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Structural Behavior of Reinforced Concrete Slabs Containing Fine Waste Aggregates of Polyvinyl Chloride

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Abstract: In several areas worldwide, the high cost and shortage of natural resources have encouraged researchers and engineers to explore the serviceability and feasibility of using recycled aggregates in concrete mixtures, substituting a normal aggregate percentage. This technique has advantages for the environment by reducing the accumulation of waste materials, while it impacts the fresh and hardened concrete performances, reducing workability, flexural strength, compressive strength, and tensile strength. However, most studies have investigated the influence of replacing normal aggregates with waste aggregates on the concrete mechanical properties without examining the impact of using waste materials on concrete structural performance. The aim of this research is to investigate the effect of replacing 75% of sand volume with polyvinyl chloride (PVC) fine waste aggregates on the performance of reinforced concrete slabs. Different thicknesses of the concrete layer (0%, 25%, 50%, and 100% of slab thickness) containing PVC fine waste aggregates are investigated. Based on the reductions in the toughness and flexural strength capacity due to incorporating 75% PVC fine aggregate dosage, two approaches are used to strengthen the slabs with 75% PVC fine aggregates. The first approach is adding polyvinyl alcohol (PVA) to the PVC fine aggregate concrete mix to improve the mechanical properties of the concrete. The PVA increases the water viscosity in the concrete, which reduces the dry out phenomenon. With that said, the PVA modified fresh concrete does enable the use of the limits of the PVC fine aggregate dosage for high dosage plastic aggregate concrete. The second approach uses two fiber wire mesh layers as an additional reinforcement in the tested slab. Results show that the PVC-30 slab exhibits an 8% decrease in total area toughness compared to the control (Con) slab, while for PVC-60 slab toughness, the total area shows 26% less. Additionally, the inclusion of PVA in the concrete with 75% PVC plastic waste fine aggregate replacement greatly influences the pre-and post-cracking ductile performance among other slabs, representing that using PVA with higher contents might increase the flexural performance. Therefore, due to the substantial effect of PVA material on the concrete flexural performance, it is proposed to utilize PVA with an optimum PCV fine aggregate dosage in the concrete mix.

Keywords: reinforced concrete slabs; polyvinyl alcohol; polyvinyl chloride; experimental

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1. Introduction

The high cost and shortage of natural resources in several areas worldwide have encouraged researchers and engineers to explore the serviceability and feasibility of using recycled aggregate in concrete mixtures by substituting a percentage of the normal aggregate. To eliminate or decrease the accumulation of the waste materials, past research has suggested using some types of the waste materials such as polyethylene terephthalate, polypropylene, polystyrene, polyethylene, and polyolefins as a substitute for all or a percentage of the aggregates used in the concrete mix [1,2]. Several studies have investigated the use of plastic waste materials as fine or crosses aggregate in concrete mixes, studying the effects of aggregate size, shape, treatment method, and replacement content. The use of plastic waste aggregates in the concrete impacts the fresh and hardened concrete performances reducing workability, density, flexural strength, compressive strength, and tensile strength. On the other hand, there are some concrete improvements on long-term performance in using waste aggregates, such as drying shrinkage, freezing and thawing resistance, chloride ion penetration, and electrical resistivity [1,3–8]. The plastic aggregates have low water absorption, strength, and stiffness, along with being lightweight compared to normal aggregates: therefore, these properties of plastic aggregates show hydrophobic characteristics by preventing water and capturing air onto its surface. However, most studies have investigated the influence of replacing normal aggregates with waste aggregates on the concrete mechanical properties without examining the impact of using waste materials on concrete structural performance.

Based on the replacement percentage of plastic waste in the concrete mix, the type and content of plastic aggregate are essential factors that influence concrete performance. Due to the effects of incorporating plastic wastes as aggregates replacement on the fresh and hardened properties along with durability performance; past research has limited the dosage percentage of plastic aggregates by 20% to avoid a considerable reduction in the concrete mechanical properties. Fundamentally, the physical properties plastic waste are a smoother surface than normal sand, which causes a feeble bond strength between the cement matrix and plastic aggregate [8,9]. Therefore, to use a large dosage of plastic aggregates, modifying the plastic aggregate surface roughness, or enhancing the bond strength between the cement matrix and plastic aggregate is required [10]. However, past research was limited by studying only low dosages of plastic aggregates. Therefore, the high dosage of plastic waste aggregates in the concrete mix has not been studied comprehensively in the concrete structures. Besides, there is limited research regarding the effect of enhancing cement matrix on mechanical properties of plastic waste aggregates concrete such as tensile, compressive, and flexural strengths.

2. Objective

The main objectives of this research are to experimentally examine the impact of using plastic waste aggregates as a partial replacement of the normal sand on the concrete mechanical properties and reinforced concrete slab performance. We cast four concrete mixtures using different replacement polyvinyl chloride (PVC) ratios of the required proportion of the normal sand. Different replacement ratios were used for normal strength concrete, 0%, 50%, and 75%, whereas one replacement ratio of 75% was used with polyvinyl alcohol (PVA) to improve the concrete mix's internal curing. Furthermore, this study aims to investigate the effect of replacing 75% of sand volume with PVC fine aggregates on the behavior of reinforced concrete slabs. For investigating the effect of replacing sand with PVC fine aggregates on the behavior of reinforced concrete slabs, a flexural test was used. In the flexural test, a steel frame was placed on the specimens to allow the reinforced concrete slabs to apply loading lines. Another objective of this study is to investigate two approaches used to strengthen the slabs with 75% PVC fine aggregates. The first approach is adding PVA to the PVC fine aggregate concrete mix to improve the concrete mechanical properties, while the second approach is by using two fiber wire mesh layers as an additional reinforcement in the tested slab.

3. Background

The effect of various replacement percentages of 0%, 10%, 20%, and 30% plastic waste aggregates in the concrete mix on the splitting tensile strength of concrete with different percentages of 28%, 40%, and 50% water-to-cement ratios was studied [11]. The results showed that the splitting strength decreased for plastic waste aggregate concrete, and the concrete failure behavior was more ductile than the normal concrete. Batayneh et al. [12] investigated the performance of concrete mix using waste materials as a part of the aggregates. Plastics and glass aggregates were used to replace up to 20% of fine aggregates in concrete mixes. The amount of reduction in the tensile strength and flexural strength values of the tested samples was lower than the compressive strength reduction due to adding the plastic particles. The compressive strength reduction for a 20% replacement up to 72%, while for 5% replacement, the compressive strength shows a 23% reduction.

Kodua [13] studied the concrete chemical and mechanical properties that contain high-density polyethylene as partial replacement of coarse aggregate (0%, 2%, 4%, 6%, and 8% of the coarse aggregate weight). Results showed that there was a decrease in plastic aggregate concrete workability compared to the normal concrete. Besides, the compressive strength decreased with increasing the percentage of high-density polyethylene in the concrete. With 2%, 4%, 6%, and 8% replacements of coarse aggregate, the compressive strength of concrete reduced by 35%, 39%, 47%, and 52%, respectively. Hameed and Hamza [14] investigated polymer concrete's mechanical and physical characteristics using waste aggregates. It was noticed that the polymer concrete mixed from epoxy waste aggregates had improved properties than the other concrete types. Results showed that the compressive, tensile, and flexural strengths were improved by 30%, 20%, and 35% compared to normal concrete specimens with increasing the polymer resin percentage added to all aggregates.

Ghernouti et al. [15] investigated replacing sand with plastic waste in the concrete mix. Results showed that concrete compressive strength decreased by 20% at 10% replacement of fine waste aggregate. Ismail and AL-Hashmi [16] used waste plastic fabric as a partial substitute of sand by 0%, 10%, 15%, and 20%. Results showed that increasing the waste plastic ratio tends to decrease the compressive and flexural strength of concrete. Senhadji et al. [17] investigated partial replacement of conventional aggregates in concrete with plastic PVC aggregates. The main conclusion was the reduction in compressive strength by 15, 27, and 49 for 30%, 50%, and 70% percentages of plastic PVC aggregates, respectively. Jibrael and Peter [18] replaced 1%, 3%, and 5% percentages of sand with two types of waste materials. Added waste in mixes decreased the compressive, tensile, and flexural strengths of concrete by 16%, 27%, and 30%, respectively. Alqahtani et al. [19] examined the ability to obtain lightweight concrete using recycled plastic aggregates. However, results showed that the compressive strength was reduced between 15% to 48% from the original compressive strength.

