



MECHANICAL PROPERTIES OF WASTE PET FIBER-REINFORCED CEMENT BOUND AGGREGATE MIXTURES

Omar Ibrahim Dulaimi ¹ and Ahmed Hilal Farhan ²

¹ MSc student, Department of Civil Engineering, College of Engineering, University of Anbar, Anbar, Iraq. Email: oma22e1010@uoanbar.edu.iq.

² Assistant Professor, Department of Civil Engineering, College of Engineering, University of Anbar, Anbar, Iraq. E-mail: ahmed.farhan2010@yahoo.com, ahmed.farhan_ce@uoanbar.edu.iq.

<https://doi.org/10.30572/2018/KJE/160326>

ABSTRACT

In many countries, cement bound granular mixtures (CBGMs) have been widely used in semi-rigid pavement as base/subbase layers to ensure better load-carrying capacity. However, due to their brittleness, CBGMs are susceptible to cracking under repeated traffic loading, which eventually accelerates pavement deterioration. To address this problem, this investigation was carried out to study the early age mechanical properties of CBGMs reinforced with polyethylene terephthalate (PET) fibers in terms of unconfined compressive strength (UCS), indirect tensile strength (ITS), bulk density, ultrasonic pulse velocity (UPV), static and dynamic modulus of elasticity, toughness, and ductility. Four fiber contents (0, 0.5, 1, and 1.5% by the volume of aggregate) were used. It was found that the inclusion of PET fiber reinforcement has significantly improved the tensile strength, toughness, and ductility by 19%, 203%, and 8.3 times, respectively. Moreover, it was noticed that incorporating PET fibers up to 1% resulted in a slight increase in compressive strength by 7.43%. Both bulk density and UPV, on the other hand, were declining due to PET fiber inclusion. Based on the outcomes of this study, CBGMs reinforced with PET fiber content of 1% are sustainable, cost-effective and environmental-friendly promising solutions..

KEYWORDS

Cement-bound pavement mixtures, Semi-rigid pavement, Tensile testing, Fiber-reinforced cement stabilized mixture, Waste plastic fiber.



1. INTRODUCTION

Cement bound granular mixtures (CBGMs) used in composite pavements are a mixture of aggregates and cement with a little amount of water. The latter amount of water is necessary to help both compaction and hydration of the cement (Farhan et al., 2018b). CBGMs have several advantages, such as high resistance to frost action, high strength, strong integrity, and cost savings. Therefore, these mixtures are employed in base and/or subbase layers within semi-rigid pavements (Zheng et al., 2019, Zhang and Li, 2010) to provide a strong base for preserving upper layers. Due to their high stiffness, cemented layers contribute protecting the lower layers by distributing traffic loads over a large area. However, one of the main drawbacks of cemented layers is their limited ability to resist tension and their susceptibility to cracking due to traffic loading and/or shrinkage. These cracks can propagate across the full thickness of the surface course, resulting in premature failure to the pavement structure (Belin et al., 2014, Chen et al., 2011, Zheng et al., 2019) and generating what is known as reflection cracking. Reflection cracking represents an obstacle to the wide use of cement-bound aggregate mixtures (Marik et al., 2024). To overcome this problem, several preventative techniques may be taken to minimize the cracks in CBGMs, such as limiting cement dosage, improving aggregate gradation, improving early-age curing conditions, using modifiers, and optimizing construction quality (Zhao et al., 2020). Although the above-mentioned techniques help to enhance the cracking resistance of CBGMs, reflective cracking, unfortunately, still a significant concern. Therefore, researchers (Farhan et al., 2020, Farhan et al., 2015) have made attempts to alleviate the high stiffness of these cemented mixtures by inclusion flexible rubber particles as a replacement of fine aggregate. Their results indicated slower propagation of cracks and better cracking patterns and susceptibility compared to conventional CBGMs containing no rubber aggregate.

Unlike conventional concrete, using fiber to reinforce cemented mixtures of low cement content is a relatively new approach. Using fiber reinforcement may be an effective method to enhance the ability of CBGMs to resist cracking and improve their mechanical performance. Zhao et al. (2020) studied the mechanical properties and crack resistance of cement-stabilized macadam base reinforced with polyvinyl alcohol fiber (PVA). Including PVA fibers into cement-stabilized macadam, using the optimal proportions enhances cracking resistance by 44.4% and significantly enhances the mechanical properties of cement-stabilized macadam. Zheng et al. (2019) studied the mechanical properties and crack resistance of cement-stabilized macadam reinforced with basalt fibers. Their findings indicated that including basalt fibers in cement-stabilized macadam can increase its flexural strength. Moreover, the reinforcement effect of basalt fibers enhanced the maximum deflection in the mid-span of the specimen.

Although many advantages are gained from utilizing industrial fibers in CBGMs, their higher cost is a potential obstacle that could restrict their widespread adoption (Coni and Pani, 2007). To address this issue, some attempts were undertaken to utilize waste fibers as a reinforcement in CBGMs. For example, Farhan et al. (2018b) studied tensile properties and cracking of cemented granular mixtures reinforced with recycled hybrid fiber. They reported better mechanical behavior and cracking resistance. Farhan et al. (2018a) investigated the combined effect of recycled steel fiber and cement content on the mechanical properties and damage propagation rate of CBGMs. The main findings indicated enhanced toughness, tensile strength, and less damage propagation speed after fiber inclusion at higher cemented content. Sobhan and Mashnad (2003) investigated the effect of recycled plastic fiber of low strength (16.4 MPa) on the tensile properties of cemented mixtures manufactured with recycled aggregate. The authors reported better tensile properties in terms of strength and toughness.

Actually, limited researches in the literature have examined the influence of waste plastic fibers of high strength extracted from bottles of soft drink on the behavior of standardized CBGMs of specific aggregate gradation despite the many studies (Vadivel and Doddurani, 2013, Fraternali et al., 2011, de Oliveira and Castro-Gomes, 2011, Ahmed et al., 2013, Nibudey et al., 2013, Allawi et al., 2021, Thomas and Moosvi, 2020) which have been undertaken to investigate the influence of these waste plastic fibers on the properties of concrete mixtures. Concrete mixtures, in fact, contained significant amounts of cement and water and different aggregate gradation and construction mechanisms. Therefore, the main aim of this paper is to examine the extent to which the polyethylene terephthalate (PET) fibers may affect the mechanical behavior of CBGMs, focusing on the early-age (7 days) performance.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials used

2.1.1. Aggregate

A crushed limestone aggregate, whose particle size ranging from 0 to 20 mm, was used in this investigation. This aggregate was brought from the 70th region, west of Ramadi, Iraq. This aggregate was dried and divided into four fraction sizes (20mm, 10mm, 4mm, and 2mm). The gradation of aggregates was performed according to BS EN 933-1:2012. Fig. 1 illustrates the gradation of each aggregate fraction size along with the design gradation of the aggregate mixture achieved by combining the four mentioned fraction sizes. Table 1 illustrates the physical properties of aggregate.

