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INVESTIGATION OF DUCTILITY OF PVA FIBRE REINFORCED BEAMS

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ABSTRACT

The current work aims to investigate the behaviour of PVA fibre reinforced beams under four-point flexural test in which the judgment is based on the peak load resistance and the ductility. To achieve this aim, four beams, which are reinforced with PVA fibres and conventional reinforcement bars are tested. Three fibre percentages (0.5, 1.0, and 1.5 %) are used, the behaviour of these beams are compared with the control beam of plain concrete. The results showed that the inclusion of 0.5 % of fibre increases the compressive strength by 48 %, the first cracking load by 104 %, and the ultimate strength by 10 %. And also, the inclusion of 1.5 % of PVA increases the beam ductility factor by 63 %. Moreover, the mentioned improvements are also affects the load initiate the first crack and crack depth of the compression zone, where the load resistance of the compression zone is increased by 8 % for that beam with 1.5 % of PVA compared to the beam of plain concrete.

ÖZET

Mevcut çalışma, PVA elyaf takviyeli kirişlerin davranışını, maksimum yük dayanımını ve sünekliğini göz önünde bulundurarak dört noktalı eğilme testi ile araştırmayı amaçlamaktadır. Bu amaca ulaşmak için, PVA elyaf ve geleneksel donatı çubukları ile güçlendirilmiş dört kiriş test edilmiştir. Üç elyaf yüzdesi (0.5, 1.0 ve 1.5) kullanılmıştır, bu kirişlerin davranışı yalın beton kontrol kirişi ile karşılaştırılmıştır. Sonuçlar, % 0.5 fiber eklenmesiyle basınç dayanımının % 48, birinci çatlama yükünün % 104 ve nihai dayanımımın % 10 arttığını göstermektedir. Ayrıca, PVA'nın % 1.5 oranında eklenmesi kiriş süneklik faktörünü % 63 arttırmaktadır. Bunlara ek olarak, bahsedilen iyileştirmeler, sıkıştırma bölgesindeki ilk çatlağı başlatan ve çatlak derinliğini etkileyen yükü belirler; buradaki basınç bölgesinin yük dayanımı, normal beton kirişine kıyasla % 1.5 PVA lifli kirişte % 8 oranında artmaktadır.

INTRODUCTION

The best interaction between the flexural strength and shear strength is a main factor that applied an preferable behaviour of structural members. The brittleness of the shear behaviour of the beams was attracted great attention, through enhancing the tensile strength of beams. Employing the short fibres that randomly distributed is one of the best and low costs reinforced materials, which is also enhancing the post peak behaviour. Using fibres in construction are old concept, where the straw can be the first fibre like materials uses as intrinsic reinforcement to the muddy blocks [**1**]. The modern usage of the fibres have started in early of the 20th century, when the asbestos cements are produced. Recently, many types of fibres are produced, ACI 544 [**2**] classified four types of fibres that are widely used nowadays, Steel Fibre Reinforced

Concrete (SFRC), Glass Fibre Reinforced Concrete (GFRC), Natural Fibre Reinforced Concrete (NFRC), and Synthetic Fibre Reinforced Concrete (SNFRC).

Polyvinyl Alcohol (PVA) can be classified as a part of SNFRC. Since early 1990s, PVA has been widely used as intrinsic reinforcement, which is introduced as new Engineering Cementitous Composite (ECC) materials. PVA fibre is known by its high strength compared to the reinforcement bars, its durability in alkali media, and the high bond with the cementitous materials. Introducing PVA in ECC shows significant effect in the cementitous matrix. The pseudo ductility of the PVA-ECC can be attributed to the water attractive nature of the PVA, in which it increases the bond between the fibres and the high fine particles matrix, which allows bridging the cracks and transfers the load between the different parts of the matrix [**3**].

According to ACI Terminology [**4**], the ductility can be defined as the ability of the beams to hold the deformation before failing, this ability has to be in inelastic range without decreasing in beam strength, therefore the beam ductility factor can be evaluated by dividing the ultimate deformation by yield deformation. On the other hand, Park [**5**] states four definitions for each deformation (Ultimate and yield), the first is the deflection corresponding to the first yielding point (which the first reinforcement bar is yielded). This point is often hard to be evaluated from the load-deflection curve, therefore it can use other definitions, such as using equivalent elastoplastic yield point, equivalent elastoplastic energy absorption, and/or using reduced stiffness equivalent elastoplastic yield [**6**]. Figure 1 depicted these definitions.

