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Effect of Adding Steel and Glass Fibers on the Mechanical Properties and the Thickness of Rigid Concrete Pavements

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ABSTRACT

A road network uses rigid pavement for various purposes, still, it can face several challenges, including cracking from temperature changes, shrinkage, load stress application, brittleness, and flexural and tensile weakness. The thickness of rigid pavement significantly influences its performance and durability. A thicker slab distributes weight more effectively on the subgrade; however, greater thickness significantly raises construction costs, requires more resources, and negatively impacts the natural environment. The purpose of this study is to find out how adding a 1% volume fraction of steel and glass fiber in single and hybrid shapes changes the mechanical properties of concrete and pavement thickness. The compressive strength test, the flexural strength test, and the splitting tensile test were used to investigate the change in mechanical properties and The software (EMS) was selected to compute the thickness of the concrete pavement. The findings indicated a significant improvement in the mechanical characteristics resulting from the reinforcement of concrete with fibers. This was shown by a modest increase in compressive strength, reaching 9.1% after 90 days, along with significant enhancements in tensile and flexural strength, achieving 72.5% and 70% after 90 days, respectively. These adjustments, along with the use of PCASE EMS, resulted in a 30% decrease in thickness relative to the reference mixture.

Keywords: Concrete pavement, Steel fiber, Glass fiber, Thickness of rigid pavement, Mechanical properties.

1. INTRODUCTION

Concrete, becoming the most commonly utilized material for construction globally, has become the second most widely used material, behind water. The combined influence of tensile and flexing forces often causes concrete failure. Given the sudden occurrence of this failure, it became essential to look into improved methods for designing concrete reinforcement structures **(Ahmed, 2021; Al-Quraishi et al., 2018).**

Concrete pavements are commonly used for carrying heavy loads and offering durable solutions on roads, bridge decks, and airports **(Taher et al., 2020; Deshmukh et al., 2017).**

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The challenges associated with using concrete pavements are numerous, including their brittleness under heavy traffic loads, which can lead to cracks, and their weakness in flexural and tensile strength compared to their ability to withstand compression. All these issues will shorten the pavement's lifespan (**Suja and Marliyas, 2016; Golewski, 2023).** In recent years, there has been growth in the use of FRC (fiber-reinforced concrete), which incorporates various types of fiber, like steel, glass, carbon (steel-glass-carbon-polypropylene), and basalt fiber **(Al-Rousan et al., 2023; Labib, 2016).** Its improved concrete mechanical characteristics, like increased tensile and flexural strength, improved toughness, reduced brittleness, and increased crack control, enhanced the durability of the concrete pavement **(Shakir et al., 2022; More and Subramanian, 2022)**. Fibers act as a bridge among microcracks, conveniently transporting stress and developing the overall performance of the composite material. This will lead to a satisfactory stress distribution on all parts of the concrete structure; Therefore, the bridge effect becomes significant when the concrete is subjected to load-bearing conditions. **(Le et al., 2019; Li, 2012).** Single-fiber reinforcement involves adding only one type of fiber to concrete. It aims to enhance specific qualities of the concrete., **(Zhang et al., 2018; Pakravan et al., 2017).** Despite this, using a single fiber significantly enhances tensile and flexural strength but may not be effective in other properties like impact resistance. In addition, the single-fiber reinforcement is regarded as a heavy material, thus, the probability of clumping and segregation of fiber will be increased, which would reduce the effectiveness of the reinforcement. Furthermore, it is essential to evaluate the high cost associated with using a single type of fiber **(Bentur and Mindess, 2007; ACI 544.4R, 2015).** Therefore, using hybrid fiber as one of the solutions involves adding multiple types of fibers to the concrete mixture, known as hybrid fiber reinforcement. This combination is intended to best utilize the advantages of each fiber type **(Vairagade and Dhale, 2023; Ma et al., 2024).**

Using a 1% volume fraction of different types of fibers (steel, polypropylene, and glass fibers) led to enhanced mechanical properties, reaching almost 60%. It also showed that steel fibers were the most effective in reducing the required pavement thickness **(Hussain et al., 2020).**

