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Tests on workability and strength of high strength-flowable concrete containing PET waste fiber

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Abstract

This study describes two workability tests, compressive strength and tensile strength tests of high strength flowable concrete containing plastic fiber prepared from polyethylene terephthalate (PET) waste bottles. For the high fluidity mix Vebe time and V-funnel time tests were carried out. Results show that there is a Vebe time increase with PET fiber addition to concrete being increased with increasing fiber volume and fiber length. V-funnel time was found to reduce when up to 0.75% fiber volume is added to concrete, followed by an increase for larger fiber volumes. When fiber length is increase, there is more time increase, but in general, V-funnel time increase was lower than that of Vebe time, indicating a different influence of PET fiber on the compactibility and flowability. The measured V-funnel time for all mixes was found to conform to the limits of European specifications on the flowability of self compacting concrete. Small descending in compressive strength was recorded for RPET fiber reinforced concrete that reached 15.74 % for 1.5 percent fiber content with 10 mm fiber length. Attractive results was recorded in split tensile strength of RPET fibrous samples which resulted in improvement up to 63.3 % for 1.5 percent of 40 mm fiber length content .

1. Introduction

Polyethylene terephthalate (PET) is one of the thermoplastic polymers, widely used beside other polymers for different purposes, such as beverage containers since the late 1970s. The amount used has increased steadily and continuously, but the majority of PET bottles used are now discarded, causing major problems in terms of resource utilization and the environment. In the United States, which first began using PET bottles, efforts have been made to recycle used PET bottles since the late 1980s, and the amount of recycling has gradually increased (Choi *et al*. 2005 p.776-

781). Research on recycling used PET bottles as construction materials has been conducted worldwide. One idea is to use recycled PET bottles as unsaturated polyester resin to apply to polymer concrete. Another idea is to use PET as a filling material for lightweight concrete. Other examples include the use of PET fibers as concrete reinforcement materials (Won *et al.* 2010 p. 660).

Workability is a fundamental property of fresh concrete. In simple words, workability means the ease of placement and compaction without any segregation. The desired workability is not the same for all types of concrete. More workability is required for a thin inaccessible section or heavily reinforced section rather than a mass concrete and cement mortar body, Workability can also be defined as the amount of useful internal work necessary to produce full compaction, Or, Workability of concrete is defined as the ease of concrete that can be mixed, transported, placed and finished easily without segregation (Neville and Brooks, 2010 pp.77-93).

Among those tests used for measuring workability of concrete, slump test is used extensively to assess workability of concrete in laboratory and at the site. This test is conducted per ASTM C 143 specification (ASTM C143, 2005. pp. 1-2). For very wet mixes or mixes containing a relatively large amount of plasticizers there is a collapse mode of slump. So, on these circumstances there are a need to assess workability using other tests.

One of these tests is Vebe test as described in EN 12350-3 (EN 12350-3, 2000 pp. 3-4), which is suitable to measure the behavior of concrete subjected to external vibration and is acceptable for determining the workability of concrete placed using vibration, including fiber reinforced concrete (FRC). It effectively evaluates the ability of fiber reinforced concrete (FRC) to flow under vibration, and helps to assess the ease with which entrapped air can be expelled (ACI 544.2R-17, P.3).

Soroushian *et al.* (1992 pp 537) conducted an investigation on low-percent PET fibrous concrete. They noted that to achieve fresh mixtures with reasonable workability [represented by a slump of (29 to 47) mm for plain mixes and a Vebe time of (10 to 15) sec for fibrous concrete mixes], and a desirable level of air content (about 10 percent), superplasticizer should be introduced to the mix, since adding fiber to concrete reduces workability. Ochi *et al.* (2007, pp. 450-451) reported that addition of plastic fiber provides poor workability for normal strength concrete (NSC). They found that the slump of control mix reduced from 16.5 cm to 16, 3.5 and 4 cm for 0.5, 1 and 1.5% of PET fiber, respectively. Pelisser *et al.* (2012, pp. 681-682) observed that for very low fiber volume content up to (0.05%), workability is increased, while, for 0.18% and 0.3% contents slump was decreased to 70% and 50%, respectively. Nibudey *et al.* (2013, p 170 & 178) reported the effects of plastic fibers with aspect ratios (length divided by diameter of fiber) of 35 and 50 on the workability of concrete when they added the plastic fiber to the concrete up to 3% by weight of cement with 0.5% increment. The plastic fiber was added to concrete up to 3% by weight of cement with 0.5% increment. The workability was started to decrease with increasing plastic fiber in concrete mix. Slump of control concrete was 67 mm for the M30 grade of concrete, and found to decrease to 32 mm and 22 mm for 3% PET fiber volume with aspect ratios of 35 and 50 respectively.