Prahallada et al. [20] examined the waste plastic fiber reinforced concrete workability and strength. The researchers adopted volume fraction with different percentages of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% waste plastic fiber. It was noticed that the compressive strength, tensile strength, flexural strength of waste plastic fiber reinforced concrete increased by adding 1% of waste plastic fibers. However, increasing waste plastic material decreased mechanical properties. Ramadevi et al. [21] replaced 0.5%, 1%, 2%, 4%, and 6% from the weight of traditional fine aggregate with plastic waste fibers. The researchers observed that the compressive and split tensile strength improved using 2% replacement of the fine aggregate with plastic waste fibers while decreasing for 4% and 6% of plastic waste fiber replacements.

Gesoglu et al. [22] examined the effect of partially replacement of normal aggregate with PVC aggregate on self-compacting concrete properties. Results showed that adding the PVC to the concrete mix negatively influenced the compressive strength of concrete by 24% reduction. The researchers reported that the reduction in the amount of hydration production impacts the interlocking between cement paste and PVC aggregates. Haghighatnejad et al. [23] investigated the mechanical properties of concrete by incorporating PVC scrapped pipe. According Haghighatnejad et al. [23], the concrete workability of PVC concrete is less compared to the normal concrete. Additionally, the compressive strength of PVC concrete was reduced by 33.5% at 50% PVC aggregate dosage, compared to the normal concrete. Similarly, Najjar et al. [24] studied the mechanical properties of PVC concrete. Results showed an increase in fresh concrete slump, and 27% of the compressive strength loss was found at 25% PVC content. Another study by Hussein et al. [25], showed that there is a loss of workability and reduction in PVC flexural strength when a partial of natural aggregate is replaced with PVC aggregates. Kou et al. [26] investigated the mechanical properties of concrete by incorporating PVC pipe. According to the test data by the researchers, the compressive strength of PVC concrete decreased by 9%, 18%, 21%, and 47% for 5%, 15%, 30% and 45% PVC aggregate dosage, respectively. In addition, Patel and Dalal [27] reported an increase in slump of fresh concrete. Results showed the flexural strengths was reduced with increasing PVC aggregate to 30%.

4. Experimental Program

In this research, two approaches, which are material and structural approaches, were conducted to investigate the effects of incorporating PVC fine aggregate dosages (0%, 50%, and 75% volume replacement) on the concrete performance. This is achieved by illustrating PVC fine aggregate concrete properties through material tests and performing slab testing of five hybrid slabs with PVC fine aggregate concrete and varying PVC concrete layer thicknesses.

4.1. Materials

Materials utilized in this study were Type-I cement, normal fine aggregate, PVC fine aggregate (see Figure 1a), normal coarse aggregate, water, PVA (see Figure 1b), and fiber wire mesh (see Figure 1c). Additionally, the mineralogical and chemical compositions of ordinary Portland cement (Type I) used in this study for all mixes are listed in Table 1. The sieve analysis test was conducted to grade the PVC and normal fine aggregates, as depicted in Figure 2. As shown in this figure, the fine aggregates used conform to grading limits following British Standard (BS) 882 [28]. From sieve analysis, the fineness modulus of sand was noticed to be 2.81. The PVC fine aggregate used in this research was collected from PVC plastic sheets accumulated manufacture waste materials. The primary source of the PVC fine aggregate was obtained from the cutting process of PVC sheets and pipes. Thus, the required particle sizes were obtained directly without any additional crushing or refining, as shown in Figure 1a. This form of PVC fine aggregate was beneficial to achieve particle uniformity, improving concrete mix workability. Figure 2 shows that the comparison between PVC fine aggregate and normal aggregate gradings shows that the PVC fine aggregate was very closed to the natural sand. More test results of the used materials in this study are listed in Table 2.

(**a**) (**b**) (**c**)

Figure 1. (**a**) PVC fine waste aggregates, (**b**) PVA as powder, and (**c**) Fiber wire mesh.

Table 1. Composition of ordinary Portland cement (Type I) used in concrete mixes.

Constituent	Ordinary Portland Cement (Type I) % by Weight
Lime (CaO)	62.6
Silica (SiO_2)	21.1
Alumina (Al_2O_3)	5.4
Iron oxide (Fe_2O_3)	3.3
Sulfite (SO_3)	2.3
Magnesia (MgO)	2.8
Loss of ignition (L.O.I)	1.4
Lime saturation factor (L.S.F)	0.9
Insoluble residue (I.R)	0.8
Tricalcium silicate (C_3S)	47.1
Dicalcium silicate (C_2S)	25.1
Tricalcium aluminate (C_3A)	8.8
Tetra calcium aluminoferrite (C_4AF)	10.0

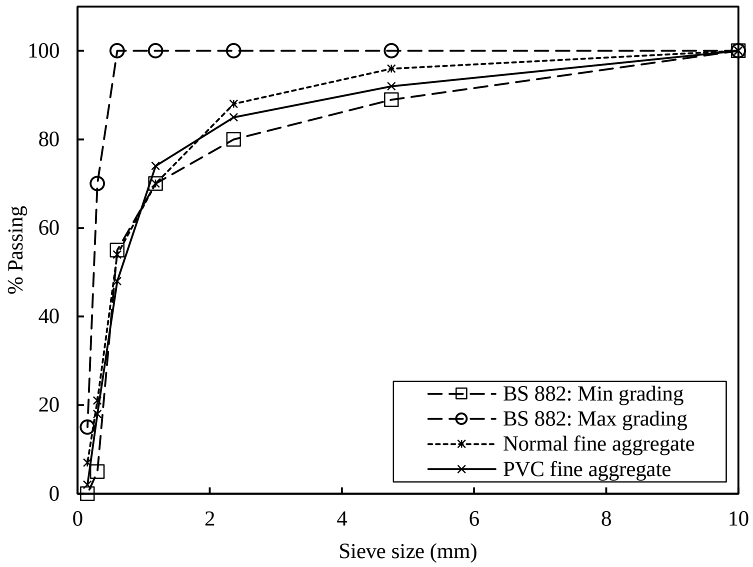


Figure 2. Fine Aggregate Sieve Analysis.

Table 2. Material Properties used in concrete mixes.

Properties	Specific Gravity	Fineness Modulus	Bulk Density (Loose) (kg/m^3)	Bulk Density (Compacted) (kg/m^3)
Cement	3.25	-	-	-
Coarse aggregate	2.65	-	1625	1740
Fine aggregate	2.6	2.64	1720	1804
PVC aggregate	1.24	2.81	114	128

Furthermore, PVA material and fiber wire mesh were used to enhance the concrete mechanical properties and structural slab performance, respectively, to incorporate the PVC waste material in the concrete mix. Adding PVA to the cement mortar and concrete improves the workability compared to the normal concrete [29–32]. According to Ohama [33,34], the PVA increases the water viscosity in the concrete, which reduces the dry out phenomenon. Yaowarat et al. [35–37] reported that adding PVA to cemented materials enhanced tensile and flexural strengths by improving ductile and toughness. Figure 1b,c show the PVA dry form and fiber wire mesh, respectively. The use of PVA improves maintaining the water in the concrete mix that helps the internal curing. The

PVA properties are listed in Table 3. Fiber wire mesh of 0.15 mm diameter and grid size of 2 × 2 mm was used to re-strength PVC reinforced concrete slab, as shown in Figure 1c. The tensile strength of fiber wire mesh was measured by testing one thread about 1120 MPa following American Society for Testing and Materials (ASTM) D412 [38].

Table 3. Properties of Polyvinyl alcohol.

Properties	Value
PH	5–7
Molecular weight (MW)	26,300–30,000
Degree of hydrolysis	86.5–89%
Bulk density	0.68 g/cm^3
Hardness	83.3 (shore D)
Decomposition point	240 °C

4.2. Concrete Mixes

The four concrete mixes were prepared, namely normal concrete mix (M-Con), a concrete mix containing 50% PVC fine aggregates of total fine aggregate volume (M-PVC50), a concrete mix containing 75% PVC fine aggregates of total fine aggregate volume (M-PVC75), and concrete mix containing 75% PVC fine aggregates of total fine aggregate volume (M-PVC75-PVA) with 0.15 PVA-to-cement ratio (by weight) (p/c). Besides, the PVA is a grainy white powder soluble in water to represent a fluid gel added to the concrete mix to enhance the mechanical properties of the concrete [29,39,40]. The quantities of concrete mixes are listed in Table 4. The PVC fine aggregates were obtained from manufacturing waste materials, as shown in Figure 1a. These fine aggregates passed through the sieve at 4.75 mm.