The thickness of rigid pavement is a crucial factor that affects structural performance and durability. A thicker slab gives better load distribution, which reduces stresses on the subgrade and enhances the pavement's ability to withstand heavy traffic and environmental conditions. However, increased thickness may significantly increase construction prices, material usage, and environmental impact, making thickness optimization a key objective in pavement design. Getting the perfect mix between lasting power and cost-effectiveness is key for today's structure development **(Hassouna and Jung, 2020; Hussain et al., 2020).**

Adding fibers in concrete pavement design has been shown to significantly reduce the thickness of the slabs required while maintaining or enhancing their performance. Fibers, for instance, steel and glass, significantly improve the mechanical properties of concrete, tensile strength, flexural capacity, and resistance to cracking. These improvements let thinner slabs perform just like thicker ones that do not use (FRC). For example, using steel fibers can decrease pavement thickness by up to 24% while improving load-bearing capacity and service life. Similarly, incorporating carbon fibers enhances the modulus of rupture, allowing reduced pavement thickness while maintaining carrying load capability **(Rangelov et al., 2020; Hussain et al., 2020).** Improvements in technology have revolutionized pavement design by simplifying the process of determining optimal pavement thickness. New software helps use methods that look at material properties, traffic loads, and environmental factors, Providing accurate and rapid suggestions for road design **(Al Fuhaid et al., 2022; Pierce and McGovern, 2014)**These tools save time and provide high accuracy, helping engineers pick materials and decrease the costs. One of these programs, EMS Desktop, is a main tool for figuring out pavement thickness. Developed as part of the PCASE suite by the U.S. Army Corps of Engineers, EMS Desktop allows engineers to input the details of elastic modulus, subgrade characteristics, and loading conditions to determine optimal pavement thickness with high precision **(ERDC, 2010).**

2. MATERIALS

An overview of the materials used in the experimental work is provided below.

2.1 Cement

The cement that was utilized for the laboratory work is Portland cement (type V) resistant to sulfates, which is widely used in Iraqi concrete pavement construction and was produced by the Iraqi company "Mass Group" **(ASTM C150/C150M, 2022)**. **Table 1** shows an Investigation of the chemical as well as physical characteristics of cement.

Table 1. Physical and Chemical Properties of Cement.

Physical Properties	Test Result	Chemical Properties	Test Result %
Fineness (m^2/kg)	360	Lime	61.21
Soundness	0.045	Silica	23.7
Initial Setting Time	90 (minutes)	Alumina	5.58
Final Setting Time	7:00 (hours)	Iron Oxide	3.48
The compression strength 3 days (MPa)	29 MPa	Sulfate	2.10
The compression strength 28 days (MPa)	42.8 MPa	Loss on Ignition	0.11

2.2 Aggregate

Regarding the aggregate, two types of aggregate were used: fine and coarse aggregate.

2.2.1 Fine Aggregate

All the fine aggregate used in this study was sourced from the vicinity of Al-Nebai, Iraq. **Table 2** below shows the physical characteristics of the fine aggregate Additionally, **Table 3** shows the grading of the fine aggregate according to the Iraqi Specification **(SCRB, 2003).**

Table 2. Physical properties and amount of sulfate for fine and coarse aggregate

Fine Aggregate	Test Result	Specification	Coarse Aggregate	Test Result	Specification
Specific Gravity	2.56	---	**Specific Gravity**	2.60	---
Absorption	1.22%	---	**Absorption**	0.38	---
Sulfate Content	0.15%	≤ 0.5%	**Sulfate Content**	0.05%	≤0.1%

Table 3. Grading of fine aggregate **(AASHTO T 27, 1993).**

Sieve Size (mm)	Passing by weight%	
	(ASSHTO T 27, 1993)	Fine Aggregate
9.5	100	100
4.75	95-100	93.27
1.18	45-80	59.18
0.3	12-30	15.55
0.15	2-10	1.73
0.075	0-3	0.45

2.2.2 Coarse Aggregate

The crushed gravel from the Iraq Al-Nebai region, its physical properties, and the amount of sulfate in the coarse aggregate and fine aggregate, while still following the rules set by (**ASTM C566, 1997),** in **Table 2,** the grading of the coarse aggregate is shown in **Table 4**.