Prahallada and Prakash (2013 pp. 9-11) studied the effects of adding fibers at different aspect ratios on the workability of concrete. Waste plastics with aspect ratios of 30, 50, 70, 90 and 110 were used. The workability was increased for concrete mix with fiber up to an aspect ratio of 50. However, further increases in the aspect ratio resulted in decreases in the workability. The poor workability after including plastic fibers with larger aspect ratios potentially resulted from the hindrance imposed by plastic fibers during the flow of concrete. Marthong (2015 pp. 114-115) observed that size of PET fiber has a major role in decreasing slump regardless to the shape of the fiber at lower volume fraction content of 0.5%, decreasing in slump was 15% for small sized fiber and 35% for large sized fiber, while, for 1%

volume fraction the reduction in workability was 50% for all types of fibers regardless of shape and size of fiber. Marthong and Sarma (2015 pp. 2-3) tested workability of four types of fibers (namely: straight, flattened end, deformed and crimped) containing 0.5% fiber fraction volume with and without superplasticizer. They reported that adding superplasticizer by 0.82% of mixed-water volume minimized the drop of slump about 35% for all types of fiber compared to the same mix without fiber. Furthermore, Wilinski *et al.* (2016 pp. 1-8) reported that addition of recycled PET (RPET) fiber to NSC having lower W/C ratio (0.45) without superplasticizer by 0.1 and 0.3% fraction volume, can decrease slump by 50% and 90%, respectively.

Among the properties of hardened concrete, compressive strength and tensile strength are the most two important properties. Structural design of reinforced concrete members is highly dependent on the compressive strength, while cracking behavior of depends on the tensile strength. Since concrete is weak in tension, different kinds of fibers were added to improve the cracking resistance. There is a relatively large amount of works carried out to highlight properties of compressive and tensile strengths of normal strength concrete containing PET fiber (Siddique *et al*. (2008), Gu and Ozbakkaloglu (2016)). However, strength properties of high strength concrete containing PET fiber were not examined by the past researchers. Recently, experimental laboratory tests on high strength concrete with control compressive strength equal to 94.36 MPa were carried out by Mohammed and Faqe Rahim (2020). Parameters investigated were the fiber volume fraction and fiber length. Different percentages of compressive strength reduction were observed depending on the fiber volume, fiber length and hybridity (according to length). Maximum compressive strength loss of about 30% was observed on using long PET fiber. According to their test data, using short fiber in concrete leads to a relatively small strength loss. The compressive strength loss was attributed to the existence of flaws between the PET fiber surface and concrete, which was considered to be the source of cracks extension and rupture of concrete. With regard to tensile strength, there was a direct tensile strength loss ranging between 9.1% and 13.6%, and splitting tensile strength loss between 3.67% and 16.97%. Accordingly, the addition of PET fiber to high strength concrete has more adverse effect on compressive strength as compared with tensile strength of concrete.

The present study deals with the workability, compressive strength and splitting tensile strength of high strength- flowable concrete, reinforced with different volume fractions of PET waste fiber of different lengths. Two different methods were used in this study (Vebe test and V-funnel test) for determining workability of high strength concrete reinforced with PRT fiber The results are useful to highlight the workability variation of HPC contained such type of plastic fiber for practical structural applications.

