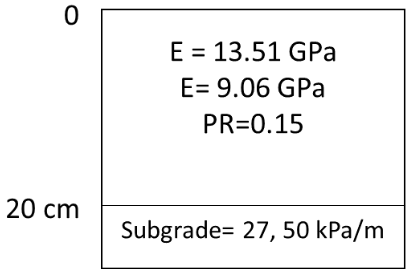

Figure 14. Depth profile for no-fine concrete pavement

The analysis utilized constant parameters, including a wheel load of F= 41.5 kN and a tire pressure of P= 690 kPa, as outlined by Huang [48]. The slab thickness was D= 20 cm. The no-fine stiffness was determined based on the ACI 318 equation; the highest value was E= 13.5 GPa, and the lowest was E= 9.06 GPa for the surface layer. The modulus of rupture, measured in the laboratory, was 4 MPa, and the subgrade reaction modulus values were K= 27 MPa/m and K= 50 MPa/m. These parameters were selected using the American Concrete Institute (ACI) design charts, consistent with findings from previous research [32, 49].

4.1. Tensile Stresses Results

Traffic loads are the primary contributors to stresses and deflections in the concrete pavement slab. Therefore, accurately calculating critical stresses is essential for effective pavement design. Analyzing no-fine concrete pavements using KENSLAB reveals that the most critical stresses typically occur along the slab edges and directly beneath the applied load, as illustrated in Figures 15 and 16.

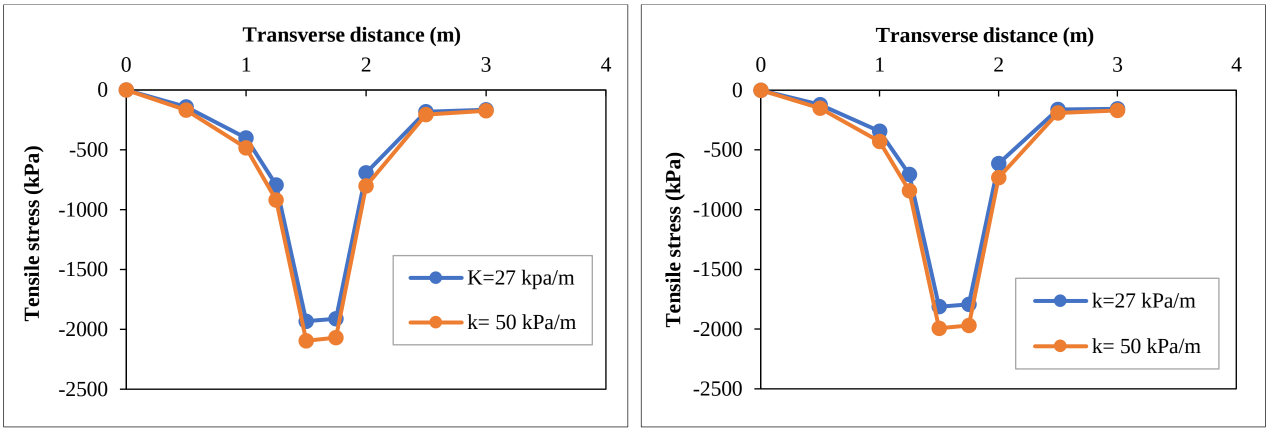

Figure 15. Relationship between tensile stress and transverse distance along the joint at slab thickness 200 mm