Table 4. Mix design of the normal concrete.

Material	Mix ID			
	M-Con	**M-PVC50**	**M-PVC75**	**M-PVC75-PVA**
Water-to-cement ratio	0.45	0.45	0.45	0.45
Water (kg/m^3)	205	205	205	205
PVA (kg/m^3)	0	0	0	68.4
Cement (kg/m^3)	456	456	456	456
Normal fine aggregate (kg/m^3)	673	336	168	168
PVC fine aggregate (kg/m^3)	0	23.6	31.4	31.4
PVC %	0	50	75	75
Coarse aggregate (kg/m^3)	1120	1120	1120	1120

4.3. Apparatus

Six reinforced concrete slabs with 870 × 870 × 60 mm dimensions were prepared and tested under two linear loads (see Figure 3). To achieve the maximum bending moment capacity of the concrete slab, a special flexural test setup showed in Figure 3a,b was used to apply the linear loads only to the concrete slab. Table 5 and Figure 4 show the details of six slab specimens. The four slab specimens were cast with one concrete mix type, namely Con, PVC-60, PVC-60-PVA, and PVC-60-Fiber cast with M-Con, 60 mm layer of M-PVC75, 60 mm layer of M-PVC75-PVA, and 60 mm layer of M-PVC75 with embedding fiber wire mesh at top and bottom surfaces, respectively, as shown in Figure 4b,e–g. The other two specimens were hybrid slabs cast with two types of concrete mixes, namely PVC-15 (cast 45 mm layer of M-Con and 15 mm layer of M-PVC75) and PVC-30 (cast 30 mm layer of M-Con and 30 mm layer of M-PVC75) (see Figure 4c,d), respectively.

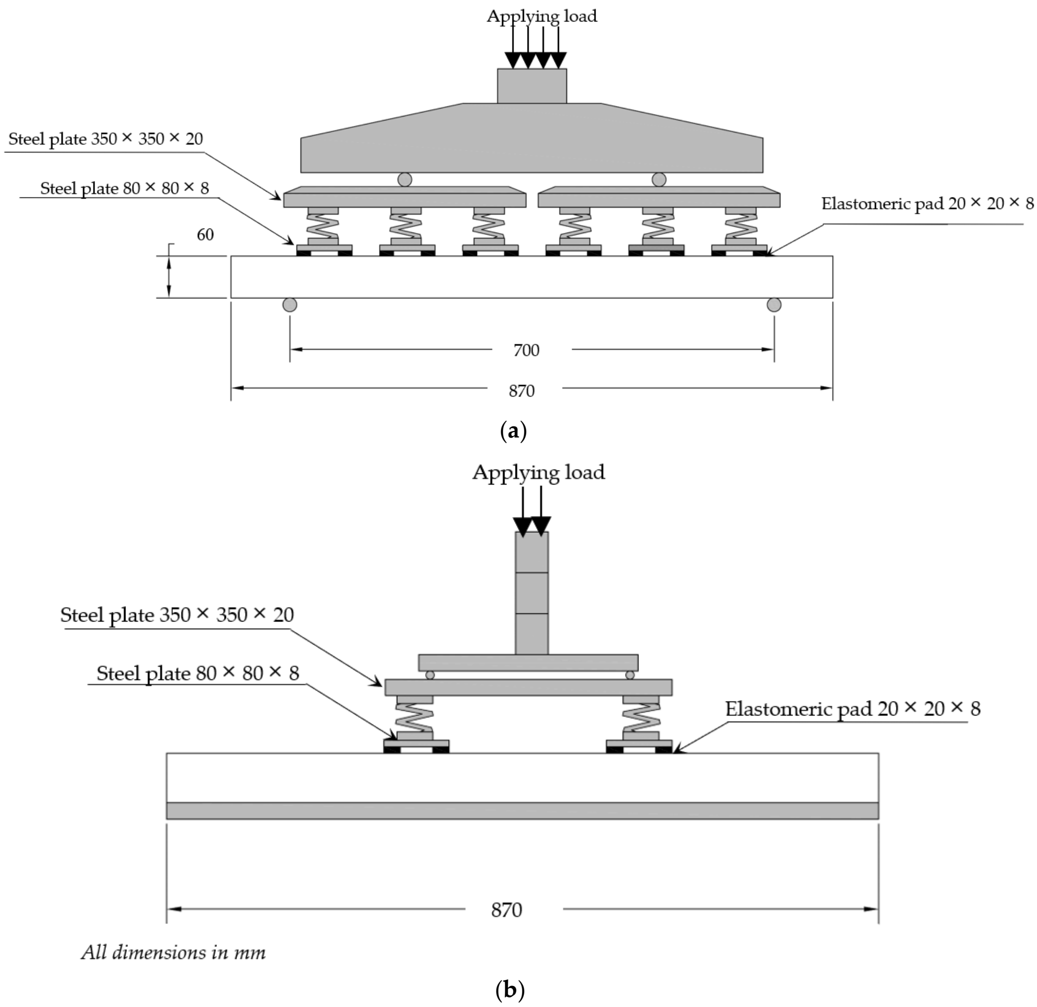


Figure 3. Details of slab (**a**) front view, (**b**) side view.

Table 5. Slab Details.

Sample ID	Slab Details	Figure 3
Con	M-Con	b
PVC-15	45 mm layer of M-Con and 15 mm layer of M-PVC75	d
PVC-30	30 mm layer of M-Con and 30 mm layer of M-PVC75	f
PVC-60	60 mm layer of M-PVC75	c
PVC-60-PVA	60 mm layer of M-PVC75-PVA	e
PVC-60-Fiber	60 mm layer of M-PVC75 with embedding fiber wire mesh at top and bottom surfaces	g

Moreover, a total thickness replacement of 75% sand volume with PVC fine waste aggregates was studied (see Figure 4e). Due to the high dosage of PVC fine waste aggregates in the concrete mixes, a decrease in the slab load capacity might be expected. Therefore, two approaches were used to strengthen the slabs with PVC fine aggregates. The first approach uses PVA to increase the strength capacity of concrete by improving the internal curing [39], as shown in Figure 4f, while the second approach uses two fiber wire mesh layers as an additional reinforcement (see Figure 4g) [41,42]. The embedding fiber wire mesh at the top surface contributes as additional reinforcement in a tension zone, while the bottom fiber wire mesh provides confinement in the compression zone to enhance the reduction in ultimate strength, caused by using PVC fine waste aggregates with high dosage. Besides, in all specimens, the steel reinforcement layer was used at the specimens' bottom, as shown in Figure 4a,h.

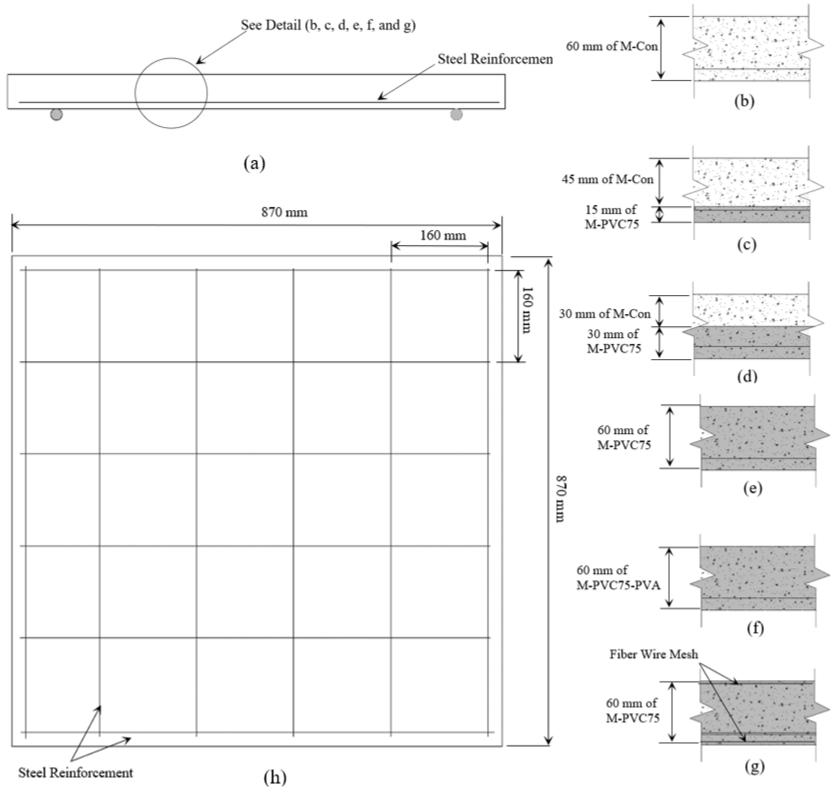


Figure 4. (**a**) Elevation view, (**b**) Con, (**c**) PVC-15, (**d**) PVC-30, (**e**) PVC-60, (**f**) PVC-60-PVA, (**g**) PVC-60-Fiber, (**h**) plan view specimens.