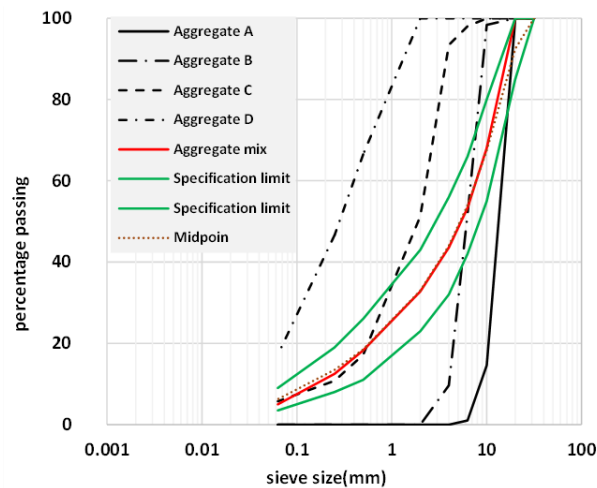


Fig. 1. Gradation of various fraction sizes of aggregate and final mixture

Table 1. Physical properties of aggregates

Property	Standard	Test results (%)	Limit ¹
Water Absorption	ASTM C127	1.01	≤ 2%
Flakiness index	BS 812.108	8.23	≤ 15%
Elongation index	BS 812.109	9.7	≤ 15%
Los Angeles abrasion	AASHTO T96	27.8	≤ 45%
Plastic limit	ASTM D4318	5.2	—
Liquid limit	ASTM D4318	10	≤ 25%
Plasticity index	ASTM D4318	4.8	≤ 6

¹ According to National Highway Authority (NHA) Specifications.

2.1.2. Cement

Ordinary Portland cement (CEM I 42.5 N) sourced from the Al-Mass company was used at a cement dosage of 7% by the total weight of PET fiber and dry aggregate to stabilize the aggregate mixture. The amount of cement used in this investigation was selected based on previous studies (Farhan et al., 2016, Farhan et al., 2018b). Chemical and physical test values are shown in Tables 2 and 3, respectively. This cement conforms to Iraqi requirements IQS No.5 (2019).

Table 2. Chemical properties of cement used in this study

Oxides	Test Results	Iraqi specification No.5/2019
Lime (CaO)	66.95	—
Iron Oxide (Fe ₂ O ₃)	5.14	—
Silica (SiO ₂)	20.06	—
Alumina (Al ₂ O ₃)	4.77	—
Sulfate (SO ₃)	2.39	Not more than 2.8 %
Magnesia (MgO)	3.2	Not more than 5%
Lime saturation factor	0.94	0.66-1
Loss on ignition	1.85	Not more than 4%
Insoluble residue	0.46	Not more than 1.5%
Main compounds		
C3A	4.11	—
C2S	19.81	—
C3S	49.83	—
C4AF	14.77	—

Table 3. Physical properties of cement

Type of Test	Results	Iraqi specification No.5/2019
Initial setting time (minutes)	168	≥ 45 min
Final setting time (minutes)	227	Not more than 600 min
Fineness by Blain method (cm ² /gm)	2549	≥ 2500
Soundness (mm)	1	≤ 10 mm
Autoclave %	0.1	$\leq 0.8\%$
Compressive strength at 2 days (MPa)	13.4	≥ 10 MPa
Compressive strength at 28 days (MPa)	42.8	≥ 32.5 MPa

2.1.3. Waste plastic fibers

PET fibers was used to reinforce cemented mixtures. These fibers were extracted from soft drink bottles. At first, bottles were gathered and cleaned using tap water. Then, a mechanical cutter was used to produce strips with a width of 2 mm. Finally, the produced strips were then cut to produce a constant fiber length of 40 mm. WPET fiber testing was conducted according to [ASTM D1708-18 \(2015\)](#) utilizing a universal testing machine WDW-200E with a maximum capacity of 200 kN. Three specimens were used for each mixtures, and the average value of the results was adopted. [Table 4](#) shows summary of the physical properties of PET fibers. [Fig. 2](#) shows the PET fibers utilized. The volumetric content used in this investigation was 0.5, 1 and 1.5% (by the volume of aggregate).

Table 4. Physical properties of fibres used.

Properties of Fiber	Description
Type of fiber	Waste Plastic fibers (WPF)
Water absorption %	0
Density (kg/m ³)	1380
Width (mm)	2
Length (mm)	40
Thickness (mm)	0.3
Specific gravity	1.12
Color	Crystalline and green
Tensile strength (MPa)*	117
Modulus of elasticity (GPa)*	0.57

**Fig. 2. Waste PET fibers used**

2.1.4. Water

This study used tap water that satisfied the standard IQS 1703 (2018) to moisturize and prepare all CBGMs.

2.2. Mixture design

To ensure achieving the gradation of CBGM2-0/20 stated in [BS EN 14227-1:2013 \(BS EN 14227-1, 2013\)](#), the four aggregate fraction sizes were blended together in different proportions. This step was essential to achieve homogeneity in the mixture because strength is significantly affected by mixture density, which is mainly influenced by the aggregate gradation. The percentages of each fraction size were 35% of 20mm, 22% of 10mm, 21% of 4mm, and 22% of 2mm. A cement content of 7% was utilized to stabilize these aggregate mixtures. To achieve the highest strength, it is necessary to determine the optimum moisture content and maximum dry density using the compaction process as stated in [BS EN 13286-4:2003 \(BS EN 13286-4, 2003\)](#). The vibratory compaction method is the most simulative method to field compaction for granular materials as documented in [Drnevich et al. \(2007\)](#) and [Chilukwa \(2013\)](#). As a result, the optimum moisture content and maximum dry density values obtained are 6.25% and 2301 Kg/m³, respectively. [Table 5](#) demonstrates the investigated mixture proportions.

Table 5. Mix proportions of investigated mixtures.

Mix number	Cement content ^a , %	Fibers content ^b , %	Water content ^c , %
1	7	0	6.25
2	7	0.5	6.25
3	7	1	6.25
4	7	1.5	6.25

^a By dry weight of aggregate (and fibers for reinforced mixtures)

^b By dry weight of aggregate

^c By dry weight of aggregate and cement (and fibers for reinforced mixtures)

2.3. Specimens fabrication and curing

The process of specimen fabrication is summarized as follows: First, both 4 mm and 2mm aggregate fraction sizes were mixed together with cement until achieving uniform color. After that, the remaining aggregate sizes (20 mm and 10 mm) and PET fiber were added to the blend and mixed for 60 sec. Finally amount of water required to moisture mixture was added and mixed for 120 minutes.

A vibrating hammer (TAAM 90 L) is used to compact the aggregate-cement-fiber mixtures into two layers. The compaction of each layer was conducted in oiled cylindrical molds for 60 seconds as stated by [BS EN 13286-51:2004 \(BS EN 13286-51, 2004\)](#). Three specimens were made for each mixture. After completing the compaction process, the specimens were left in

their molds for 24 hours. Then, they were extracted [Fig. 3a](#) and covered with nylon film to avoid shrinkage cracking resulting from rapid evaporation from specimens' upper surfaces ([Al-Khafaji and Behaya, 2015](#)), then extracted from their molds and placed in moist plastic bags, and closed [Fig. 3b](#) to prevent moisture loss. Finally, the specimens were cured for 7 days at a temperature of 20o C and a humidity of 90%.