2. Materials and preparation

2.1. Materials

Cement, water, sand, gravel, silica fume slurry and high range water reducer admixture were used in this investigation. The cement that used in this investigation was ordinary Portland cement (Type I ASTM). It was manufactured by Tasluja factory- Sulaimani/Iraq. The physical properties and chemical composition of the cement are shown in Tables 1 and 2, respectively. The results indicate that the cement properties are conforming to the ASTM C150 specification limits (ASTM C150, 2017 pp. 2-3). The fine aggregate was clean natural river sand, having a coarse grading obtained from Darbandikhan quarry. Sieve analysis test indicates that the gradation of sand is within the limits of ASTM C33 specification (ASTM C33, 2016 pp.2-4) as illustrated in Fig. 1. For the fine aggregate fineness modulus was 3.8, saturated surface dry specific gravity was 2.52, water absorption was 1.7%, loose bulk density 1877 kg/m^3, and dry compacted density was 1989 kg/m^3. Crushed stone with maximum size of 10 mm obtained from Tanjaro quarry was used as coarse aggregate. Sieve analysis was carried out and the grading was found to conform to ASTM C33 specification limits (ASTM C33, 2013 pp. 3-5) as shown in Fig. 2. For the coarse aggregate saturated surface dry specific gravity was 2.65, water absorption was 1.2%, loose bulk density 1454 kg/m^3,

Tap water was used for washing coarse aggregate, mixing concrete and curing specimens throughout the investigation. Silica fume slurry was used to produce high performance concrete with a dense matrix. Micro silica slurry of Admix MS560 type shown in Fig. 3 was used. According to the manufacturer report, solid content was found to be 40%, Specific gravity was 1.4, and PH was 9.5. High range water reducer admixture (HRWRA) used was Polycarboxylate based super-plasticizer (Gantre 99) provided by Idea company-Sulaimani. For the superplasticizer, specific gravity was 1.09, PH was 6, color was waxy and solid content was 33%.

The polyethylene terephthalate (PET) fiber used in this study, was prepared by hand cutting of post-consumer bottles. It is required to investigate the performance of low-cost reinforcing technique of concrete, which is based on the insertion of recycled polyethylene terephthalate (RPET) strips of various length. For this purpose, post-consumer bottles which they were randomly wasted were collected. The examined strips are obtained through hand cutting of post-consumer PET bottles with 17 L capacity and about 0.45 mm wall thickness. Hand cutting process was made by removing the neck and the base of the PET bottles by hand scissors. Then, the wall of the bottles were longitudinally cut in order to get corrugated RPET strips with (10, 20 and 40 mm) width and 300 mm length. In the final stage, the above macro-strips were transversally cut into a number of smaller strips having 2 mm width and three different lengths (10 mm, 20 mm and 40 mm) as shown in Fig.4. Furthermore, specific gravity of the PET fiber was found to be 1.35.

2.2. Mix proportion and test variables

The mix design of concrete referred to the process of deciding what type of raw material and how much of each raw material needs to be selected and mixed to make concrete that can provide requirements such as strength, durability and workability. The required properties of hardened concrete and the properties of fresh concrete are governed by the type of construction and by the techniques of placing and transporting. These two sets of requirements are the main factors that determine the composition of the mix, also taking account of the construction experience on site.

Mix design can, therefore, be defined as the processes of selecting suitable ingredients and determining their relative quantities, with the tenacity of producing an economical concrete that has certain minimum properties such as workability, strength, and durability.

For concrete mix design, the recommendation given by Aïtcin (1998, pp. 215-261) was followed to optimize target compressive strength of 80 MPa. The method of mix design was developed at the University of Sherbrook which is a modification of the (ACI 211, 1991) specification for mix design. Based on several trial mixes, the best mix was found that 28 days cube compressive strength equal to 88.73 MPa, with standard deviation.

A total of sixteen concrete mixes were prepared to investigate the effect of PET waste fiber parameters on workability of HPC. Plastic fiber volumes were 0, 0.5, 0.75, 1, 1.25, and 1.5%. Three types of plastic fiber were tested with constant cross sectional area and three lengths of 10 mm, 20 mm, and 40 mm. Concrete mixes are designed in table 4 as follows: M is for mix, 1, 2, and 4 are fiber lengths (in cm) and 0.5, 0.75, 1, 1.25, and 1.5 are fiber volume fractions.

Natural aggregates were prepared under the SSD state before blending, and PET fiber was used in a dry state. The cement, fine aggregate, coarse aggregate was weighed first and mixed homogeneously for about five minutes using an electrical rotary drum of 0.16 m^3 capacity. Then, 70% of the total mixing water added and after two minutes of mixing, the remained mixing water, silica fume slurry and HRWRA were also added. Finally, the PET fiber was spread gently on the mix to avoid fiber balling. Mixing was ceased after about five minutes when a homogenous mixture has been obtained.