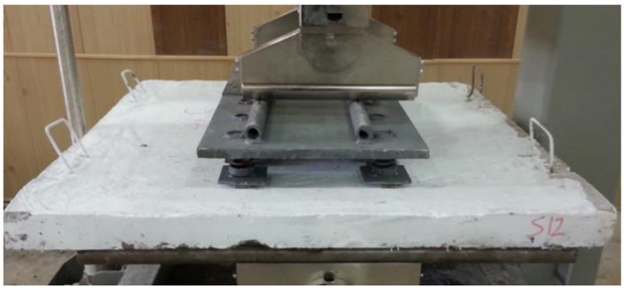
4.4. Specimen Preparation

For every mix design, to test the mechanical properties, the concrete constituents of concrete mixes depicted in Table 5 were mixed and cast cubes and cylinders for compressive strength and splitting tensile strength according to EN B.-12390-2 [43] and ASTM C496/C496M-17 [44], respectively. Three specimens were tested following each group test's requirements, and the specimens were cured for 28 days in accordance with ASTM C192/C192M-02 [45]. Additionally, in accordance with the IQS 354 [46] standard, the slump test was checked for every mix design.

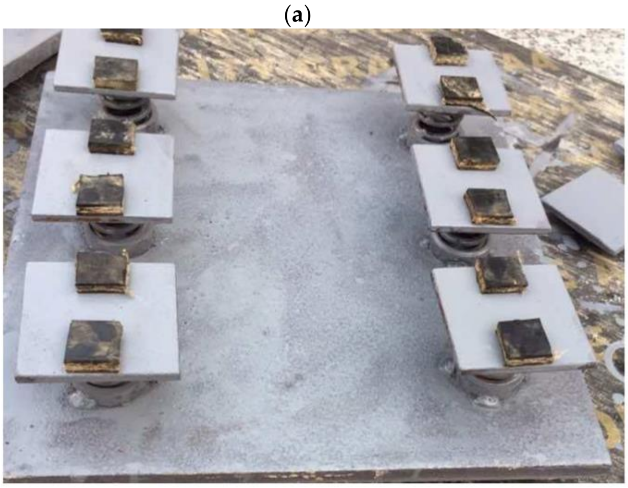
For the control slab specimen construction, the slab was designed in accordance with the American Concrete Institute (ACI) code [47]. The tested slabs were reinforced with six 8 mm diameter bars at 160 mm in both directions, as shown in Figures 4h and 5. The average yield strength of reinforcement was about 524.5 MPa, obtained from testing three specimens according to ASTM A615/A615M-12 [48]. Wood molds were built, and the steel reinforcement layer was placed at 10 mm at the bottom of the molds, as shown in Figure 4a and Figure 6. Then, the concrete mixes were placed in the molds. After placing the concrete, each specimen was vibrated for 30 s. Then, the tested slabs were covered with a plastic cover. Finally, the molds were opened after 24 h, and the slab specimens were cured for 28 days in accordance with ASTM C192/C192M-02 [45].

Figure 5. Steel reinforcement and mold.

(a)



(b)



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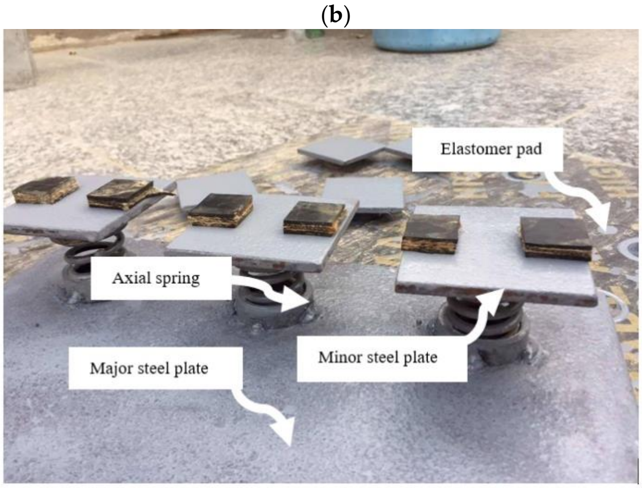


(d)

Figure 6. Load system (**a**) and (**b**) Two steel shaft on a major steel plate, (**c**) Lower face of large major steel plate, and (**d**) One line of major steel plate.

4.5. Test Procedure

For each mix, the cubes were tested in accordance with EN, B.-12390-2 [43] standard to measure the compressive strengths at 28 days. The splitting tensile strength tests were performed following ASTM C496/C496M-17 [44]. In the flexural slab test, two points of load mechanism were employed to apply uniform load on the slab specimens (see Figure 3). The specimens were located in an MTS material test system machine with a capacity of 670 kN, as shown in Figure 6a. Each load point rests on two steel shafts (30 mm diameter and 300 mm long). The two steel shafts were welded on top of the major steel plate (350 × 350 × 20 mm) and spaced at 150 mm, as shown in Figure 6. The major steel plate was supported by two lines of 200 mm axial springs, as shown in Figure 6c,d, to eliminate the load eccentricity during testing. Each line constituted of three axial springs. At the end of the axial spring, a small steel plate of 80 × 80 × 8 mm was installed. On the other face of the small steel plate, two elastomeric pads of 20 × 20 × 8 mm were glued, as shown in Figure 6d.

The load was applied until the slab failed. This test setup ensured the load on the slab specimen was uniformly applied. Load and deflection were recorded using a displacement gauge at the center of the slab as the load was applied until failure. Furthermore, to identify in the load-displacement curves, cracking load (L_{cr}), ultimate load (L_{ult}), and failure load (L_f) stages were depicted in Figure 7. In this figure, the energy absorbed by the slabs was separated into three flexural toughness areas, namely Area I, Area II, and Area III. These areas characterize the flexural toughness for pre-cracking (Area I), cracked before achieving ultimate load (Area II), and post-cracking (Area III). Additionally, the initial stiffness (k) of the flexural load-displacement curve was calculated for the linear portion, as shown in Figure 7.

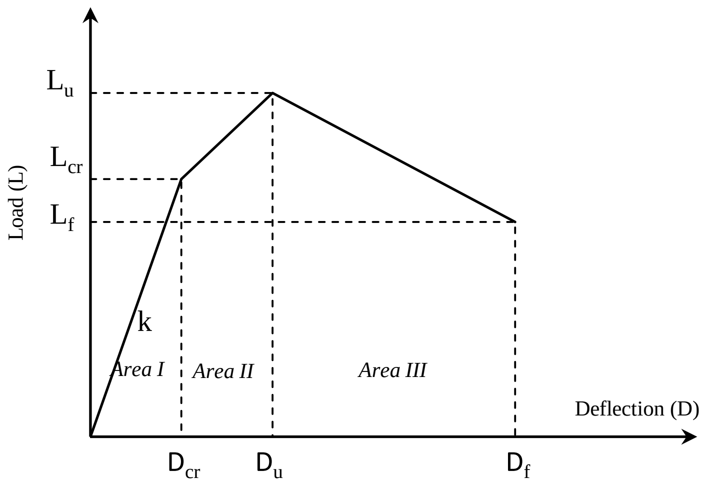


Figure 7. Toughness model.