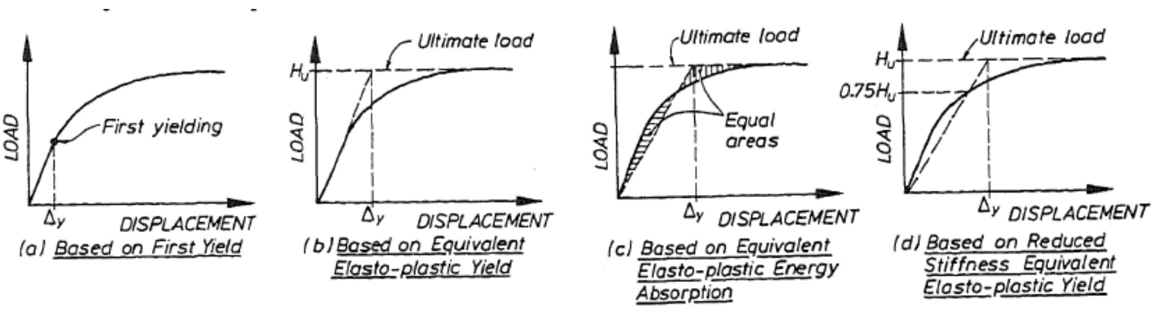


Figure 1. Yield displacement definition according to Park [5]

In spite of the great attention that is given on the performance of the mechanical properties of PVA/ECC, there has not been much investigation on the structural behaviour of PVA fibres added to conventional concrete (PVA/FRC) [**7**] [**8**]. Noushini et al. [**7**] found that inclusion 0.25 % of PVA with conventional concrete increased the ductility by 13 %, while duplicating this percentages led to increasing the ductility factor by 30 %. In the current work, a matrix with high fine aggregate content is used to cast four beams with different PVA percentages, so that the binder surfaces areas are increased ten times (because of using the silica fume). The presence of the high percentage of fine aggregates is participating in good distribution of stress alongside with the three directions of beam, moreover, enhancing the bond between the fibres and the coarse aggregate, and early gaining strength, because of the high contact particles area. All previous improvements led to improving the post-behaviour of the beams.

EXPERIMENTAL WORK

Materials

This research aims to employ the PVA fibre to reinforce beams in addition to conventional reinforcing bars, the fibres properties are summarized in Table 1. Three dosages of (0.5, 1.0, and 1.5 %) fibres of 12 mm length and 0.015 mm diameters are used. To investigate the effect of the fibre on reinforced normal concrete, moreover, in order to improve the stresses flow through the beams section and enhancing the bond between the matrix and the fibres, a concrete with high fine aggregate is used. In addition, the binder surface area is increased by using silica fume by 7 % of the total binder weight (cement + silica fume), which increases the surface area from 40 to 100 times. CEM II/ A-LL 42.5 R type of Portland cement that agrees with EN 197-1 provisions was used.

Table 1. PVA Fibres characteristics

Density (kg/m^3)	*Length* (mm)	*Diameter* (mm)	*Aspect ratio* (mm/mm)	Tensile strength (MPa)	Elastic modulus (GPa)
1260	12	0.015	800	1600	34

Mixing and curing

The mix is designed to achieve 28 days compressive strength of 30 MPa of normal concrete, and it is expected to be increased due to inclusion of the PVA fibres. The materials volume proportions are summarized in Table 2. Firstly, dry fine and coarse aggregate (river sand and crashed stone) were mixed together for 10 minutes, once the mix shows a consistence form, the cementitous materials are added, and the mixer revolute for another 5 minutes, water then gradually added, the slump are checked in this stage, the water reducer were added prior to adding the fibres. The fibrous concrete was poured in wooden beam moulds and six standard cylinders of 100 mm diameter and 200 mm height, to override the errors, three cylinders are used for each standard test. After 24 hours, both beams and cylinders were removed from the moulds and cured in water tanks of 22 ºC for 28 days.