3. Methodology

3.1. Vebe test

The slump test is a common, convenient, and inexpensive test, but it may not be a good indicator of workability for FRC. The addition of fibers hinders the flow behavior of the fresh concrete, especially if no adjustment is made to the mixture composition. An example is the rearrangement of coarse aggregate grading in consideration of the effects of fibers on the void ratio of the solid particle skeleton. Therefore, the addition of fibers can lead to a decrease in the measured slump with increasing the fiber factor, which is the product of the fiber volume fraction and the fiber aspect ratio. The rate of change in the measured slump with the fiber factor is directly related to the fiber type. Therefore, the Vebe consistometer test which described in EN 12350-3, (2000 p. 3), measures the behavior of concrete subjected to the external vibration is acceptable for determining the workability of concrete placed using vibration, including FRC. It effectively evaluates the ability of FRC to flow under vibration, and helps to assess the ease with which entrapped air can be expelled. Vebe test apparatus is shown in Fig. 5, and the procedure followed to perform this test is described here. The apparatus is placed on top of a vibrating table. Then, the fresh concrete is compacted into a conical slump mold with three layers. The mold is removed and a clear plastic disc is placed on the top of the concrete. The vibrating table is started and the time taken for the transparent disc to be fully in contact with the concrete (the Vebe time), is measured (ACI 544.2R-17).

3.2. V-funnel test

The V-funnel test is used to measure the filling ability of self compacting concrete (SCC) and can also be used to judge segregation resistance. The typical test apparatus is shown in Fig. 6. The test procedure followed in this study was done via the successive steps given below:

- The V-funnel was placed so that a container can be positioned underneath the funnel opening.
- The funnel's internal surfaces of V-funnel were damped by wiping with a squeezed wet cloth and the gate closed.

- V-funnel was filled in to its upper level with concrete. (11.2 liters capacity) without tamping or vibration
- The concrete was stayed for one minute in the V-funnel to rest.
- The gate was opened, timing started exactly when the gate was opened.
- The time was recorded for the all concrete to flow out of the V-funnel (Flow time = T_v).

3.3. Compressive strength

The measurement of concrete compressive strength was performed on the standard 150*300 mm cylinders using a digital compression machine of 4000 KN capacity of CONTROLS model-Italy, according to ASTM C39 (2012). 3 days before testing, all cylinders were capped using a sulfur- sand mix (1:1) to give a uniform stress distribution on the specimen's surface during testing. The loading rate was (0.25 MPa/sec) as per the ASTM C39 specification limit [0.15-0.35] MPa/sec. The average result of three tested cylinders was determined at the age of 28 days (ASTM C39, 2012 pp1-4).

3.4. Split tensile strength

This test method consists of applying a diametral compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs. This loading induces tensile stresses on the plane containing the applied load and relatively high compressive stresses in the area immediately around the applied load. Tensile failure occurs rather than compressive failure because the areas of load application are in a state of triaxial compression, thereby allowing them to withstand much higher compressive stresses than would be indicated by a uniaxial compressive strength test result. The measurement of concrete splitting tensile strength was performed on the 100*200 mm cylinders using the same machine utilized for compression test using loading rate of 1200 KPa/min as proposed (689 to 1380 KPa/min), according to ASTM C496 (2011). The average result of three cylinders was determined at the age of 28 days (ASTM C496, 2011 pp 1-3).

4. Results and discussion

4.1. Vebe time

Table 4 shows test results of Vebe time of different concrete mixes. Fig. 7 shows Vebe time (mix with PET fiber/ mix without fiber) variation with percent of fiber volume. For the control mix Vebe time is 6.86 sec being increased with increasing PET fiber in concrete mix, to a maximum value of 9.5 sec (38.5% increase), 13.5 sec (96.8% increase) and 15.21 sec (121.7% increase) at 1.5% fiber volume of 10 mm, 20 mm and 40 mm respectively. Fig. 7 show that the Vebe time for the mix of 10 mm length fiber is relatively small up to 1.25% fiber volume and there is sudden increase afterwards. This level is roughly 1% for the mix of 20 mm fiber and 0.75% for the mix of 40 mm fiber, as observed from Fig. 7. Consequently, Vebe time for a relatively large PET fiber volume (0.75%) is increased well with the increase in fiber length. The results owed to need of more vibrating time "without risk of segregation" to fiber reinforced mixes in order to reach the same compaction compared to the control mix, this increasing in the time varies depending on fiber length and fiber fraction volume. The test results agree with Ochi et al. (2007, pp. 450-451), in which they found a slump loss for normal concrete with PET fiber. The results are in good agreement with Nibudey et al. (2013, p 170 & 178) and Prahallada and Prakash (2013 pp. 9-11), in which they observed more slump loss for concrete mix with larger aspect ratio PET fiber. Test data also agree with the observation made by Wilinski et al. (2016 p.7) for concrete mixes with relatively low w/c ratio without superplasticizer.