5. Results and Discussion

5.1. Mechanical Properties

5.1.1. Workability of Fresh Properties

The slump test results, along with the compressive and splitting tensile strengths for control mix (M-Con) and other mixes with PVC fine aggregates, as listed in Table 6. The M-Con mix slump is 125 mm, while the slump decreased due to the use of PVC waste fine aggregates in the concrete mixes. Adding PVC fine aggregates decreased the fresh concrete slump significantly in an amount proportional to the PVC fine aggregates dosage. The slump reduces by 16% compared to the M-Con mix when 50% of PVC fine aggregate was used. For the 75% of PVC fine aggregate replacement, the slump is reduced to 31% compared to the control mix. According to Li et al. [1], past research has indicated that the workability depends on plastic aggregate shape and quantity, which impact the friction between concrete constituents and plastic aggregate. It should be noted that due to the rough surface of the PVC fine aggregate compared to normal fine aggregates, the slump test results showed a significant reduction, especially in the M-PVC75 concrete mix. This can be clarified by increasing the inner friction between PVC fine aggregate with other concrete compositions. Correspondingly, Coppola et al. [49] reported that the inclusion of plastic aggregates with 10% and 25% reduced the workability of mortars by about 13% and 27%, respectively. However, in this study, adding PVC aggregates with 50% and 75%

of fine aggregate reduced the workability of mortars by about 16% and 31%, respectively. The majority of past research has reported increasing the fine plastic aggregates impact the workability by decreasing the concrete slump [6,12,16,50–54]. Therefore, keeping the water-to-cement ratio constant in all mixes with the high dosage of PVC fine aggregates, an enhancement of fresh concrete workability is required to increase the amount of PVC dosage used. In this study, 0.15 PVA-to-cement ratio (by weight) (p/c) was added to the concrete mix (M-PVC75-PVA mix) with 75% PVC replacement dosage. In Table 6, the PVA increased the workability of the M-PVC75-PVA mix by 7% compared to the M-PVC75 mix, which has the same amount of the PVC. Thus, this observation was found by other researchers that adding PVA to the cement mortar and concrete improves the workability compared to the normal concrete [29,31,32]. According to Ohama [33,34], the PVA increases the water viscosity in the concrete, which reduces the dry out phenomenon. With that said, the PVA modified fresh concrete does enable the limits of the PVC fine aggregate dosage for high dosage plastic aggregate concrete to be further explored.

Table 6. Mechanical properties of concrete mixes.

Mix ID	f_t (MPa)	Diff. (MPa)	TSC %	$f_{cu'}$ (MPa)	Diff. (MPa)	CSC %	Brittleness Ratio	Slump (mm)
M-Con	3.41	0	0	33.41	0	0	9.8	125
M-PVC50	2.94	−0.47	−13.8	31.26	−2.15	−6.4	10.6	105
M-PVC75	2.65	−0.76	−22.3	25.67	−7.74	−23.2	9.7	86
M-PVC75-PVA	3.85	0.44	12.9	38.50	5.09	15.2	10.0	92

Splitting tensile (f_t); Compression strength ($f_{cu'}$); Tensile Strength Change (TSC) = Diff/$f_{c\cdot\text{M-Con}}$ × 100%; Compressive Strength Change (CSC) = Diff/$f_{c\cdot\text{M-Con}}$ × 100%; Brittleness ratio = compressive strength to tensile strength.

5.1.2. Hardened Properties

The compressive and tensile strengths measured along with calculating the brittleness ratio for all mixes are listed in Table 6. In order to obtain the brittleness ratio, the ratio of compressive to splitting tensile strengths was used [55]. Due to the importance of concrete tensile and compressive strength rules in concrete design, the brittleness associated with the influent of PVC fine aggregate was investigated in this section. As shown in Table 6, the M-Con mix produced the highest tensile and compressive strengths among other mixes with PVC dosage, while the M-PVC75 mix showed the lowest strength. The addition of 50% PVC to the concrete mix lowers the tensile and compressive strengths by 13.8% and 6.4% compared to the control mix, respectively. The M-PVC mix with 75% PVC aggregate exhibited smaller tensile and compressive strengths, approximately 22.3% and 23.2%, than the M-Con mix, respectively, even if all concrete mixes have the same mix design. It should be highlighted that the addition of a PVC dosage drops the compressive and tensile strengths of the concrete specimens. The amount of reduction in the strength values for PVC concrete is essentially correlated to the PVC dosage. According to Gesoglu et al. [22], the reduction in the hydration products developed at the interface between the concrete past and the plastic aggregate may be the main reason for decreased tensile and compressive strengths. Additionally, the configuration of fine plastic aggregates may significantly increase the surface area, causing more water demand and leading to the inadequate strength of the transition zone region [56,57].

On the other hand, incorporating PVA to the mix design improved the PVC concrete performance with 75% replacement, about 12.9% and 15.2% in the tensile and compressive strengths, respectively, in comparison with the control mix. Furthermore, the inclusion of 0.15 PVA-to-cement ratio into PVC concrete mix enhanced the ratio of splitting tensile and compressive strength, as shown in Table 6. Yaowarat et al. [35–37] reported that adding PVA to cemented materials enhanced tensile and flexural strengths by improving ductile and toughness. This performance is mainly credited to the increase in cementitious products at an early age that improving the transition zone strength between concrete constituents and cement matrix [40]. Thus, the M-PVC75-PVA mix, strengthened with the

PVA, exhibited the highest tensile and compressive strength performances among other mixes, signifying that utilizing 75% PVC fine aggregate with PVA material enhanced the mechanical properties substantially. Moreover, the increases in the tensile and compressive strengths of the M-PVC75-PVA mix were 12.9% and 15.2%, respectively, compared to the M-Con mix for the reason that the effect of PVA on the concrete matrix by creating a denser microstructure during the hydration process of cement phases [29]. Therefore, the fresh and hardened properties for the four concrete mixes showed the M-PVC75-PVA mix was the best mix among other mixes. Then, in the next section, the effect of replacing 75% of sand volume with PVC fine aggregates on the behavior of reinforced concrete slabs was investigated. For investigating the effect of replacing sand with PVC fine aggregates on the behavior of reinforced concrete slabs, a flexural test was used.

5.2. Slab Behaviors

A replacement of 75% sand volume with PVC fine waste aggregates was investigated in this section. For investigating the effect of replacing sand with PVC fine aggregates on the behavior of reinforced concrete slabs, a flexural test was used, as shown in Figures 3 and 4. In the flexural test, a steel frame was placed on the specimens to allow the reinforced concrete slabs to experience flexural load. Figure 8a–e depict the comparisons of load-mid-span deflection curves between the Con slab and PVC-15, PVC-30, PVC-60, PVC-60-PVA, and PVC-60-Fiber slabs, respectively. The comparisons of flexural behavior between the Con slab and PVC-15, PVC-30, and PVC-60 slabs without any additional improvement are drawn from Figure 8a–c, respectively. In these figures, the load-deflection is approximately linear until 45 kN, 40 kN, 38 kN, and 30 kN, for Con with 100% normal concrete, PVC-15 with 25% M-PVC75 concrete, PVC-30 with 50% M-PVC75, and PVC-60 with 100% M-PVC75 concrete, respectively. Then, the notable nonlinear curves with hardening behavior occurred with limited fine crack recorded. After the ultimate load was reached, the softening behavior was recorded until the specimen approached failure. This result highlights the influence of adding PVC with 75% fine aggregate replacement to the concrete mixture for decreasing the flexural strength of the slab.

Due to the use of a high dosage of PVC fine waste aggregates in the concrete mixes, the results showed a decrease in the slab load capacity. Therefore, two approaches were used to strengthen the slabs with PVC fine aggregates. The first approach uses PVA to increase concrete strength by improving the concrete machinal properties (see Figure 8f), while the second approach uses two fiber wire mesh layers as additional reinforcement, as shown in Figure 8g. Figure 8d,e show the comparisons of flexural behavior between Con slab and PVC-60-PVA, and PVC-60-Fiber slabs, respectively. Figure 8 shows that the ultimate and failure loads with the initial flexural stiffness are obtained and listed in Table 7 and Figure 9a.

Table 7. Test Results of the Tested Specimens.