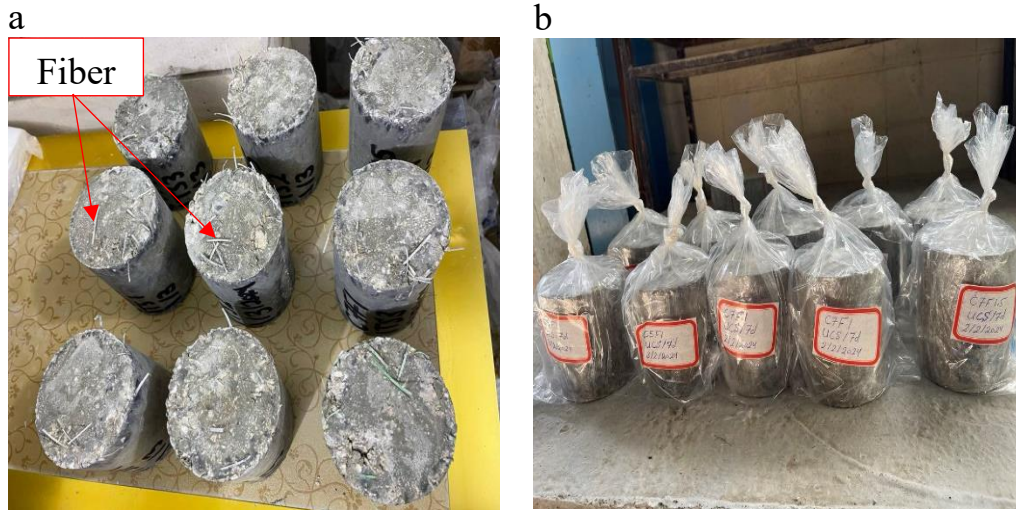


Fig. 3. a- Samples appearance for various fiber contents, b- Curing of specimens.

2.4. Testing methodology

2.4.1. Bulk density

The density was measured using water displacement procedure on cylindrical specimens with dimensions of 100 mm (dia.) and 100 mm (height). Density measurement involves calculating the weight of the specimen first in air and then in water. Finally, the bulk density was computed using [Eq.1](#).

$$\rho_b = \frac{w_a}{w_a - w_w} \cdot 1000 \quad (1)$$

Where: ρ_b = bulk density, kg/m³, w_a = weight of specimen in air, g, w_w = weight of specimen in water, g.

2.4.2. Unconfined compressive strength (UCS)

For categorizing CBGMs, the compressive strength test is frequently since it is a simple and low cost test in addition to its established correlations with other mechanical properties ([Jitsangiam and Nikraz, 2011](#), [Piratheepan et al., 2010](#)). Moreover, European specifications BS EN 14227-1:2013 (BS EN 14227-1, 2013) was adopts this test as a method for classifying CBGMs. Following BS EN 13286-51:2004, three cylindrical specimens (100*100) mm have been manufactured and tested for each mixture. After a curing period of 7 days, specimens were tested using a specialized testing machine according to BS EN 13268-41:2003 (BS EN 13286-

41, 2003) by applying compressive load up to failure, as depicted in Fig. 4. The UCS value was computed by Eq. 2:

$$UCS = \frac{P}{A} \quad (2)$$

where P= ultimate load, N, A= area of specimen cross-section, mm².

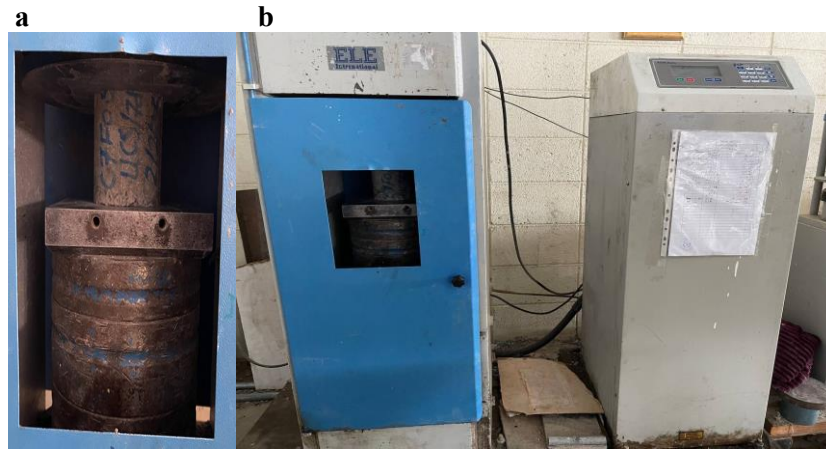


Fig. 4. UCS testing.

2.4.3. Indirect tensile strength (ITS)

Indirect tensile strength test was conducted in accordance with European specifications (BS EN 13286-42, 2003) using a hydraulic pressure universal testing machine, as illustrated in Fig. 5. Three cylindrical specimens (100 mm, height *100 mm, diameter) were manufactured for each investigated mixture. The tested cylindrical sample was placed horizontally and the load was applied diametrically at a rate of 0.5 mm/min until failure occurred. Lateral deformation was measured using a linear variable differential transformer (LVDT) which was fixed on the specimen face. The ITS was determined using the following equation.

$$ITS = \frac{2P}{\pi h d} \quad (3)$$

where: P = the maximum load, N, h = the height of the sample, mm, d = the diameter of the sample, mm.

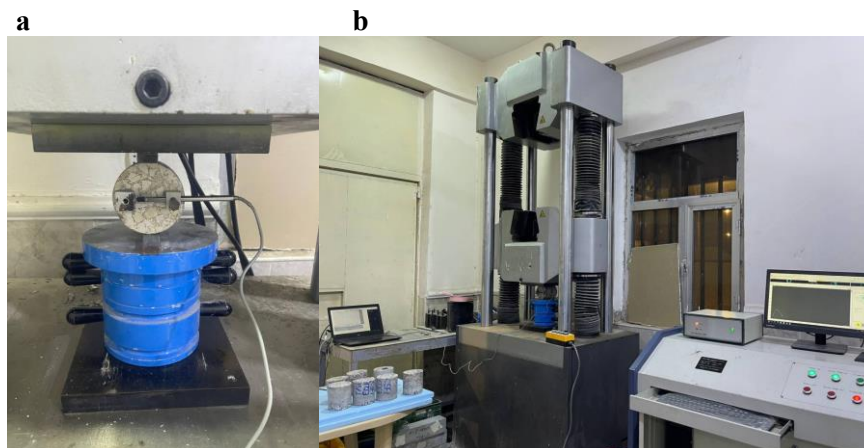


Fig. 5. Indirect tensile strength testing.