4.2. V-funnel time

Table 4 shows test results of V-funnel time of different concrete mixes. Fig. 8 shows percentage of V-funnel time (mix with PET fiber/ mix without fiber) variation with percent of fiber volume. For the control mix V-funnel time is 9.71 sec. A reduction in the V-funnel time is observed with increasing PET fiber to 0.75% in general. Maximum reduction in V-funnel time is indicated at using 0.5% PET fiber in the mix of percentages between 19.2% and 22.1% for all different fiber lengths. Accordingly, the effect of fiber length on the V-funnel time is not important at low plastic fiber content. There is a recovery in the V-funnel time with increasing PET fiber up to 1%, and up to this fiber volume the effect of fiber length is less important except for fibers of 40 mm length. At 1% fiber volume there is 44.3% V-funnel time increase for mix with 40 mm fiber length. For larger fiber volumes there are relatively low V-funnel time increase of maximum value equal to 13.7% and 31.7% for fiber length of 10 mm and 20 mm, respectively. However, the increase for 40 mm length fiber is relatively high which is 83%. Since, V-funnel test is a measure of flowability of concrete, the existence of PET fiber in concrete mix has some effect on flowability of fresh concrete, especially when plastic fiber of large length is used. According to the data, up to 0.75% PET fiber volume has no effect on the flowability of concrete. This observation may be important for practical applications of using PET waste fiber in concrete.

According to the European federations: (BIBM, CEMBUREAU, ERMCO, EFCA, EFNARC 2005, p.46), for the viscosity class VS1/VF1, V-funnel time (T_v) is smaller than 8 sec, and for the viscosity class VS2/VF2, V-funnel time is between 9 and 25 sec. On the other hand, EN 206-9 (2010 p.505) prescribes limit values of V-funnel time (T_v) for the definition of funnel-viscosity classes VF1 if $T_v < 9$ sec and VF2 if $9 < T_v < 25$ sec of SCC and related classification.

It can be observed that the results in this study are with these limits of workability of self compacting concrete, the V-funnel times for concrete mixes contained 1%, 1.25% and 1.5% PET fiber are within the limits of viscosity class VS2/VF2. However, concrete mixes contained 0.5% and 0.75% PET fiber are classified as viscosity class of VF1, indicating a useful effect of addition of PET fiber up to 0.75% to concrete

It is of interest to compare the variation of V-funnel time with Vebe time with the existence of PET fiber in concrete tested in this investigation. The two cases are essentially different, while Vebe test concerns the ease of compaction using vibration, the V-funnel describes the ease of flowability. Therefore, it is not surprised to see different response because of PET fiber addition. In general, regardless of fiber volume and length, Vebe time increasing is larger than that of V-funnel as observed from Figs. 7 and 8. In particular, for the case of low fiber content (0.5%), the two behaviors are different, because fiber addition has a beneficial effect on V-funnel time, and hence the flowability, whilst there is an adverse effect on the Vebe time and hence the need of vibration for compaction. In other words, PET fiber has Positive effect on passingability and negative effect on compaction. The authors think that if the data obtained on V-funnel time is required to be compared with those of past investigation, there is need to review the past works on workability of self-compacting concrete with PET fiber, because V-funnel test is usually made on this type of concrete. Therefore, comparison observed with an investigation on self compacting concrete of design compressive strength equal to 50 MPa reinforced with PET waste fiber which was performed by Al-Hadithi et al. (2019 pp.4-7). PET fiber of 35 mm length and 4 mm width was added to concrete up to 2%. Their results showed an increase in the measured time from 7 sec to 16.5 sec at 2% PET fibers volume. The inclusion of low to moderate volumes of PET fibers (from 0.5% to 0.75%) did not show any significant effect on V-funnel time. However, even beyond the 1% PET fibers volume, the values of the funnel time were still within the limitations of EFNARC (2019). According to Al-Hadithi et al. (2019 pp.4-7) linear relationship was obtained between V-funnel time and PET fiber volume. As shown in Fig.8 there is no linear relationship between V-funnel time and PET fiber percentage tested in this study. The difference can be attributed to the fact that our mix is designed as high strength concrete of cube compressive strength 88.73 MPa, while the tested by Al-Hadithi et al. (2019) was normal strength of 50 MPa compressive strength. In addition, the difference may be due to the influence of wider PET fibers tested by Al-Hadithi et al. (2019) (i.e. 4 mm) compared with the 2 mm width PET fiber used in this study, also, may due to the difference with that of Al-Hadithi et al. (2019) in fine and coarse aggregate percent and type of super plasticizer that lead to pure self compacted concrete in Al-Hadithi et al. (2019) while, the current study used high strength flowable concrete.