Table 2. Concrete mixture amount per cubic meter

mix code	V_f† (%)	C kg	G kg	S kg	S.fm kg	HWR kg	W Lt
N	-	465	680	1170	35	6.6	216
PVA0.5	0.5						
PVA1.0	1.0						
PVA1.5	1.5						

† V_f is the fibre volume fraction, **C**; Cement, **G**; Gravel, **S**; Sand, **S.fm**; Silica fume, **HWR**; High water reducer, **W**; Water

Geometry and test setup

In order to compare the ultimate load resistance and the ductility of the PVA-FRC beams, four beams of 150 × 150 × 850 mm were casted. The beams are reinforced on tension zone by three ϕ 8 mm flexural reinforced bars, and two more bars on compression part, ten stirrups of ϕ 6.3 are included as shear reinforcement, the yielding strength of the ϕ 8 mm and the ϕ 6.3 mm bars were 503 and 558 MPa respectively. Figure 2 shows the geometry and reinforcing details of the beams used in test.

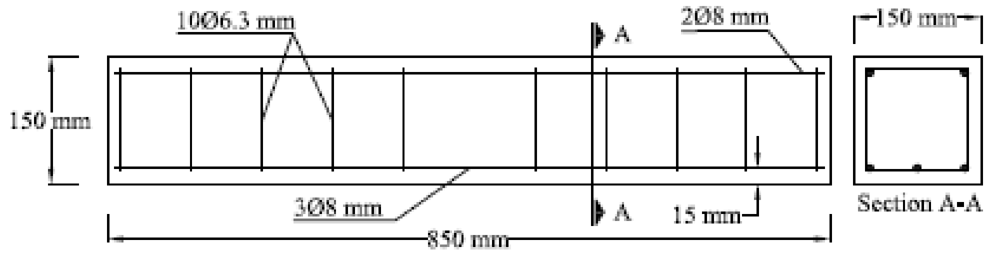
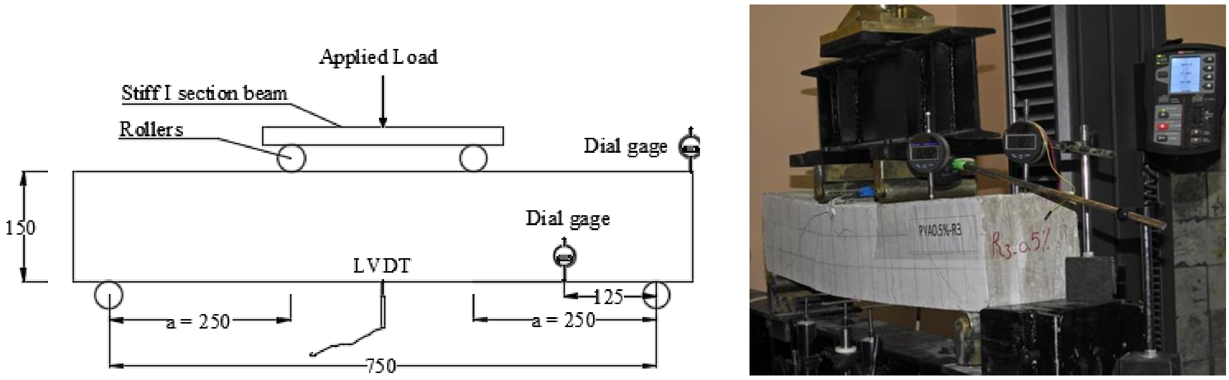


Figure 2. Geometry and reinforcement details

The beams are tested by using four-points simply supported configuration, the distance between the loading point and the support (a) is 250 mm, so that the shear arm (a/d) is 1.85 (Figure 3), using INSTRON test machine, the load applied in displacement control mode of 0.4 mm/min loading rate. The load is applied until the specimen fails. Figure 3 shows the test setup, A special made support is attached to the device, so that the load applied by two stiff roller and beams are supported by two roller, the roller is used for freely rotation of the beam without a significant resistance. Most resistances are due to friction induce from axial forces. In addition to the jack displacement measurement, one more LVDT is attached to the beam at mid-span from bottom side. Two dial gages were used to measure the edge lifting and the deflection at the quarter distance of the beam (125 mm from the support).