2.4.4. Load-deformation curves and modulus of elasticity

The lateral deformation of the specimen was measured parallelly with the tensile testing using a linear variable differential transducer (LVDT) which was fixed on the face of the specimen. Then, the load-deformation relationship was constructed, and the static modulus of elasticity was estimated. The test setup is shown in Fig. 5 (Section 2.4.3). The static modulus of elasticity was determined using the load-deformation curve on the basis of thirty percent of the ultimate load and corresponding lateral deformation, based on BS EN 13286-43:2003. However, due to the differences in the LVDT arrangements utilized in this investigation and those specified in BS EN 13286-43:2003, the formula suggested by Solanki and Zaman (2013) was used.

$$E_{it} = \frac{2P}{\pi \cdot D \cdot h \cdot \Delta H (D^2 + D_G^2)} * \{ (3 + \nu) D^2 \cdot D_G + (1 + \nu) [D_G^3 - 2D (D^2 + D_G^2) \tan^{-1}(\frac{D_G}{D})] \} \quad (4)$$

where: E_{it} = static modulus of elasticity, MPa, P = 30% of maximum load, N, D = specimen diameter, mm, h = thickness of the specimen, mm, ΔH = lateral displacement corresponding to 30% of the maximum load, mm, D_G = LVDT gauge distance, mm, ν = Poisson's ratio, Poisson's ratio was assumed to be 0.25 for all mixtures (Barišić et al., 2015).

2.4.5. Absolute toughness and ductility

Toughness is defined as the ability of material to absorb energy in the plastic domain until it ruptures (AL-Turaihi & Al-Katib, 2024). In order to evaluate the toughness or the load-carrying capacity of the reinforced mixtures, the area under the load-deformation curve was determined (Farhan et al., 2018b). For all examined mixtures, this area was determined up to a deformation of 4 mm. Such estimation as reported by Sobhan and Mashnad (2000) considers the improvement of strength and ductility caused by adding fiber reinforcement. In addition, ductility was estimated in terms of the index of deformability (D_i) suggested by Park (2011), as shown in the equation below.

$$D_i = \Delta_{\text{fiber-reinforced}} / \Delta_{\text{unreinforced}} \quad (5)$$

where: $\Delta_{\text{fiber-reinforced}}$ and $\Delta_{\text{unreinforced}}$ are denoted to the deformations at the maximum load of reinforced and unreinforced specimens, respectively.

2.4.6. Ultrasonic Pulse Velocity (UPV) and dynamic modulus of elasticity

This non-destructive test assesses the cementitious specimen's homogeneity, integrity, and quality (Dulaimi and Farhan, 2024). This test was conducted based on ASTM C597-09 (ASTM, 2009) specification. A pundit apparatus has been utilized. The testing involves measuring the time (T) it takes for a pulse to pass through a cylindrical specimen across a certain distance (L). To ensure better wave transmission from the transducer to the CBGMs specimen, a coupling gel was used to ensure full contact of transducer and receiver with the surface of specimen. The

transducer and receiver were positioned on opposite sides of the cylindrical specimens, and the transmission time was measured. Then, UPV was calculated using the following equation.

$$UPV = \frac{L}{T} \quad (6)$$

where, L= specimen length, m, T= transit time, sec.

The dynamic modulus of elasticity can be computed using the UPV and bulk density as stated in the formula (7) shown below (Mardani-Aghabaglou et al., 2013).

$$Edu = \frac{\rho UPV^2 (1 + \nu)(1 - 2\nu)}{1 - \nu} \quad (7)$$

where: Edu= dynamic elasticity modulus, GPa, ρ = bulk density, kg/m³, ν = Poisson's ratio.

3. RESULTS AND THEIR INTERPRETATION

3.1. Effect of PET fibers on bulk density

Fig. 6 illustrates the influence of PET reinforcement on the bulk density. As can be seen from this figure, mixture density declined by 0.53%, 1.10%, and 2.21% due to PET fiber reinforcement of 0.5%, 1%, and 1.5%, respectively. The decline in density observed can be explained in the light of lower specific gravity (i.e., 1.12) of the plastic fibers compared to that of other constituents (cement and aggregate). In addition, the presence of plastic fibers might have negative effect on the compaction efficiency. The reduced compaction efficiency appears to be increased as PET fiber contents increase. Furthermore, it can be observed from the latter figure that the big drop in density occurred when fiber content increased from 1% to 1.5%. Al-Hadithi et al. (2024) reported that the density of concrete mixtures reduced as waste PET fiber was incorporated.

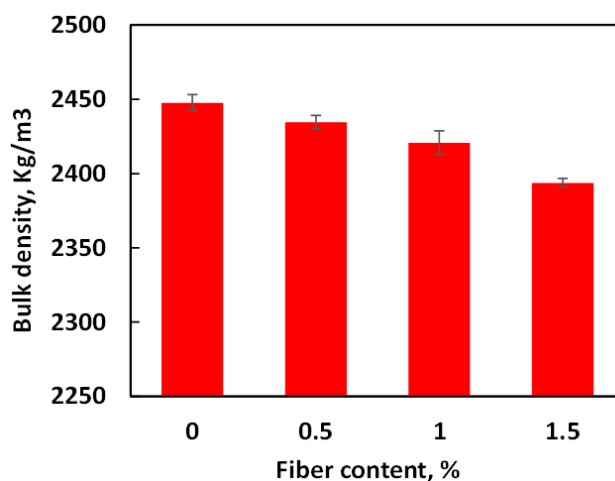


Fig. 6. Indirect tensile strength testing.

3.2. Effect of PET fibers on UCS

Fig. 7 shows the effect of PET fiber reinforcement on UCS. It was found that the compressive strength increased slightly as fiber content increased. Where UCS improved by 7.42% and

3.36% at fiber content of 0.5% and 1%, respectively. However, a drop of approximately 8.19% in the UCS occurred at a PET fiber content of 1.5%. The reason for the increase in compressive strength can be attributed to a delay in the crack propagation, which caused an increase in the amount of energy absorbed to fail the specimen. Fibers behave like a bridge between the two opposing sides of the crack, improving the load-carrying capacity and intactness of the specimen [Fig. 8](#) after failure. However, the reduction in compressive strength observed at fiber percentages of 1.5% can be attributed to the reduction of density occurred due to less compaction efficiency (Section 3.1) which led to formation of voids around fibers. These voids represent places for cracking initiation. In addition, high air-voids accelerate the crack propagation since these air voids might be interconnected. Authors ([Ismail Al-Hadithi & Ahmed Abbas, 2018](#)) have observed that the compressive strength of concrete mixtures increases as WPET fibers increase up to a 1% volume fraction, which is in high agreement with this study. [Hasan \(2024\)](#) stated that adding a 2% volume fraction of recycled steel fibers improved compressive strength by 9%.