4.3. Compressive strength

Compressive strength test results are shown in Table 5 for each mix, Figure 9 shows variation of HSC compression with fiber length and fraction volume, regarding to the results; it can be concluded that incorporating fiber to HSC reduces compressive strength for all mixes irrespective to the fiber length and volume fractions. Maximum compressive strength reduction outcome was 15.74, 14.37 and 10.28% for 10, 20 and 40 mm length RPET fiber respectively. Concluding that shorter RPET fibers weakened HSC structure more, due to feeble bond between RPET fiber and concrete paste, and had minimum support to strengthening of samples against compression load. There is a continuous strength reduction with increasing fiber volume up to 1.25% for the 10 mm length PET fiber. With increasing fiber length the strength loss will reduce. This may be because of the fact that longer fibers imparts resisting load against compression by bridging and improving post crack behavior of samples since long fibers has superior embedded part that improves friction provided maximum resistance against pullout. Typical mode of failure of samples showed sudden failure of control samples with rapid crushing while others that contained PET fiber displayed cracks up to failure as shown in figure 10.The test results are in harmony with those by Kim et al. (2010), but showed smaller reduction in compressive strength for the same fiber aspect ratio and fraction volume compared to previous studies like [Soroushian et al. (1992), Nibudey et al. (2013)]. This may be due to the existence of the supplementary material used in the mixes that provided pozzolanic reaction lead to an improved strength.

4.4. Split tensile strength

The variations of tensile strength for different concrete mixes are shown in Table 6, Figure 11 shows split tensile strength of HSC with different RPET fiber length and fraction volumes. Owing to good dispersions of fibers which resulted in a better bridging action in concrete matrix, the concrete containing no fibers suddenly split out once the concrete cracked. Meanwhile the PET fibers concrete exhibited cracking but did not fully separated out, mode of failure under split tensile showed fully separation of control samples while others exhibited resistance after first crack as shown in figure 12. All fibers showed improvement in the tensile strength. However, the tensile strength increased about 30% for all mixes with at 0.5% fiber content, far ahead, this increasing stopped and descended for 10 mm length regardless to the fraction volume, but split tensile strength remained above that observed for control mix by 5 %. For other fiber length (20 and 40 mm) ascending was continued up to 1.5 % fiber content, improving more than 60% in split tensile strength. This shows that PET fibers-reinforced concrete has the ability in dissipating the energy in the post-cracking state.

Splitting tensile strength enhancements are greater than those observed in previous studies like [Muthukumar and Maruthachalam (2013), Prahallada and Prakash (2013) and Marthong (2015)] and this may be due to bond improvement between RPET fiber and concrete paste since silica fume provides denser concrete paste by pozzolanic reaction.

5. Conclusions

From the experimental study described in this paper the following conclusions are made

1- Vebe time is increased slightly with increasing 10 mm length PET fiber volume up to 1.25% in concrete mix (i.e. the elapsed time is increased with increasing fiber length and fiber volume).

2- There is a reduction of V-funnel time due to PET fiber addition to concrete up to 0.75%. The time is close to the control concrete in 1% PET fiber, except for 40 mm length fiber. For larger PET fiber volume, there is a moderate V-funnel time increase, but for the 40 mm fiber length, the time increase is relatively large.