Table 4. Grading of Coarse aggregate **(AASHTO M 43, 2005).**

Sieve Size (mm)	Passing by weight%	
	AASHTO M 43 Size No. 67	Coarse aggregate
25	100	100
19	90-100	92
9.5	20-55	37
4.75	0-10	6
2.36	0-5	1.5

2.3 Water and Superplasticizer Admixture

The potable water in Baghdad is used for the procedures of casting and curing. The product is called Sika (Visco-Crete)-171. This is an additive that accelerates the curing process and reduces the water requirement for concrete manufacturing **(Sika® ViscoCrete®-171 Precast, 2022).**

2.4 Fiber

Regarding the fibers, two specific types have been used:

2.4.1 Steel Fiber

Bundrex company uses Kosteel steel fibers; all of their characteristics are listed in **Table 5,** and **Fig. 1** shows selected steel fiber specimens.

Figure 1. Steel Fiber

Table 5. The characteristics of steel fiber **(Kosteel, 2023).**

Type of steel fiber	Properties	Specifications
Hooked ends	Density of steel fiber	7800 kg/m^3
	Tensile Strength	900-2200 MPa
	Modulus of Elasticity	200x10^3 MPa
	Strain at Proportion Limit	5650 x10^{-6}
	Poisson's Ratio	0.28
	Average Length	50mm
	Nominal Diameter	0.7 mm
	Aspect Ratio	71
	Cost	9,000 IQD for 1 kg

2.4.2 Glass fiber

The Oscrete (12mm) HP fiber fits the requirements established by **(ASTM C1116/C, 2007; EN 15422, 2008)**. Alkali-resistant glass fibers are utilized. The properties of glass fiber are in **Table 6,** and the picked glass fiber sample is in **Fig. 2** below.

Table 6. The characteristics of glass fiber **(Oscete Construction Products, 2020).**

Type of glass fiber	Properties	Specifications
AR-glass	The specific gravity of glass fiber	2.68 g/cm^3
	Tensile Strength	1700 MPa
	Modulus of Elasticity	72 GPa
	Average Length	12 mm
	Nominal Diameter	-
	Cost	15,000 IQD for 1 kg

Figure 2. Glass Fiber.

3. MIXING, CASTING, AND CURING

The first phase of the mixing process is to prepare all the raw materials according to the mix-specific design percentage(cement 360 Kg, fine aggregate 800 Kg, coarse aggregate 994 Kg, water 117 Kg) per m^3 to achieve to 30 Mpa compressive strength. The dry mixing phase starts with the addition of gravel to the mixer, followed by sand. The mixer is turned on for one minute, followed by the addition of cement to complete the dry mixing process. It is continued for 4 minutes. Afterwards, half of the water was added to the mixture and mixed for 2 minutes. The other half of the water was mixed with superplasticizing admixture, then added incrementally with fiber and mixed for 2 minutes. After the mixing process, the concrete mixture was cast into the previously prepared molds in three layers, with each layer being compacted with 35 blows using a tamping rod. Finally, the surface of the concrete is leveled meticulously, and after 24 hours of casting, the specimens are extracted to start the curing stage in the water basin.

Figure 3. Mix process

4. TESTING

4.1 Compressive Strength Test

The compressive strength test evaluates the ability of concrete to resist pressure, an Essential factor in guaranteeing the safety and longevity of pavements. The test utilized cubes as molds, with dimensions of 150*150*150 mm (6*6*6 inches) as specified by (**AASHTO T 22, 2020; ASTM C39/C39M, 2021).** The specification restricts the loading rate to a range of 0.14 to 0.34 MPa/sec (20 to 50 psi/sec). The test for this study was conducted by the materials laboratory at the Civil Engineering Department. **Fig. 4** shows the Compressive Strength Test.

$$Fcu = \frac{P}{A} \tag{1}$$

F_{uc}: Compressive strength (MPa or in psi)
P: The load that is applied in units (pounds or kN)
A: The face area of the cube (m^2)

Figure 4. Compressive Strength Test.