Sample ID	Ultimate Load (L_u)			Failure Load (L_f)			Initial Stiffness (k) (kN/mm)
	Load (kN)	LC %	Deflection (mm)	Load (kN)	LC %	Deflection (mm)	
Con	48.1	0.0	17.5	25.4	0.0	28.45	3.98
PVC-15	44.4	−8.3	16.6	24.0	−5.5	29.2	3.84
PVC-30	43.8	−8.8	17.5	22.0	−13.4	28.24	3.73
PVC-60	37.2	−22.9	20.0	18.45	−27.4	29	2.35
PVC-60-PVA	58.3	20.8	20.3	45.8	80.3	28.6	4.14
PVC-60-Fiber	53.1	10.4	9.5	41.9	65.0	29.3	8.83

Load Change (LC) = Diff/$Load_{Con}$ × 100%.

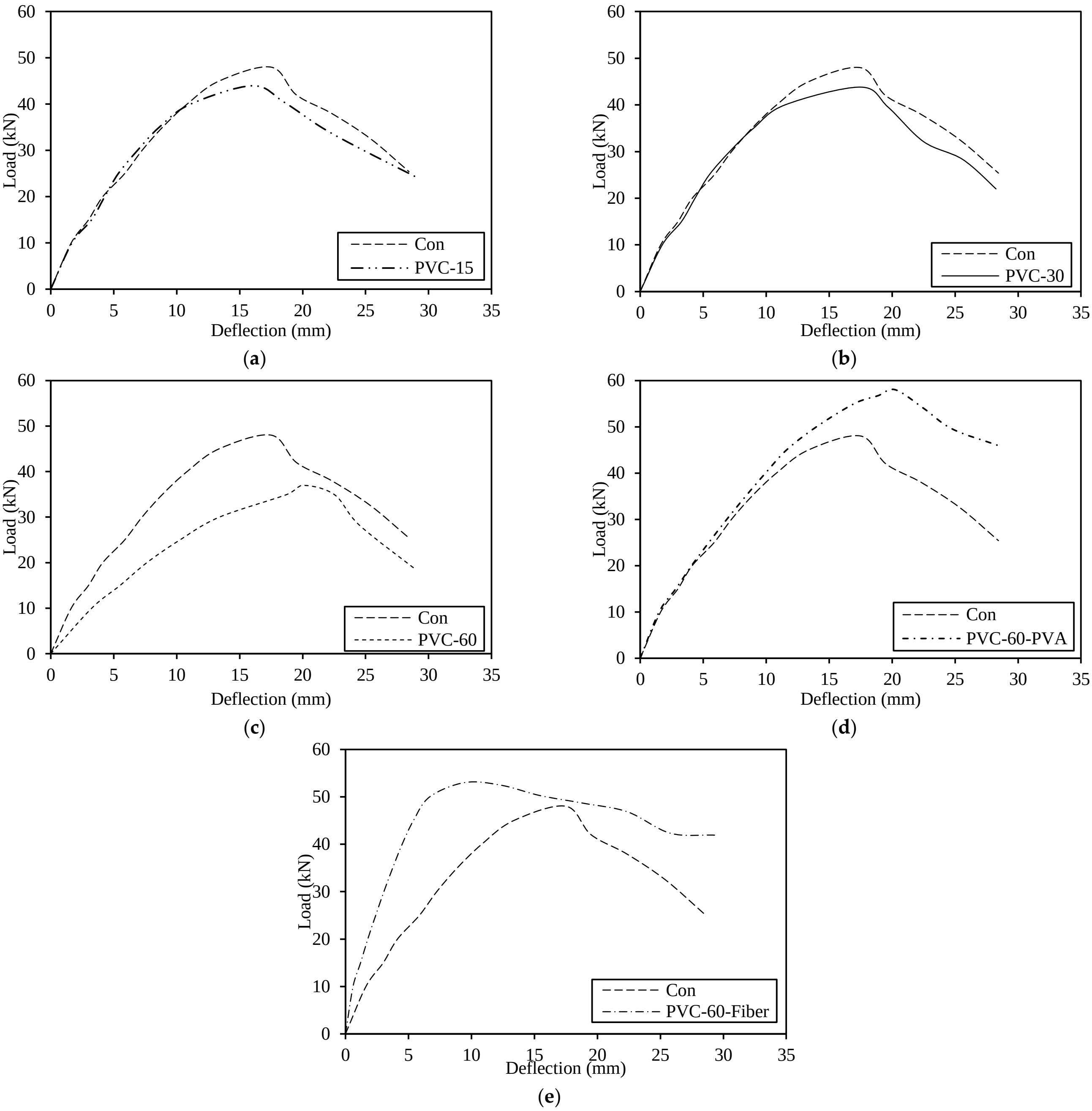


Figure 8. Load-deflection curve of Con specimen with (**a**) PVC-15, (**b**) PVC-30, (**c**) PVC-60, (**d**) PVC-60-PVA, and (**e**) PVC-60-Fiber specimens.

Applying the toughness model introduced in Figure 7 on Figure 8, the flexural toughness of the three areas was computed and plotted in Figure 9b. in Figure 8d,e, the load-deflection are approximately linear until 48 kN and 50 kN for PVC-60-PVA with 100% M-PVC75 concrete and PVC-60-Fiber with 100% M-PVC75 concrete that strength with PVA and fiber mesh, respectively. Then, the notable nonlinear curves with hardening behavior occurred with limited fine crack recorded. After the ultimate load was reached, the softening behavior was recorded until the specimen approached failure. Thus, material or structural enhancement can improve the slab flexural strength of 100% M-PVC75 concrete slab with 75% fine aggregate replacement in the concrete mixture to maximize the use of plastic waste materials.

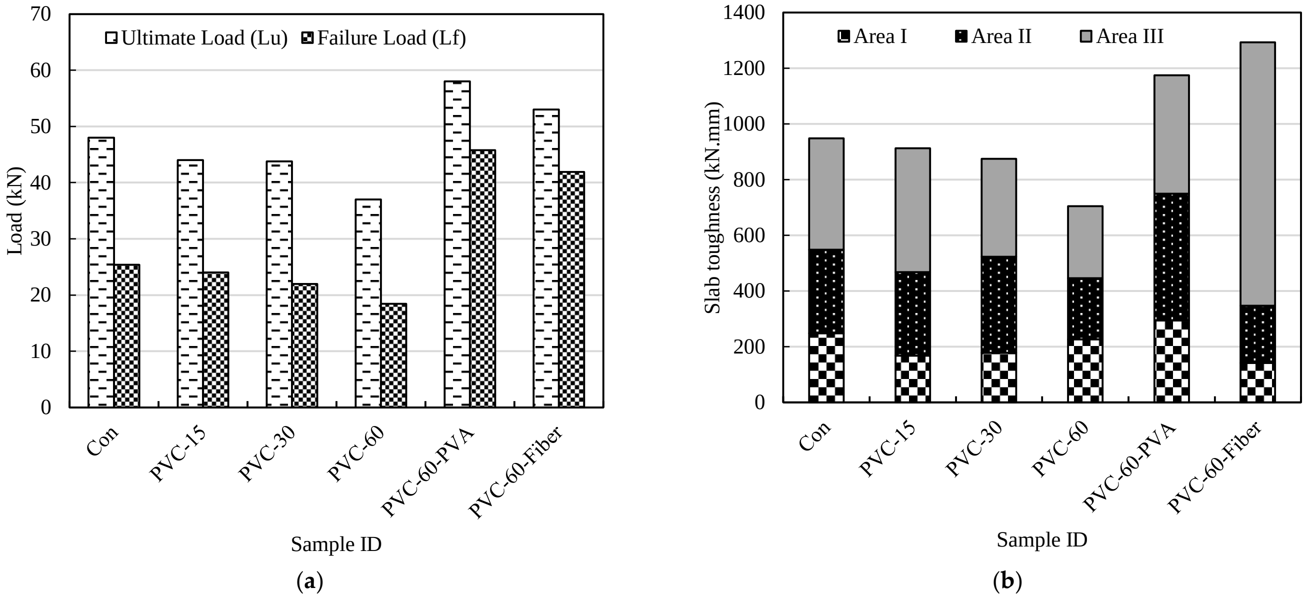


Figure 9. (**a**) Ultimate and failure loads and (**b**) slab toughness.

5.2.1. Comparison between Control and PVC Concrete Slabs

Figures 8a and 9a show a good agreement between the Con slab (100% of normal concrete) and PVC-15 slab (25% of M-PVC75 concrete and 75% of normal concrete). The Con slab and PVC-15 slab exhibited an initial flexural stiffness of about 3.98 kN/mm and 3.84 kN/mm, respectively. For the PVC-15 slab, the lower ultimate load was presented with an ultimate deflection of 17.5 mm, which is about 8.3% lower than the Con slab. The PVC fine aggregate causes a reduction in the ultimate load of the PVC-15. Therefore, using a hybrid slab with 25% M-PVC75 at the tension zone is not significantly impact the slab performance.