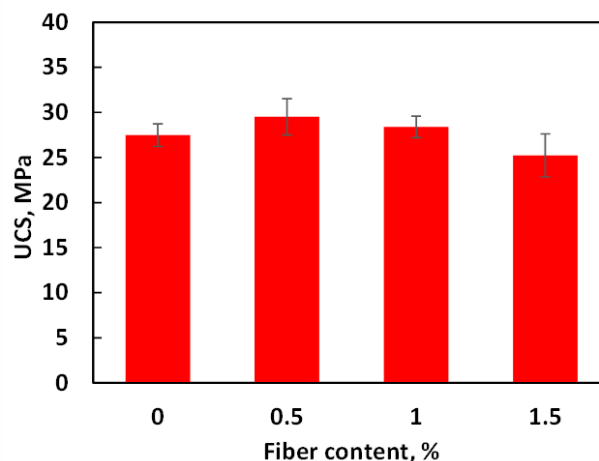


Fig. 7. Effect of fiber content on the UCS.

3.3. Influence of PET fibers on ITS

[Fig. 9](#) shows the influence of PET fiber reinforcement on the ITS value. This figure clearly indicates that the 7d splitting strength of the specimens is positively affected by the addition of PET fibers. The splitting tensile strength increased as the percentage of fiber increased, up to 1% (the highest value recorded during the splitting tensile test). After that, an increase in the amount of fiber resulted in a decline in the ITS value. ITS improved by 9.15%, 19%, and 4.22% due to PET fiber incorporation at 0.5%, 1%, and 1.5%, respectively. This improvement can be attributed to PET fiber's higher tensile strength and elastic modulus compared to CBGMs. This might enable fibers to carry part of the applied load when cement stabilizes the aggregate ([Ji et al., 2022](#)). In addition, after cracking, the fiber across cracks act as a bridge, which in turn help specimen to carry further loading [Fig. 10](#).

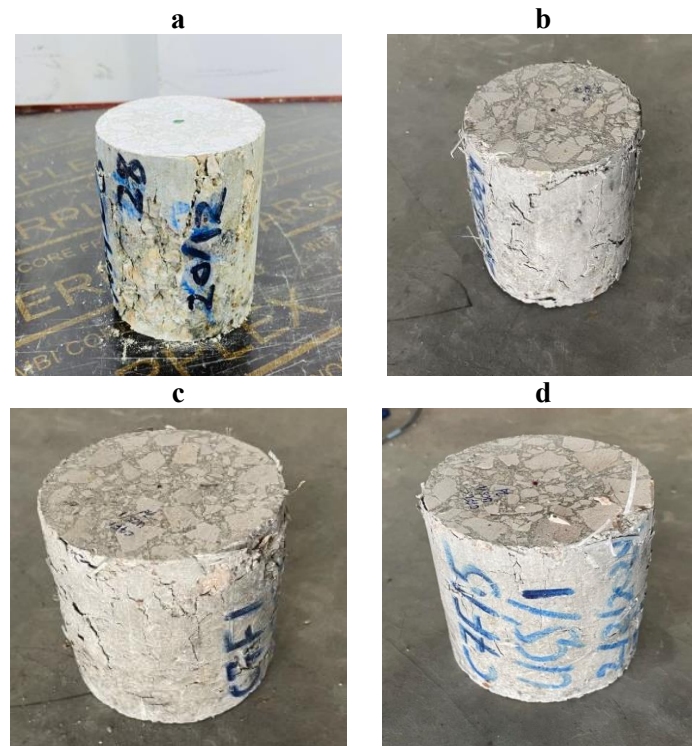


Fig. 8. Failure patterns of UCS specimens for different fiber levels:
a. 0%; b. 0.5%; c. 1%; d. 1.5%.

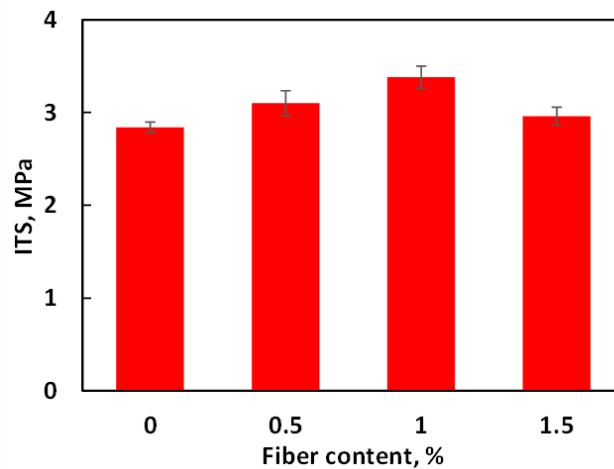


Fig. 9. Effect of fiber content on the ITS

3.4. Influence of PET fibers on load-deformation curves and moduli of elasticity

Fig. 11 illustrates the load-deformation relationships for the examined mixtures. It can be seen from this figure that the unreinforced CBGMs showed a deformation softening immediately after the first crack. On the other hand, all FRCBGMs exhibit a deformation-hardening zone subsequent to the first crack point. Then, the deformation-softening occurs gradually. As the stiffness of the mixture is largely influenced by the stiffness of its constituents, the inclusion of PET fibers having a modulus of elasticity of 0.57 GPa, which is much lower than that of aggregate, which is 57 GPa, caused a drop in the stiffness of the fiber reinforced mixture (FRCBGMs). Fig. 12 illustrates the influence of different PET fiber content on the modulus of

elasticity of the bounded mixture containing 7% cement content. It is clear from Fig. 12 that the FRCBGMs showed lower modulus of elasticity compared to that of the CBGMs. Adding fiber content of 0.5%, 1%, and 1.5% (by volume) caused a drop in the modulus of elasticity to 3.54%, 7.72%, and 15.92%, respectively, compared with the unreinforced mixture. This might reduce the susceptibility of the layers made from such mixtures to cracking under traffic loading, hence promoting pavement performance and increasing pavement life. Farhan et al. (2018b) show that the recycled hybrid steel fiber with 0.25%, 0.5%, and 0.75% volumetric contents reduced the stiffness of cement-stabilized pavement mixtures.

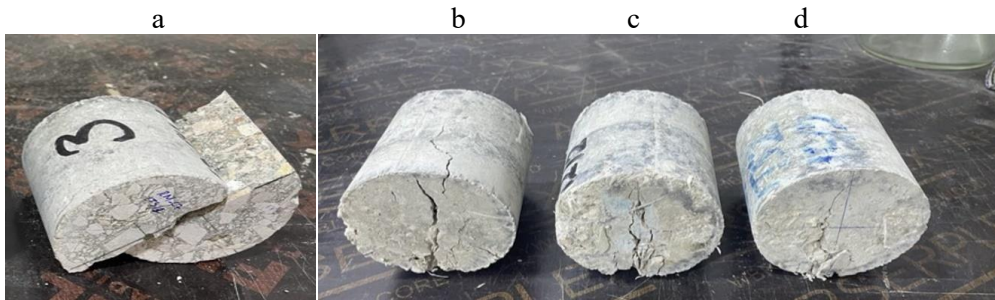


Fig. 10. Failure patterns of ITS specimens for different fiber levels:
a. 0%; b. 0.5%; c. 1%; d. 1.5%.