4.2 Flexural Strength Test

The Flexural Strength Test measures the capability of concrete pavement to withstand flexural stress, an important consideration to ensure long-term durability and crack avoidance. This study relied on beam measurements with dimensions of 100*100*400 mm. The applied stress rate was 0.9-1.2 MPa per minute. According to **(ASTM C293/C293M, 2018)**. This equation computes the flexural strength. **Fig. 5** shows the Flexural Strength Test.

$$F = \frac{3PL}{2bh^2} \quad (2)$$

F: Flexural Strength (MPa or in psi)
P: Max load that is applied on the beam till failure (pounds or kN)
L: The span between the supports (inches or mm)
b: the beam width (inches or mm)
h: the beam height (inches or mm).

Figure 5. Flexural Strength Test**.**

4.3 Splitting Tensile Strength Test

The splitting tensile strength test determines concrete's ability to resist cracking and failure when subjected to tensile stresses. This is crucial for determining the service life of rigid pavements. The specimen's dimensions are 100 by 200 millimeters, according to (**ASTM C496/C496, 2017; AASHTO T 198, 2022)**, which suggests that the load should be applied gradually, without any sudden impact, and increased steadily from (1.2 $N/mm^2/min$ to 2.4 $N/mm^2/min$)**.** The following equation computes the splitting tensile strength, and **Fig. 6** shows the Splitting Tensile Strength Test.

$$Ft = \frac{2P}{\pi LD} \quad (3)$$

F_t: Splitting Tensile (MPa or in psi)
P: Max load that is applied on the beam till failure (pounds or kN)
L: The length of the cylinder (inches or mm)
D: Diameter of the cylinder (inches or mm)

Figure 6. Splitting Tensile Strength Test.

4.4 Application of PCASE EMS in Concrete Pavement Design

The U.S. Army Corps of Engineers designed PCASE EMS (Pavement-Transportation Computer Assisted Structural Engineering) as a tool to assist in the design and analysis of pavement systems. This study employed PCASE EMS to model the structural behavior of fiber-reinforced concrete pavements. This study utilized PCASE EMS to determine the necessary thickness of concrete pavement layers. The software integrates various input parameters, such as material properties, traffic loads, and subgrade conditions, allowing for a comprehensive evaluation of pavement performance. Its ability to incorporate experimental data, such as modulus of rupture and elasticity, made it an ideal choice for this research **(ERDC, 2010).**

5. DETAILS OF MIX COMPOSITION

150 samples were cured in water for three different age groups (7, 28, and 90) days. Six mixtures were tested, including the control mix, two single fiber mixes, and the other a hybrid mix. The proportion of fiber added to the concrete was 1%. The reduction in workability caused by fiber addition is attributed to the increased surface area of the fibers, which disturbs the mixture uniformity and requires changes to preserve it **(ACI 544.4R, 2015).** The table below lists all the mixes and the percentages of fiber and superplasticizer percentage change.

Table 7. The mixes and percentages of fiber.

Type of The Mix	Symbol	Steel Fiber	Glass Fiber	superplasticizer
Control Mix	Con.	----	----	0.50%
Concrete Mix with adding 1% steel fiber (single mix)	SF1%	1%	----	0.60%
Concrete Mix with adding 1% Glass fiber (single mix)	GF1%	----	1%	0.90%
Concrete Mix with adding 0.75% steel fiber and 0.25% glass fiber (hybrid mix)	SF0.75GF0.25	0.75%	0.25%	0.68%
Concrete Mix with adding 0.25% steel fiber and 0.75% glass fiber (hybrid mix)	SF0.25GF0.75	0.25%	0.75%	0.82%
Concrete Mix with adding 0.50% steel fiber and 0.50% glass fiber (hybrid mix)	SF0.50GF0.50	0.50%	0.50%	0.64%

6. RESULTS AND DISCUSSION

6.1 Compressive Strength Test

After conducting tests to evaluate the compressive strength of the aforementioned specimens, it appeared that the mixture containing 1% steel fiber exhibited the greatest enhancement, reaching 9.1% in comparison to the other mixtures. The compressive strength of the glass and hybrid fiber mixtures increased by 6.45% and 8.97%, respectively. The test was conducted in the materials laboratory of the Civil Engineering Division at the University of Baghdad**. Table 8** and **Fig. 7** show all of the compressive strength test results in detail.