(a) (b)

Figure 3. Beams test setup (a) Location of the LVDT and the dial gages (b) test configuration

TEST RESULTS AND DISCUSSION

In order to overcome the errors, average of three cylinders of 100 × 200 mm are tested for both compressive strength (f'_c) and tensile strength (f_{sp}), Table 3 summarizes the test results and the age of the specimens and beams at the test moment. Figure 4a shows the effective compressive and tensile strength (in term of splitting) by PVA as a unity for plain concrete. It is clear from Figure 4(a) that the f'_c is significantly affected by the inclusion of fibre, where adding 0.5, 1.0, and 1.5 % increases the compressive strength by 47, 42, and 44 %, while the f_{sp} is not affected. ACI318-14 [**9**] defined the relation between the f_{sp} and the f'_c in terms of square root as $f_{sp} = 0.56\sqrt{f'_c}$, this correlation is valid for plain concrete. Fig. 4(b) depicted the relation between f_{sp} and f'_c that governs the FRC used in current work. It is clear that for normal concrete, the correlation factor ($f_{sp}/\sqrt{f'_c}$) is higher than 0.56 (adopted by ACI318) by approximately 100 %, this is attributed to the good stress distribution due to proper distribution of the matrix particles. For PVA reinforced concrete, the correlation factors are reduced due to high sensitivity of the compressive strength to the inclusion of the PVA.

Table 3. Concrete mechanical properties

Spec.	PVA V_f (%)	Age (days)	f 'c (MPa)	f_{sp} (MPa)
N	0	62	30	6.56
PVA0.5	0.5	52	44.36	6.74
PVA1.0	1.0	49	42.86	6.17
PVA1.5	1.5	49	43.38	6.56

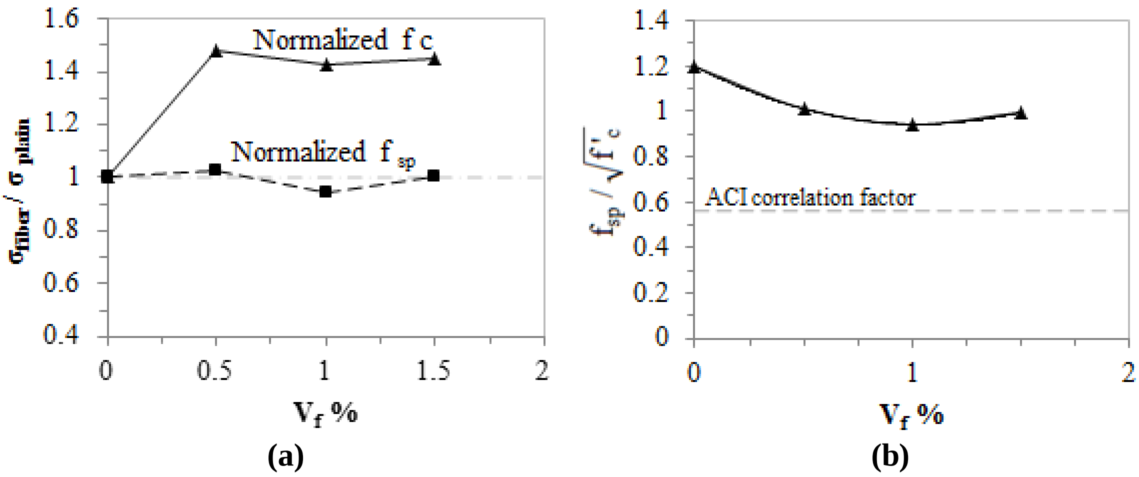


Figure 4. Effect of PVA on concrete strength (a) effective PVA-FRC compressive and splitting tensile strength as a unity for plain concrete (b) correlation of splitting strength to square root compressive strength in PVA reinforced concrete

Table 4 and Figure 5 shows the four characterized resistance load and their corresponding displacement. It can be clearly seen from Table 4 that the inclusion of PVA fibres is significantly enhanced the first crack load (P_{cr}) and the ultimate load P_u, but the yielding loads are not affected because they are depending on the reinforcement bars. The first crack resistance loads are increased by 82, 96, and 104 % for beams of 0.5, 1.0, 1.5 % PVA respectively, moreover, the ultimate loads are increased by 6, 8, and 10 % respectively, this means that the elastic portion of the load-deflection curve (Figure 5) is extended and the concrete cover plays an important role in beam's behaviour under serviceability load. Figure 7 shows the improvement of the ultimate resistance load.