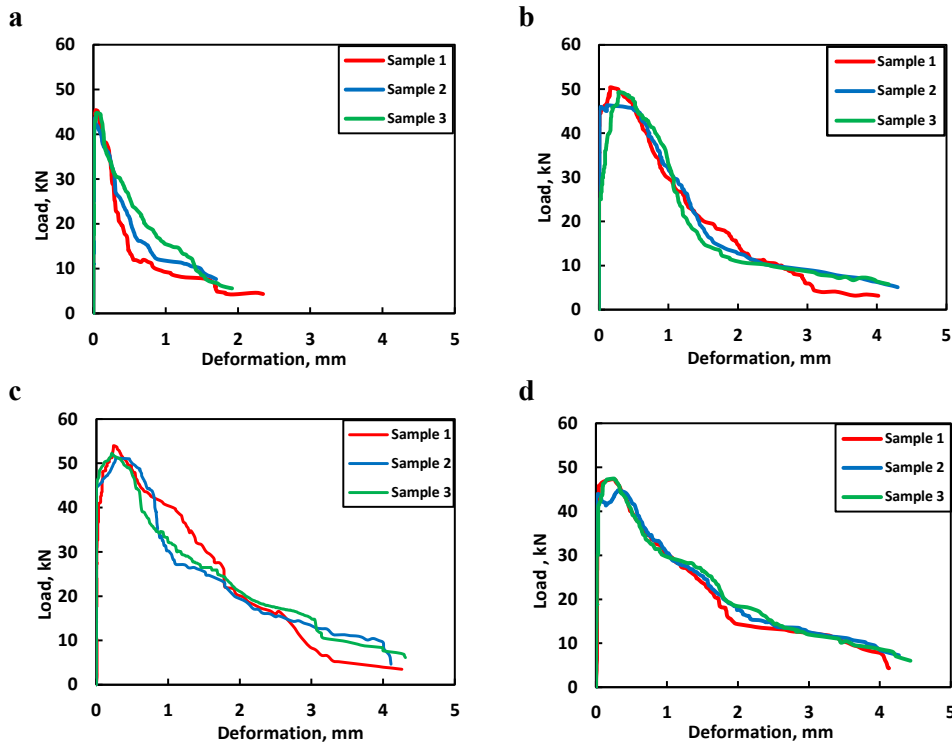


Fig. 11. Load-deformation curves for different fiber levels:
a. 0%; b. 0.5%; c. 1%; d. 1.5%

3.5. Influence of PET fibers on toughness and ductility

Based on the results shown in Fig. 13, it conclude that the toughness of the FRCBGMs increases as amount of reinforcement increases. At a fiber content of 1%, a drop in toughness value results as the percentage of fiber increases. Nevertheless, it is still much greater than the value of the

conventional CBGMs containing no fibers. The improvement in toughness ranges from 144 to 203%. This enhancement is attributed to the presence of fibers that serve as bridges to transmit load across the crack ends. In addition, fiber delays the propagation of cracks. In their investigation, [Farhan et al. \(2018a\)](#) characterized the speed of crack propagation in fiber-reinforced mixtures. They reported that the speed of crack propagation in fiber-reinforced mixtures is much lower than that of unreinforced mixtures. These findings indicate that FRCBGMs have a higher energy absorption capacity before failure in comparison to unreinforced mixtures.

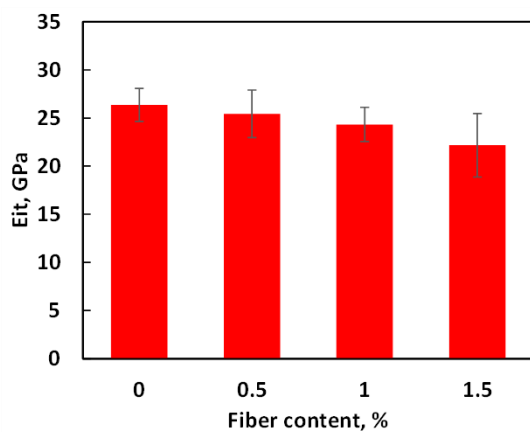


Fig. 12. Elastic modulus for different fiber dosages.

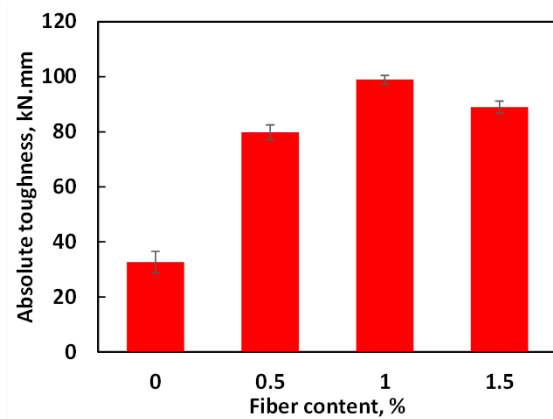


Fig. 13. Absolute toughness for investigated mixtures.

Regarding ductility, it was found that the deformation indices of reinforced mixtures are higher compared to mixtures without fibers [Fig. 14](#), indicating ductile behavior. Moreover, ductility is enhanced as the fiber content increases. When amounts of fiber incorporated are 0.5%, 0.1%, and 1.5%, the deformability of the mixture is enhanced by 6.1, 7.8, and 8.3 times that of unreinforced mixtures, respectively. The presence of fiber reinforcement helps to control both cracking speed and cracking width. Such control may prevent cracks' propagation after initiation and ensure better ductility. The highest ductility value was recorded at a fiber content of 1.5%.

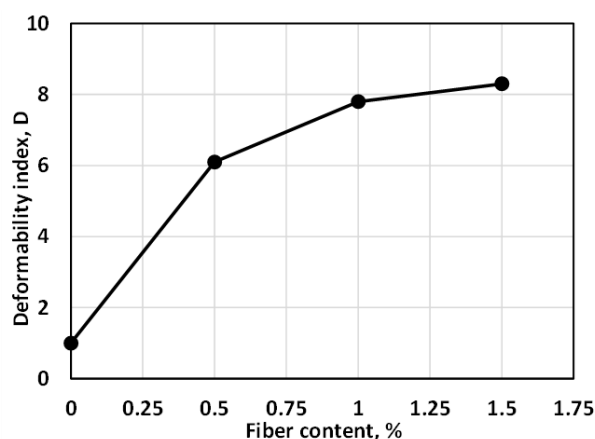


Fig. 14. Deformability indices for various investigated mixtures.

3.6. Influence of PET fibers on UPV and Edu

Fig. 15 shows the influence of fiber content on the UPV for investigated mixtures. As illustrated in Fig. 15, the UPV decreased upon incorporating more fibers in the CBGMs. The reasons behind this decrease can be explained as follows: Firstly, a probable decrease in the compaction efficiency might cause some voids in the specimen (i.e., an increase in the porosity), which in turn decelerated the speed of the transmitted wave. Secondly, the presence of fibers of low specific gravity represents an impedance to the wave transmission (Khalaf and Khalil, 2015). In fact, these two reasons become more obvious as fiber content increase.