Table 8. Compressive Strength Test Results.

Mix Type	Compressive Strength Test (MPa)		
	7days	**28 days**	**90 days**
Con.	24.4	32.5	34.1
S1%	26.2	35.4	37.2
G1%	25.7	34.4	36.3
S0.75G0.25	26.0	35.1	37.1
S0.25G0.75	25.8	34.6	36.5
S0.50G0.50	25.9	34.9	36.8

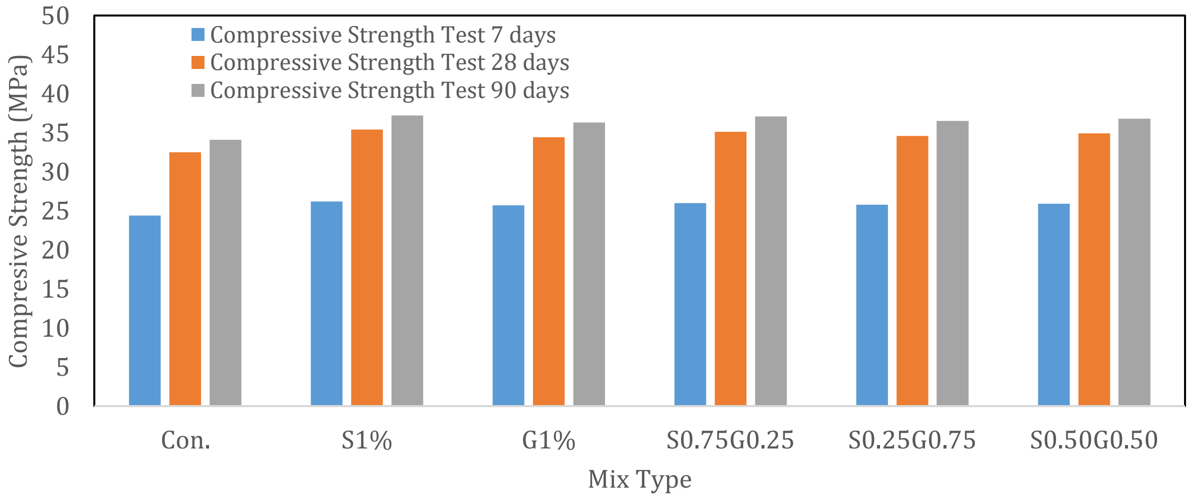

Figure 7. Compressive Strength Test Results Over Time.

6.2 Flexural Strength Test

Table 9 and **Fig. 8** below show the results of the flexural strength test, which was conducted in the Consulting Engineering Bureau at the College of Engineering, University of Baghdad, using a central axial load apparatus. The result indicates that the mix, which contained 1% steel fiber, improved the most (72.56%). Conversely, the glass fiber mix and hybrid fiber showed increases of 43.20% and 67.61%, respectively.

Table 9. Flexural Strength Test Results

Mix Type	Flexural Strength Test (MPa)		
	7 days	28 days	90 days
Con.	3.160	3.991	4.19
S1%	5.239	6.804	7.228
G1%	4.291	5.595	6
S0.75G0.25	5.024	6.557	7.023
S0.25G0.75	4.623	6.082	6.553
S0.50G0.50	4.708	6.225	6.646