Moreover, when the amount of M-PVC75 mix increases in the concrete slab, the initial flexural stiffness and ultimate load were significantly decreased, as listed in Table 7 and Figure 9a. These results showed the same reduction trend noted in the tensile and compressive strengths of concretes with the incorporation of PVC fine aggregate. This reduction was caused by the insufficient bond strength of the transition zone region, which was related to the dosage replacement content of the PVC fine aggregate [56,58]. The weak strength of the transition zone region between PVC particle and cement matrix may be related to the free water accumulation [59]. In addition, as shown in Figure 8a–c, the PVC concrete slabs showed more increment in flexibility and plasticity, impacting the failure to be less brittle than the Con slab when increasing PVC fine aggregate dosage [9].

By investigating Figure 9b, the Area I flexural toughness of PVC-15 slab was determined to be 32% less than the Con slab. For both PVC-15 and Con slabs, the slabs appeared cracking and ultimate deflections at the same time with an 8.3% difference in the ultimate load. Additionally, the Area II and Area III were almost 300 and 400 kN-mm toughness, respectively, for both slabs. It should be highlighted that the PVC-30 slab exhibited an 8% decrease in total area toughness compared to the Con slab, while for PVC-60 slab toughness, the total area showed 26% less. The Con, PVC-15, PVC-30, and PVC-60 slabs' failure deflection was ranged from 28 to 29 mm at failure load. Based on the reductions in the toughness and flexural strength capacity due to the incorporation of high PVC fine aggregate dosage, improving the slabs with PVC fine aggregates is warranted. In the next section, two approaches were used to strengthen the slabs with PVC fine aggregates. The first approach is adding PVA to the concrete mix to improve the concrete mechanical properties, while the second approach is by using two fiber wire mesh layers as an additional reinforcement in the tested slab.

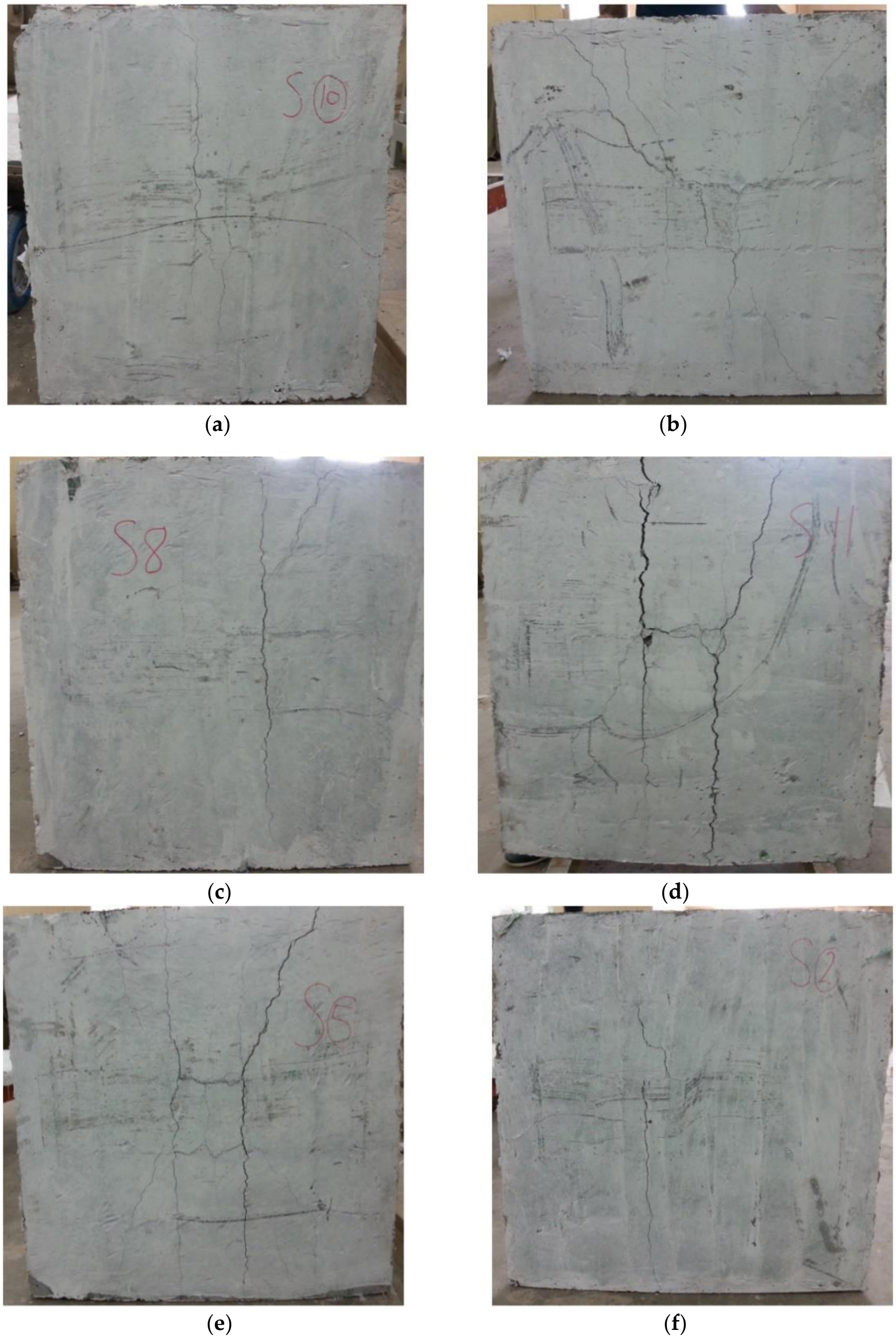
5.2.2. Comparison between PVC Concrete Slabs and Enhanced PVC Concrete Slabs

In this section, the flexural testing program was used to identify the effect of the enhanced mechanical properties and structural performance on the flexural behavior of the PVC fine aggregate concrete slab. Figure 8d,e presented the enhancement effects of PVA and fiber wire mesh layer on the load-deflection curves, respectively. As listed in Table 7, the ultimate load and failure load were improved by 20.8% and 80.3% for the PVC-60-PVA slab, as well as 10.4% and 65.0% for the PVC-60-Fiber slab, compared to the Con slab. On the other hand, these improvements were to be two times compared to the PVC-60 slab without any enhancement. The scale of increase in the ultimate load after the first crack is considerably associated with the improvement in the tensile strengths. It should be emphasized that the improvement of the flexural performance for the PVC-60-PVA slab was greater than the PVC-60-Fiber slab. This enhancement in the PVC-60-PVA slab performance was relative to improving the transition zone strength between the aggregates and cement matrix using PVA material to the concrete mix [29]. For the ultimate load, the tested PVC-60-PVA and PVC-60-Fiber slabs showed approximately 58.3 and 53.1 kN, respectively. Additionally, the PVC-60-PVA slab enhanced using PVA material exhibited the highest ultimate load value, among other tested slabs. In comparing the two approach effects on the slab flexural behavior, the PVC-60-PVA slab with the inclusion of PVA material outperformed the using fiber wire mesh layer by providing the most considerable enhancement, including ultimate and failure loads, as shown in Table 7. This performance is mainly attributed to an increase in bonded strength between the aggregates and cement matrix. Although PVC-60-Fiber slabs have a tensile strength of 1120 MPa, PVC-60-PVA slab reinforced with improving the cement matrix showed better flexural behavior, representing that utilizing PVA is enough to enhance the mechanical properties. Furthermore, a high crack resistance M-PVC75-PVA concrete was achieved compared to the other concrete mixes due to the improved strength of the transition zone region to the concrete matrix.

As shown in Table 7, it should be noted that the addition of PVA to the M-PVC75 concrete mix decreased the brittleness of the concrete compared to the PVC-60-Fiber slab. This performance was primarily due to increases in the tensile and compressive strength attributed to the formation of the concrete matrix by creating a denser microstructure during the hydration process of cement phases [60]. For the slab reinforced with fiber wire mesh, post-cracking behavior was the highest among all other tested slabs, as shown in Figure 9b. However, the PVC-60-PVA slab displayed exhibited better ductile performance in Area I and Area II. Consequently, the inclusion of PVA in the concrete with 75% PVC plastic waste fine aggregate replacement greatly influenced the pre-and post-cracking ductile performance among other slabs, representing that using PVA with higher contents might increase the flexural performance. Therefore, due to the substantial effect of PVA material on the concrete flexural performance, it is proposed to utilize PVA with an optimum 75% PCV fine aggregate in the concrete mix.