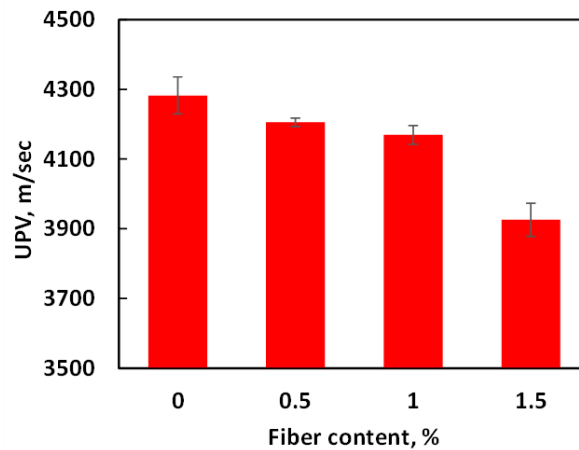


Fig. 15. Effect of fiber content on the ultrasonic pulse velocity.

As in the case of the static modulus of elasticity, the dynamic modulus of elasticity is also reduced due to fiber inclusion, as illustrated in Fig. 16. The dynamic modulus of elasticity is influenced by the density of the material and the velocity through which the ultrasonic waves pass. Based on the results presented in Section 3.3 and Section 3.4 above, plastic fibers led to a drop in both density and ultrasonic pulse velocity. Therefore, CBGMs have a greater dynamic modulus of elasticity compared to the FRCBGM. Incorporating volumetric fiber content of 0.5%, 1%, and 1.5% caused a decline in the dynamic modulus of elasticity by 3.20%, 6.06%, and 17.82%, respectively, compared with that of unreinforced mixture.

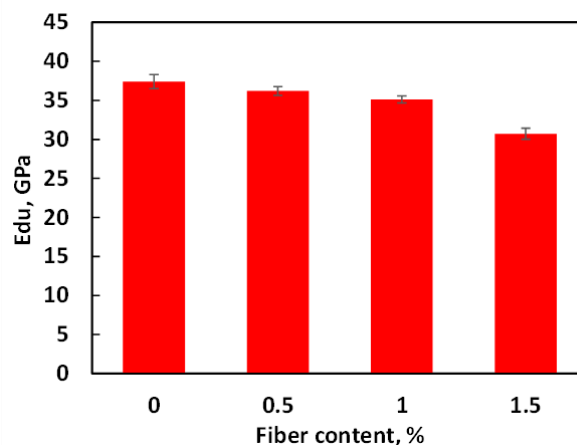


Fig. 16. Dynamic modulus for different fiber contents

4. CONCLUSIONS

In this investigation, the influence of PET fiber reinforcement on the mechanical properties of CBGMs was experimentally studied from mechanical properties point of view. Based on the outcomes of this study, it can be conclude the following:

- In comparison to the reference mixture, the unconfined compressive strength slightly improved by 7.42% and 3.36% at fiber content of 0.5% and 1%, respectively. Whereas it decreased by 8.19% when incorporating a fiber content of 1.5%. This might indicate that the inclusion of PET fiber up to 1% does not negatively affect the local crushing of the cemented pavement layer surface.
- Indirect tensile strength enhanced noticeably as a result of PET fiber incorporation. The maximum improvement was 19% which occurred when fiber reinforcement of 1% was used. From pavement design standpoint, this will reduce the thickness of pavement.
- The inclusion of PET fiber at volumetric contents of 0.5%, 1%, and 1.5% resulted in a decrease of both the density and UPV of CBGMs reinforced with PET fibers when compared to the reference mix. The biggest reduction was seen when the volumetric fiber content was 1.5%.
- The fiber-reinforced cemented composite showed considerable improvement in toughness and deformability, indicating a better ductile material which probably affects fatigue life positively. Pavements made of this material may have less fast post-failure deterioration. This, in fact, might increase the period needed to perform maintenance. In addition, the integrity of this layer, even after failure, may help to reduce the possibility of reflection cracking occurring.
- The inclusion of PET fiber in cement bond granular mixtures reduced both the static and dynamic elasticity modulus, which might ensure a cemented layer of less rigidity. This might also reduce its susceptibility to cracking under traffic loading. Consequently, better pavement performance will be achieved.
- The results have proven that 1% fiber content is the optimal percentage for enhancing the mechanical properties of CBGMs, which makes it a promising solution for sustainable CBGMs applications.

5. REFERENCES

A. S. for T. and Materials, "Standard test method for tensile properties of plastics by use of microtensile specimens" ASTM Int., 2015.

Ahmed, H.K., Abbas, W.A. and Abdul-Razzaq, D.M., 2013. Effect of plastic fibers on properties of foamed concrete. *Eng Technol J*, 31(Part A (7), pp.1313-30.

- Al-Hadithi, A. I., Farhan, A. H., & Ali, D. H. (2024). Investigating mechanical properties of SIFCONs produced with waste PET fibers. *Construction and building materials*, 448, 138220.
- Al-Khafaji, B.T. and Behaya, S.A., 2015. Effect of ceramic powder (cp) on compressive strength and drying shrinkage cracks of cement mortar. *Kufa Journal of Engineering*, 6(2), pp.63-75.
- Allawi, A.H., AL-Hadithi, A.I. and Mohmoud, A.S., 2021. Effects of waste plastic pet fibers on the fresh and hardened of normal concrete. *Iraqi Journal of Civil Engineering*, 15(1), pp.47-58.
- AL-Turaihi, A. A., & Al-Katib, H. A. (2024). Behavior of hybrid reinforced concrete beams on flexural strength. *Kufa Journal of Engineering*, 15(2), 27-38.
- ASTM, C.J.A.I., 2009. 597, Standard test method for pulse velocity through concrete. ASTM International, West Conshohocken, PA.
- Barišić, I., Dokšanović, T. and Draganić, H., 2015. Characterization of hydraulically bound base materials through digital image correlation. *Construction and building materials*, 83, pp.299-307.
- Belin, P., Habert, G., Thiery, M. and Roussel, N., 2014. Cement paste content and water absorption of recycled concrete coarse aggregates. *Materials and Structures*, 47, pp.1451-1465.
- BS EN 13286-4, 2003. Unbound and hydraulically bound mixtures- Part 3: Methods for laboratory reference density and water content-Vibrating hammer.
- BS EN 13286-41, 2003. Hydraulically bound mixtures- Part 41: Test method for determination of the compressive strength of hydraulically bound mixtures, British Standards Institutes, London.
- BS EN 13286-42, 2003. Hydraulically bound mixtures- Part 42: Test method for determination of the indirect tensile strength of hydraulically bound mixtures, British Standards Institutes, London.
- BS EN 13286-51, 2004. Unbound and hydraulically bound mixtures- Part 51: Methods for the manufacture of test specimens of hydraulically bound mixtures using vibrating hammer compaction.
- BS EN 14227-1, 2013. Hydraulically bound mixtures, in: cement bound granular mixtures, The British Standards Institution, London, UK,..