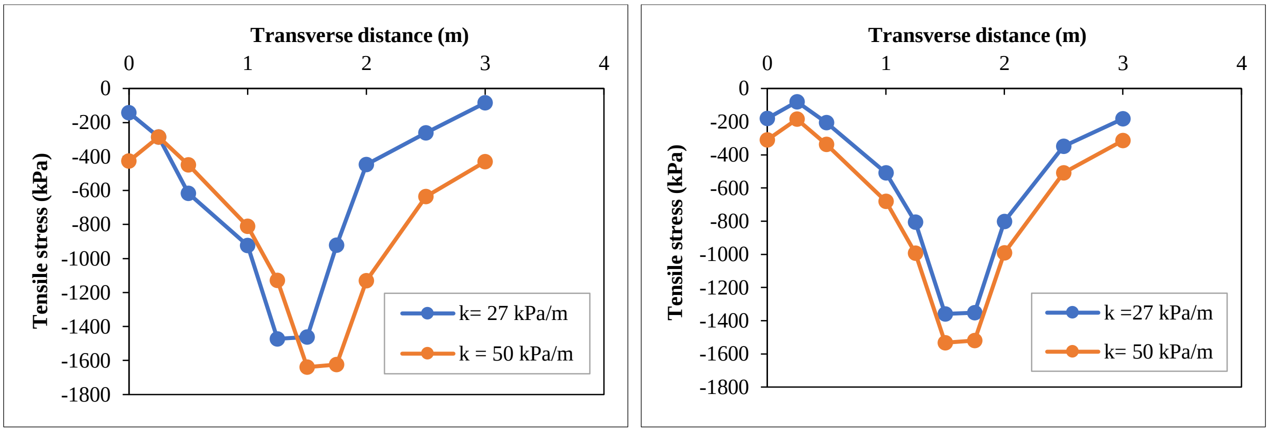

Figure 16. Relationship between tensile stress and transverse distance at the midpoint of the slab thickness 200 mm

The figures depict the relationship between tensile stresses and the vertical position within the slab, considering varying levels of slab stiffness and subgrade stiffness. The analysis shows that increasing both slab and subgrade stiffness reduces the stresses within the slab, while decreasing these stiffness parameters leads to higher tensile stresses. Specifically, stress reductions of 13%, 12%, 10%, and 8% were observed for lower subgrade stiffness at the slab center and edges, whereas reductions in the modulus of elasticity resulted in decreases of 5%, 6.5%, 7%, and 7.5% at the same points. To minimize stresses and enhance the pavement's lifespan, the design should focus on accommodating maximum stress levels through appropriate slab thickness and sufficient stiffness.

5. Conclusion

Based on the findings of this research, which focused on designing no-fines concrete using epoxy for pavement applications, the following conclusions can be drawn:

Laboratory Results: The experimental results demonstrated improvements in both compressive and flexural strength when 45% and 100% of the cement were replaced with epoxy, identifying these as the most effective replacement ratios. Additionally, the bulk density results indicated a reduction in concrete weight with full (100%) cement replacement by epoxy, showing a density decrease of approximately 6.13% at 28 days. At 45% epoxy replacement, a slight increase in density (about 2.44% at 28 days) was observed, suggesting improved packing and bonding. In contrast, mixes with 65% and 85% epoxy exhibited reductions across all performance metrics, likely due to negative interactions between epoxy and water during the mixing process. Regarding durability, the 100% epoxy mix showed an increase in bulk density after five cycles of wetting and drying, attributed to stronger internal bonding. However, most other mixes experienced reductions in bulk density, with the 85W% mix displaying the greatest change, indicating reduced resistance to environmental stress.

Structural Design Insights: From the structural design analysis of no-fines concrete pavement, it was observed that increasing slab thickness and subgrade stiffness effectively reduces tensile stresses in the pavement system. Conversely, reductions in these properties lead to a significant increase in stress levels. For optimal performance, pavement designs must include adequate slab thickness and stiffness to limit stress concentrations. This is supported by the observed decrease in tensile stress with improved material characteristics. Employing established design tools such as KENSLAB, along with insights from previous research, ensures the pavement structure is capable of withstanding expected loads while maintaining a long service life. In summary, careful selection of material properties—especially epoxy content—and proper structural design are critical to enhancing the durability, strength, and longevity of no-fines concrete pavements.

6. Declarations

6.1. Author Contributions

Conceptualization, H.O.; methodology, H.O.; software, H.A.M.; validation, H.A.M.; formal analysis, H.O.; data curation, H.O.; writing—original draft preparation, H.O.; writing—review and editing, H.A.M.; supervision, N.M.F.; project administration, N.M.F. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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