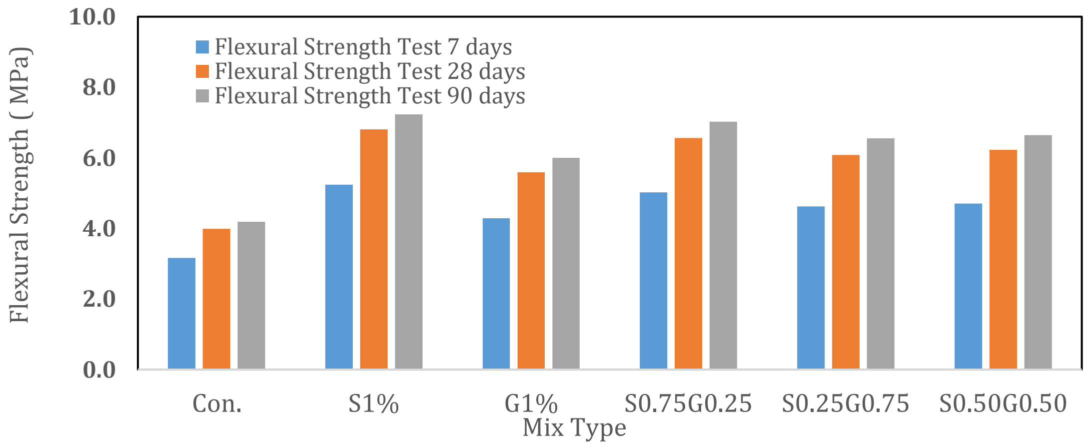

Figure 8. Flexural Strength Test Results Over Time.

6.3 Splitting Tensile Strength Test

Regarding the tensile strength test conducted in the material laboratory in the civil engineering division of the University of Baghdad, the results are shown below in **Table 10** and **Fig. 9**. It demonstrates an impressive rise in the mixtures containing steel fibers, whether in single or hybrid mixtures, with developments reaching 70% and 64%, respectively. However, mixtures containing glass fibers showed a lower improvement in both single and hybrid mixtures, with improvements of 42.43% and 52%, respectively. The mixture with a comparable proportion of steel and glass fibers exhibited an average improvement.

Table 10. Splitting Tensile Strength Test.

Mix Type	Splitting Tensile Strength Test (MPa)		
	7 days	28 days	90 days
Con.	2.736	3.649	3.94
S1%	4.466	6.155	6.699
G1%	3.618	5.053	5.611
S0.75G0.25	4.277	5.874	6.47
S0.25G0.75	3.905	5.414	6.017
S0.50G0.50	4.042	5.597	6.155

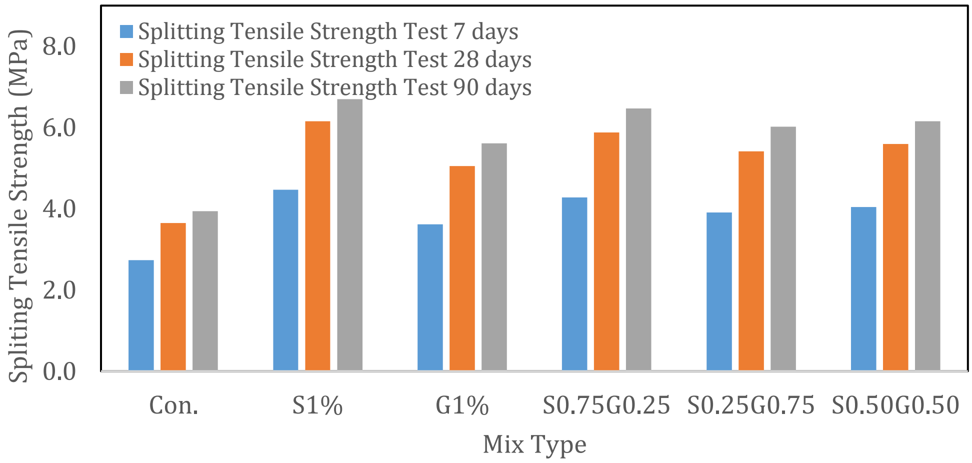

Figure 9. Splitting Tensile Strength Test Results Over Time.