3- In general, the effect of PET fiber on Vebe time increase was found to be larger than that of V-funnel time, indicating that PET fiber has a different response on the compactibility and flowability.

4- When RPET fiber is added to HSC mix, this will lead to a compressive strength loss. This because PET fiber has minimum impartment against compression forces, also weak bond between RPET fiber and the paste causes crack propagation under compression loads.

5- All fibrous mixes showed improvement in the tensile strength due to distribution of fibers which resulted in a better bridging action under tension load, the concrete containing no fibers rapidly failed once the concrete cracked. Meanwhile the PET fibers concrete exhibited cracking but did not fully separate out. Longer fibers provides better resistance for the same fiber content compared for the short ones, owing that longer imbedded parts of fiber in the failure plane is important rather than fiber number.

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فحوصات مختبرية على قابلية العمل و المقاومة لخرسانة عالية المقاومة القابلة للتدفق الحاوية على ألياف نفايات PET

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المستخلص

هذا البحث تصف نتائج لاختبارين على قابلية العمل مع مقاومة الانضغاط و الانشطار للخرسانة عالية المقاومة القابلة للتدفق التي تحتوي على ألياف بلاستيكية محضرة من زجاجات النفايات من الإيثيلين تيريفثاليت (PET). بالنسبة لمزيج العالية الانهيال تم إجراء اختبارات Vebe time و V-funnel. أظهرت النتائج أن هناك زيادة في وقت Vebe مع إضافة ألياف PET إلى الخرسانة التي تتم زيادتها بزيادة حجم الألياف وطول الألياف. تم العثور على التقليله في وقت V-funnel عند إضافة ما يصل إلى 0.75% من حجم الألياف إلى الخرسانة، تليها زيادة في أحجام الألياف الكبيرة. عندما يزداد طول الألياف، هناك زيادة في الوقت، ولكن بشكل عام، كانت زيادة وقت V-funnel تم العثور على وقت V-funnel المقاس لجميع الخلطات لتتوافق مع حدود المواصفات الأوروبية بشأن قابلية تدفق الخرسانة المضغوطة ذاتيًا. تم تسجيل هبوط صغير في قوة الانضغاط للخرسانة المسلحة بالألياف RPET التي وصلت إلى 15.74 % لمحتوى الألياف 1.5 بالمائة بطول 10 ملم من الألياف. تم تسجيل نتائج جذابة في مقاومة الانشطار لعينات ليفية RPET مما أدى إلى تحسن يصل إلى 63.3% لـ 1.5% من محتوى الألياف بطول 40 ملم.

الكلمات المفتاحية: مقاومة الانضغاط، التدفق، مقاومة الانشطار، وقت Vebe، وقت V-funnel، قابلية العمل.

Table 1: Physical properties of cement.

Physical properties	Test results	ASTM C150 specification limits
Specific surface area (Blaine method), (m^2/kg)	365	≥160
Setting time (min)		
1) Initial setting time	161.9	≥ 45 min.
2) Final setting time	230	≤ 600 min
Compressive strength (MPa)		
1) 3 days compressive strength	23.5	≥ 12
2) 7 days compressive strength	28.3	≥ 19
Soundness (%) (autoclave method)	0.27	≤ 0.8%

Table 2: Chemical composition of cement.

Oxide Composition	Content, %	ASTM C150 specification limits
SiO_2	21.2	-
Al_2O_3	4.7	-
Fe_2O_3	3.25	-
CaO	61.45	-
MgO	2.95	≤ 6%
SO_3	2.4	≤ 3.0%
Loss On Ignition (L.O.I)	2.2	≤ 3%
Lime Saturation Factor (L.S.F)	0.88	0.66–1.02
Insoluble residue (I.R)	0.71	≤ 0.75
Main Compounds (Bogue's equations)		
C3S	46.9	-
C2S	25.85	-
C3A	6.7	-

Table 3: Concrete mix proportion (kg/m^3)

w/b*	Cement	Silica fume	Coarse aggregate	Fine aggregate	Water	HRWRA
0.23	493	20% **	1075	689	66	0.5%

** b is the binder mass (cement + silica fume)*

*** Silica fume slurry contains 60% water.*

Table 4: Tests data of workability.