- Chen, D.H., Hong, F. and Zhou, F., 2011. Premature cracking from cement-treated base and treatment to mitigate its effect. *Journal of Performance of Constructed Facilities*, 25(2), pp.113-120.
- Chilukwa, N.N., 2013. Vibratory hammer compaction of granular materials (Doctoral dissertation, Stellenbosch: Stellenbosch University).
- Coni, M.A.U.R.O. and Pani, S., 2007. Fatigue analysis of fiber-reinforced cement treated bases. In *Proc. SIIV Congress*.
- Drnevich, V., Evans, A.C. and Prochaska, A., 2007. A study of effective soil compaction control of granular soils. *Joint Transportation Research Program*, p.234.
- Dulaimi, O.I. and Farhan, A.H., 2024, August. Combined effect of fiber and degree of stabilization on the early age behavior of cement bound granular mixtures. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1374, No. 1, p. 012080). IOP Publishing.
- Farhan A.H., Dawson A.R. and Thom, N.H., 2015. Rubber modification of cement-stabilized aggregate delivering more sustainable pavement mixes. 9th international conference on road and airfield pavements (ICPT2015); Dalian, China.
- Farhan, A.H., Dawson, A.R. and Thom, N.H., (2018a). Damage propagation rate and mechanical properties of recycled steel fiber-reinforced and cement-bound granular materials used in pavement structure. *Construction and Building Materials*, 172, pp.112-124.
- Farhan, A.H., Dawson, A.R. and Thom, N.H., (2018b). Recycled hybrid fiber-reinforced & cement-stabilized pavement mixtures: Tensile properties and cracking characterization. *Construction and Building Materials*, 179, pp.488-499.
- Farhan, A.H., Dawson, A.R. and Thom, N.H., 2016. Effect of cementation level on performance of rubberized cement-stabilized aggregate mixtures. *Materials & Design*, 97, pp.98-107.
- Farhan, A.H., Dawson, A.R. and Thom, N.H., 2020. Effect of rubber incorporation on the behavior of pavement cemented mixtures under cyclic flexural loading: a preliminary study. *Journal of Testing and Evaluation*, 48(4), pp.2813-2828.
- Fraternali, F., Ciancea, V., Chechile, R., Rizzano, G., Feo, L. and Incarnato, L., 2011. Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete. *Composite structures*, 93(9), pp.2368-2374.

Hasan, S. S. (2024). Effect of using waste fibers on the strength properties of sustainable reactive powder concrete. *Kufa Journal of Engineering*, 15(1), 95-107.

Hong-hui, Y.A.N.G., Pei-wen, H.A.O. and Jing-liang, D.A.I., 2006. Road Performance of Cement-Stabilized Aggregate Mixture with Expansion Agent. 6(1), pp.48-51.

I.Q.S. No. 5/2019 Specification, P.C., " Central Organization for Standardization & Quality Control (COSQC), Baghdad, Iraq", 2019.

IQS 1703. (2018). Water Used for Concrete and Mortar. Ministry of Planning - Central Agency for Standardization and Quality Control. 1-4.

Ismail Al-Hadithi, A., & Ahmed Abbas, M. (2018). The effects of adding waste plastic fibers on the mechanical properties and shear strength of reinforced concrete beams. *Iraqi Journal of Civil Engineering*, 12(1), 110-124.

Ji, Y., Ji, W., Zhang, Z. and Wang, R., 2022. Road performance investigation on fiber-reinforced recycled cement base material. *Polymers*, 14(19), p.4102.

Jitsangiam, P. and Nikraz, H., 2011. Mix design of cementitious basecourse. In *Proceedings of the International Conference on Advances in Geotechnical Engineering* (pp. 379-385). Australian Geomechanics Society.

Khalaf, K.J. and Khalil, W.I., 2015. Studying the utilization of polymeric wastes to produce sustainable concrete (Doctoral dissertation, MSc. Thesis, Building & Construction Dept., Univ. of Technology, Iraq).

Mardani-Aghabaglou, A., Andiç-Çakir, Ö. and Ramyar, K., 2013. Freeze–thaw resistance and transport properties of high-volume fly ash roller compacted concrete designed by maximum density method. *Cement and Concrete Composites*, 37, pp.259-266.

Marik, S., Ransinchung, G., Mondal, A., & Kumar, D. (2024). Characterization of cement-modified mixtures and their typical characteristics: a review. *Journal of Building Engineering*, 110526.

Nibudey, R.N., Nagarnaik, P.B., Parbat, D.K. and Pande, A.M., 2013. Strength and fracture properties of post consumed waste plastic fiber reinforced concrete. *Int. J. Civ. Struct. Environ. Infrastruct. Eng. Res. Dev*, 3(2), pp.9-16.

Oliveira, L.A.P. and Castro-Gomes, J.P., 2011. Physical and mechanical behaviour of recycled PET fibre reinforced mortar. *Construction and Building Materials*, 25(4), pp.1712-1717.

- Park, S.S., 2011. Unconfined compressive strength and ductility of fiber-reinforced cemented sand. *Construction and building materials*, 25(2), pp.1134-1138.
- Piratheepan, J.G.C.T., Gnanendran, C.T. and Lo, S.C., 2010. Characterization of cementitiously stabilized granular materials for pavement design using unconfined compression and IDT testings with internal displacement measurements. *Journal of Materials in Civil Engineering*, 22(5), pp.495-505.
- Sobhan, K. and Mashnad, M., 2000. Fatigue durability of stabilized recycled aggregate base course containing fly ash and waste-plastic strip reinforcement. Final Rep. Submitted to the Recycled Materials Resource Centre, Univ. of New Hampshire.
- Sobhan, K. and Mashnad, M., 2003. Fatigue behavior of a pavement foundation with recycled aggregate and waste HDPE strips. *Journal of geotechnical and geoenvironmental engineering*, 129(7), pp.630-638.
- Thomas, L.M. and Moosvi, S.A., 2020. Hardened properties of binary cement concrete with recycled PET bottle fiber: An experimental study. *Materials Today: Proceedings*, 32, pp.632-637.
- Vadivel, T.S. and Doddurani, M., 2013. An experimental study on mechanical properties of waste plastic fiber reinforced concrete. *International Journal of Emerging Trends in Engineering and Development*, 3(2), pp.395-401.
- Zhang, P. and Li, Q., 2010. Experimental study on shrinkage properties of cement-stabilized macadam reinforced with polypropylene fiber. *Journal of reinforced plastics and composites*, 29(12), pp.1851-1860.
- Zhao, Y., Yang, X., Zhang, Q., Liang, N., Xiang, Y. and Qin, M., 2020. Crack Resistance and Mechanical Properties of Polyvinyl Alcohol Fiber-Reinforced Cement-Stabilized Macadam Base. *Advances in Civil Engineering*, 2020(1), p.6564076.
- Zheng, Y., Zhang, P., Cai, Y., Jin, Z. and Moshtagh, E., 2019. Cracking resistance and mechanical properties of basalt fibers reinforced cement-stabilized macadam. *Composites Part B: Engineering*, 165, pp.312-334.