6.4 Application of PCASE EMS in Concrete Pavement Design

The application EMS was used to determine the thickness of the concrete pavement by inputting the modules of rupture for each combination under the same applied load across all mixes. The incorporation of fiber resulted in a reduction in thickness by as much as thirty percent compared to the reference mixture. **Table 11** below presents all relevant information and findings, while Figure 10 shows the relationship between thickness and flexural strength. This enhancement is caused by the incorporation of fibers into concrete, which improves its stress strength and reduces cracking, hence enhancing durability and load-bearing capacity. This improvement allows the use of minimized concrete thicknesses without compromising pavement performance. Fibers serve to enhance load distribution and decrease the impact of specific stresses.

Table 11. Inputs and Results of PCASE EMS.

MixType	K (psi)	Flexural Strength(Mpa)	Thickness of pavement(mm)
Con.	100	3.991	209
SF1%	100	6.804	147
GF1%	100	5.595	169
SF0.75GF0.25	100	6.557	153
SF0.25GF0.75	100	6.082	160
SF0.5GF0.5	100	6.225	158

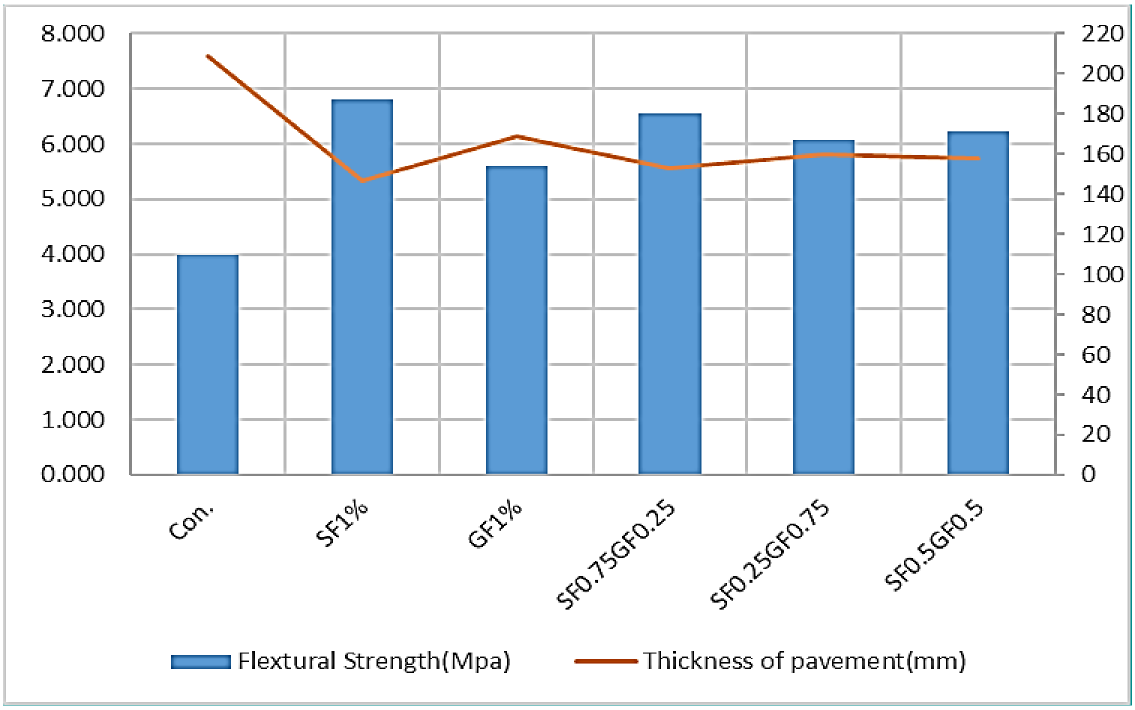

Figure 10. Relationship Between Flexural Strength and Pavement Thickness for Different Concrete Mixes.