Figure 5 shows the load-deflection curves for the tested beams, the curves are separated (2 mm between each curve) in order to clarifying the behaviour. For these curves, the data is collected from LVDT attached to the beam at mid-span from bottom side. From Figure 5, there were nonlinear extraneous displacements, because it is often associated to such a test. Up to the first initiation crack, the displacement is proportional to the applied load linearly, the first cracks are hardly and carefully located on the curve, After first crack, the curve slope is slightly changed but still looks to be in linear increasing rate, the increasing rate continues up to yield point. After yielding of the reinforcement, the curves are increasing in nonlinear manner up to the maximum resistance load, the test is continuing until the beam is collapsed. The beams include 1.0 and 1.5 % PVA show more deformation than the N and PVA0.5 up to yield point, the maximum deflection is achieved by PVA1 and PVA`1.5 that is increased by 41 and 47 % respectively compared to the normal concrete beam, while 25 % was achieved by PVA 0.5.

Table 4. Beams test results

Spec.	P_{cr} (kN)	δ_{cr} (mm)	P_y (kN)	δ_y (mm)	P_u (kN)	δ_u (mm)	$\frac{P_{cr}}{P_u}$	μ	μ_{fiber}/μ_{normal}
N	12.59	0.19	78.77	2.74	90.75	9.20	0.14	3.36	1
PVA0.5	22.95	0.23	85.45	2.62	96.62	11.51	0.24	4.38	1.30
PVA1.0	24.72	0.26	79.75	2.44	97.99	12.95	0.25	5.30	1.58
PVA1.5	25.63	0.64	81.27	2.46	99.95	13.50	0.26	5.49	1.63

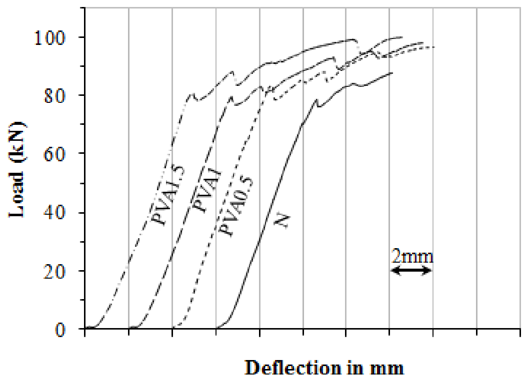


Figure 5. Load-deflection curves for all tested beams (except specimen PVA1.5, remain deflections are extended 2 mm in order to clarifying the curves)

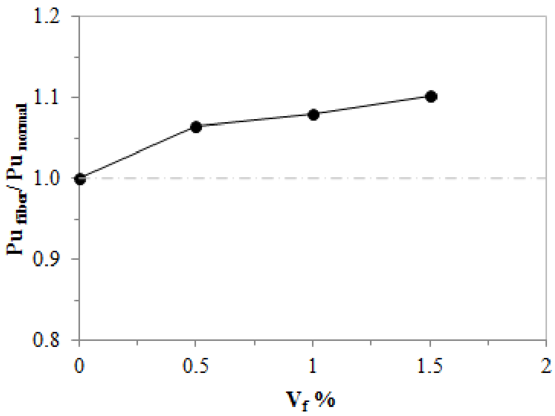


Figure 6. Effect of PVA on beam ultimate load resistance

The ductility factor (μ) defined herein, as the proportional of the ultimate deformation (δ_u) to the yield deformation (δ_y), where the ultimate deformation is that the deformation corresponding to the maximum resistance load, and the yield deformation is that the displacement corresponding to the yield load. Figure 7 demonstrates the evaluation of ductility factor (μ) considered in current work. Figure 8 depicted the effect of PVA dosages on the μ, Table 4 summarized the values of the μ and the ductility of the fibrous beams as unity for plain concrete. The comparison showed that the including of PVA in the concrete increases the ductilities of the tested beams. Where 0.5 % of PVA increases the ductility by 30 %, duplicating the volume of PVA approximately duplicated the enhancement of ductility (58 %) compared to 0.5 % V_f. Increasing the PVA to 1.5 % is not significantly altered then 1 %, where μ is increased by 63 %.