5.3. Cracking Patterns and Failure Mode

Failure modes of the slabs are shown in Figure 10. Figure 10a–f is a photograph of Con, PVC-15, PVC-30, PVC-60, PVC-60-PVA, and PVC-60-Fiber slabs, respectively, after testing. It was detected that flexural cracks began at the mid-span during the test and spread to the slab edges along with the support lines. The results demonstrated the benefit of utilizing the steel frame system for flexural measures applying loading lines. Figure 10a,b displayed the crack patterns for the Con slab. These cracks were spread in an inclined path at the bottom surface (tension side) and propagated from the center of the slab in the direction of the corners. For both Con and PVC-15 slabs, the first crack was spotted at an applied load of 12.4 and 11.9 kN, respectively. The slabs were failed when the load reached 48.1 and 44.4 kN, respectively. Then, both slabs showed a ductile performance because of the steel reinforcement. For the PVC-30 slab, at an applied load of 10.2 kN, the first crack was developed parallel to the support line. Figure 10c reveals the failure occurred as the load arrives at 22.0 kN, which is less than the Con slab's load by 13.4%. The ultimate load of PVC-30 slab with respect to Con slab was decreased by 8.8%. Therefore, cast PVC concrete mix in tension zone only (the lower half of the slab) exhibited similar behavior to the control slab behavior. It can be noticed that the ultimate loading capacity of slabs that contains a concrete layer on the bottom containing a PVC fine waste aggregates instead of 75% sand volume with thickness 25% and 50% of the total slab.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 10. Failure mode of (**a**) Con, (**b**) PVC-15, (**c**) PVC-30, (**d**) PVC-60, (**e**) PVC-60-PVA, and (**f**) PVC-60-Fiber slabs.

By investigating Figure 10d and Table 7, for the PVC-60 slab containing 75% PVC fine waste aggregates replacement, the first crack began at the mid-span of the slab at the load of 8.5 kN. The failure took place as the applied load reached 18.45 kN, which is lower than the Con slab by 27.9%. The ultimate load capacity was reduced by 22.9% compared to the Con slab. In addition, the ultimate deflection was increased by 14.3% compared to the Con slab, and the slabs become more ductile at failure with wide cracks compared with other slabs (see Figures 10d and 11). Adding PVC fine waste aggregates reduced the compressive strength of concrete by decreasing the bond between cement paste and aggregate. When the slabs were cast with the PVC fine aggregate concrete, there was a dramatic change in the load-deflection behavior, especially in ultimate load capacity compared to the control slab.

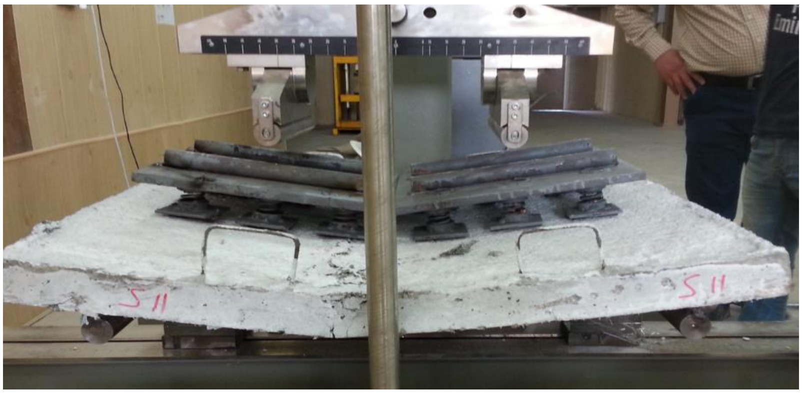


Figure 11. Ductile failure of slap PVC-60.

In this study, the two approaches were used to enhance the reduction in ultimate strength caused by using PVC fine waste aggregates with high dosage. Figure 10e shows the crack patterns of the PVC-60-PVA slab, where its first visible cracks appeared at load about 13.9 kN at mid-span. Additionally, some fine cracks were initiated along with the main cracks in the PVC-60-PVA slab. The slab failed at a load of 45.8 kN, with a raise in the ultimate load by 20.8% compared to the Con slab. It should be emphasized that the crack configurations of the PVC-60-PVA slab looked widely spread in an inclined path toward the corners as the load raised. The failure mode for the PVC-60-PVA slab was the same pattern as the Con slab failure mode, as shown in Figure 10. Therefore, adding PVA to the concrete mix, which increases the cohesion between concrete components, increased the ultimate strength more significantly than the control slab (normal concrete slab). Contribution of PVA in the concrete mix, to handle the PVC fine waste aggregates, increased the load-carrying capacity by 20.8% from the control slab.

For the second approach, using fiber wire mesh in the slab containing PVC fine waste aggregates, instead of 75% sand volume, enhanced the ultimate loading capacity by 10%, with respect to the control slab. Additionally, the maximum ultimate deflection was decreased by about 45.7%. This change is due to the contribution of fiber wire mesh in a tension zone as additional reinforcement and the confinement in the compression zone. The smaller crack opening in the PVC-60-Fiber slab was noted in Figure 10f and further continued the loads compared with the Con slab. As a result, the fibers wire mesh significantly decreased the cracks' width compared to the other slabs. As a result, the best approach that impacts the flexural performance and slab toughness of PVC fine aggregate concrete is achieved, incorporating PVA material in the concrete mix to provide the most substantial mechanical effect compared to the fiber wire mesh approach. Similarly, adding PVA material in the concrete mix was a better approach to improve the strength of the PVC concrete slab in terms of the quick, efficient, and economical construction comparing to the fiber wire mesh approach.

6. Conclusions

Plastic waste materials are used in various engineering applications to eliminate or decrease the accumulation of these materials in the environment. The use of plastic waste aggregates in the concrete impacts the fresh and hardened concrete performances reducing workability, density, flexural strength, compressive strength, and tensile strength. Based on the reductions in the toughness and flexural strength capacity due to the incorporation of high PVC fine aggregate dosage, improving the slabs with PVC fine aggregates is warranted. Therefore, two approaches were used to strengthen the slabs with PVC fine aggregates. The first approach is to add PVA material to the concrete mix to improve the concrete mechanical properties. The second approach is to use two fiber wire mesh layers as an additional reinforcement in the tested slab. Based on the results, the significant points are concluded:

(1) For the concrete slab containing PVC fine waste aggregates as a total replacement, the ultimate load capacity was reduced by 22.9%. The ultimate deflection was also increased by 14.3%, and the slabs become more ductile at failure.
(2) The ultimate load capacity of slabs that contained a concrete layer, on the bottom, containing PVC fine waste aggregates with thickness 25% and 50% of total slab thickness receded slightly lower by 8.30% and 8.8% than the Con slab, respectively.
(3) The addition of fiber wire mesh to the slab containing PVC fine waste aggregates, instead of sand, as a total replacement enhanced the ultimate load capacity by 10% with respect to the control specimen. Additionally, the ultimate deflection was decreased by 45.7%.
(4) At higher plastic aggregate content, flexural strength reduction was more noticeable due to the weak strength of the transition zone region between PVC particle and cement matrix related to the accumulation of free water. However, adding the PVA in the concrete mix increased the ultimate load capacity by 20.8% from the control slab.
(5) Using fiber wire mesh was a better approach to re-strength the PVC concrete slab than using PVA material to cast concrete slabs containing PVC fine waste aggregates in terms of the ultimate deflection and the cost. On the other hand, the best approach that impacts the flexural performance and toughness of slab containing PVC fine aggregate concrete is achieved, incorporating PVA material in the concrete mix to provide the most substantial mechanical effect compared to the fibers wire mesh approach.
(6) Also, Adding PVA material in the concrete mix was a better approach to re-strength the PVC concrete slab than the fiber wire mesh approach in terms of the quick, efficient, and economical construction. It is also feasible to use an optimized PVC fine aggregate in structural components to decrease structural elements' concrete density, resulting in lower concrete consumption.

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