7. CONCLUSIONS

The study investigates the effect of incorporating steel fibers and glass fibers on the mechanical characteristics of rigid pavements and the thickness of concrete pavements. The main findings of the study are as follows:

1- The incorporation of fibers into the concrete road enhanced the mechanical qualities, demonstrating a slight rise in compressive strength, with a more significant enhancement in flexural and tensile strength.
2- The most significant enhancement occurred with the addition of steel fibers at a percentage of 1% alone, but the optimal enhancement for hybrid mixes was seen when using SF0.75GF0.25.
3- Although using a single fiber mixture might produce better results compared to a hybrid fiber mixture, it is currently more beneficial to use a hybrid fiber mixture in proportions that make results similar to those of a single fiber mixture. This is because incorporating multiple types of fibers allows the concrete mixture to leverage the benefits of each type rather than being dependent on the advantages of a single type.
4- The incorporation of fibers adversely affected the workability of the concrete mixture. Therefore, the ratio of admixtures increased to provide acceptable workability standards.
5- Pavement thickness reduction: The PCASE EMS study found that adding fibers to concrete reduced pavement thickness by 30% compared to the reference combination, lowering costs and boosting material efficiency.

NOMENCLATURE

Symbol	Description
Con.	Control Mix
SF1%	Concrete mixture with 1% steel fiber
GF1%	Concrete mixture with 1% Glass fiber
SF0.75GF0.25	Concrete mixture using 0.75% steel fiber and 0.25% glass fiber
SF0.25GF0.75	Concrete mixture using 0.25% steel fiber and 0.75% glass fiber
SF0.5GF0.5	Concrete mixture using 0.50% steel fiber and 0.50% glass fiber

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Credit authorship contribution statement

Mahmood Ghanim Abdul Jawad: Analysis and writing of original manuscript.
Amjad Hamad Khalil: Conceptualization, Methodology, and Supervising.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير إضافة الألياف الفولاذية والزجاجية على الخصائص الميكانيكية وسمك التبليط الخرساني

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الخلاصة

تستخدم الطرق الخرسانية في العديد من الاغراض في شبكات الطرق, ولكن تواجه العديد من المعوقات مثل التشقق نتيجة لتغيرات درجة الحرارة والانكماش وتحمل الإجهادات المختلفة بالاضافة الى ذلك الهشاشة والضعف في مقاومة الشد والانحناء كل هذه العوامل لديها القدرة على تقليل متانة واداء التبليط, يؤثر سمك التبليط الخرساني بشكل كبير على أدائه ومتانته. توزع البلاطة الأكثر سماكة الوزن بشكل أكثر فعالية على الأساس؛ ومع ذلك، فإن السماكة الأكبر ترفع بشكل كبير تكاليف البناء، وتتطلب المزيد من الموارد، وتؤثر سلبًا على البيئة الطبيعية. الغرض من هذه الدراسة هو معرفة كيف يؤثر إضافة جزء 1٪ من الالياف الفولاذية والألياف الزجاجية في الشكلين المفردة والهجينة على تغيير الخصائص الميكانيكية للخرسانة وسمك التبليط. تم استخدام اختبار قوة الضغط واختبار قوة الانحناء واختبار الشد الانقسامي للتحقيق في التغيير في الخصائص الميكانيكية وتم اختيار برنامج (EMS) لحساب سمك الرصف الخرساني. أشارت النتائج إلى تحسن كبير في الخصائص الميكانيكية الناتجة عن تعزيز الخرسانة بالألياف. وقد ثبت ذلك من خلال زيادة متواضعة في قوة الضغط، حيث وصلت إلى 9.1% بعد 90 يومًا، إلى جانب تحسينات كبيرة في قوة الشد والانحناء، حيث بلغت 72.5% و70% بعد 90 يومًا على التوالي.وقد بين استخدام برنامج (PCASE EMS) إلى انخفاض بنسبة 30% في السُمك مقارنة بخلطة المرجعية. وهذه التحسينات في الخصائص الميكانيكية ونقصان سمك التبليط تنتج إطالة في عمر الخدمة للطريق وتقليل كلفة الصيانة وكذلك التقليل من استخدام المواد وبالنتيجة تقليل التأثيرات البيئية.

الكلمات المفتاحية : التبليط الخرساني, الاياف الفولاذية, الالياف الزجاجية, سمك الطريق الخرساني, الخصائص الميكانيكية.