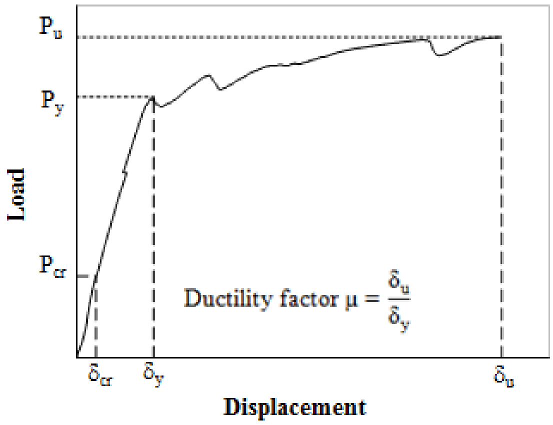


Figure 7. Definition of the ductility factor (μ)

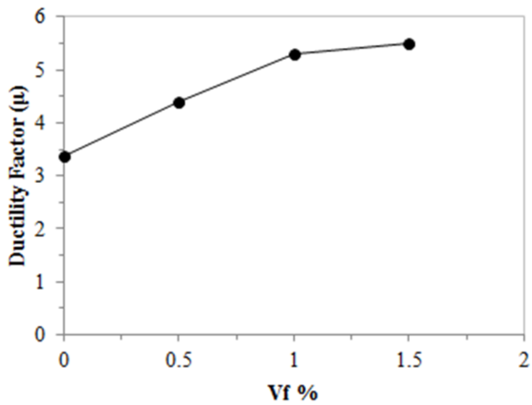


Figure 8. Effect of PVA on ductility factor (μ)

The beams were tested based on 4-points flexural test, the load is applied beyond the maximum resistance load and continued until the specimen fails. Camera is programed to take a photo every 5 minutes, as it appears in Figure 3b. From the taken photos, the load required to initiation first crack at compression zone (area between the applied load rollers) is listed in Table 5. It shows that the inclusion of PVA is not just improving the maximum load resistance, but also increasing the load required to initiate the cracks at the compression zone (top edge of beam). Furthermore, the inclusion of 1.0 and 1.5 % of PVA increased the flexural cracks number that increases the curvature of the beam which leads to reducing the stress on compression zones.

Table 5. initiation and shape of first crack at compression zone

Specimen	**Load to initiate first compression crack** (kN)	**Crack distance from upper fibre** (mm)	**Shape of crack**
N	87.3	50	V-shape
PVA0.5	87.54	45	Trapezoidal
PVA1	89.2	21	horizontal
PVA1.5	94.4	15	Very small

The shear cracks at beam of normal concrete are extended from the support up to the loads points, whereas inclusion the fibres are decreased the shear effect, this can be recognized from the uncompleted shear cracks at beams of PVA-FRC (Figure 9).

Figure 9. Crack patterns of the tested beams

CONCLUSION

The following conclusion is derived from the results obtained through the discussions,

a- Compressive strength is increased significantly by about 47 %, when PVA is used, whereas the tensile strength is not affected.
b- Using of PVA fibres in concrete made from high fine aggregate percentages are increases the load required to initiate the first crack, and the ultimate load resistance, where using 1.5 % of PVA are increases to ultimate load by 10 %..
c- The PVA-FRC beams maximum deflection are increased compared to the plain concrete beams by 47 %.
d- Fibres transferred the brittle type failure to the flexural failure by discontinuing the shear cracks.
e- By increasing the post-cracking, the ductility of the beams is increased significantly where inclusion of 1.0% to 1.5 % of PVA, the ductility is increased 58 to 62 %.
f- Compression resistance is increased with increasing the fibre content, moreover the compression cracks failure also varying in its shape and distance from the upper fibre.

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