Concrete ID	Vebe time (sec)	Change in Vebe time (%)	V-funnel time (sec)	Change in V-funnel time (%)
M0	6.86	0	9.71	0
M1×0.5	7.63	11	7.56	-22
M1×0.75	7.85	14	7.71	-21
M1×1	8.05	17	9.88	2
M1×1.25	8.18	19	10.84	12
M1×1.5	9.50	38	11.04	14
M2×0.5	8.50	24	7.81	-20
M2×0.75	8.65	26	7.97	-18
M2×1	9.15	33	9.36	-4
M2×1.25	10.25	39	12.43	28
M2×1.5	13.50	97	12.79	32
M4×0.5	8.85	29	7.85	-19
M4×0.75	9.60	40	8.85	-9
M4×1	11.73	71	14.01	44
M4×1.25	13.52	97	15.15	56
M4×1.5	15.21	122	17.77	83

Table 5: Compressive strength results.

Concrete ID	Compressive strength(MPa)	Change in Compressive strength (%)
M0	80.12	0.00
M1×0.5	78.24	-2.35
M1×0.75	73.31	-8.50
M1×1	70.12	-12.48
M1×1.25	67.51	-15.74
M1×1.5	69.22	-13.60
M2×0.5	77.20	-3.64
M2×0.75	70.34	-12.21
M2×1	68.61	-14.37
M2×1.25	69.48	-13.28
M2×1.5	68.62	-14.35
M4×0.5	74.93	-6.48
M4×0.75	71.88	-10.28
M4×1	72.81	-9.12
M4×1.25	74.13	-7.48
M4×1.5	73.50	-8.26

Table 6: Split tensile strength results.

Concrete ID	Split tensile strength(MPa)	Change in split tensile strength (%)
M0	4.55	0.00
M1×0.5	5.97	31.21
M1×0.75	5.42	19.12
M1×1	4.83	6.15
M1×1.25	4.81	5.71
M1×1.5	4.78	5.05
M2×0.5	5.83	28.13
M2×0.75	6.48	42.42
M2×1	6.54	43.74
M2×1.25	6.56	44.18
M2×1.5	7.42	63.08
M4×0.5	5.91	29.89
M4×0.75	6.78	49.01
M4×1	6.83	50.11
M4×1.25	6.96	52.97
M4×1.5	7.43	63.30

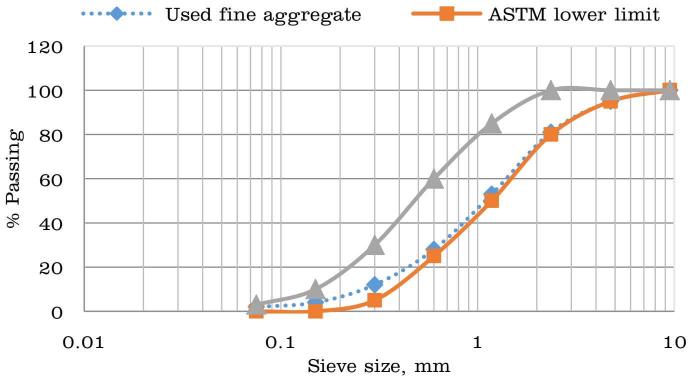

Fig. 1: Grading of fine aggregate and ASTM C33 limits.

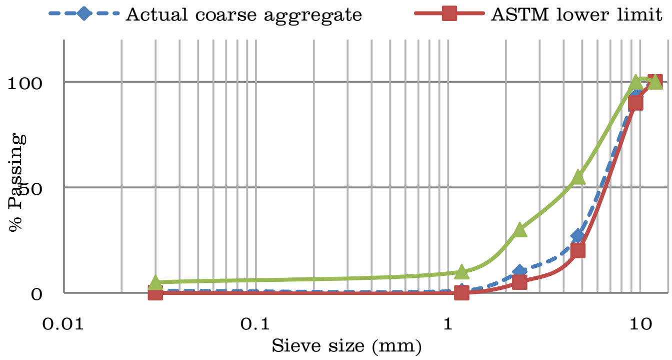

Fig. 2: Grading of coarse aggregate and ASTM C33 limits.

Fig. 3: Silica fume slurry.

(a) (b)

(c) (d)

(e) (f)

Fig. 4: Process of preparing recycled PET fiber; a) collecting PET bottles, b) cutting necks and bases, c) scissors used, d) PET strips, e) cutting strips in to small fibers, f) PET fiber.

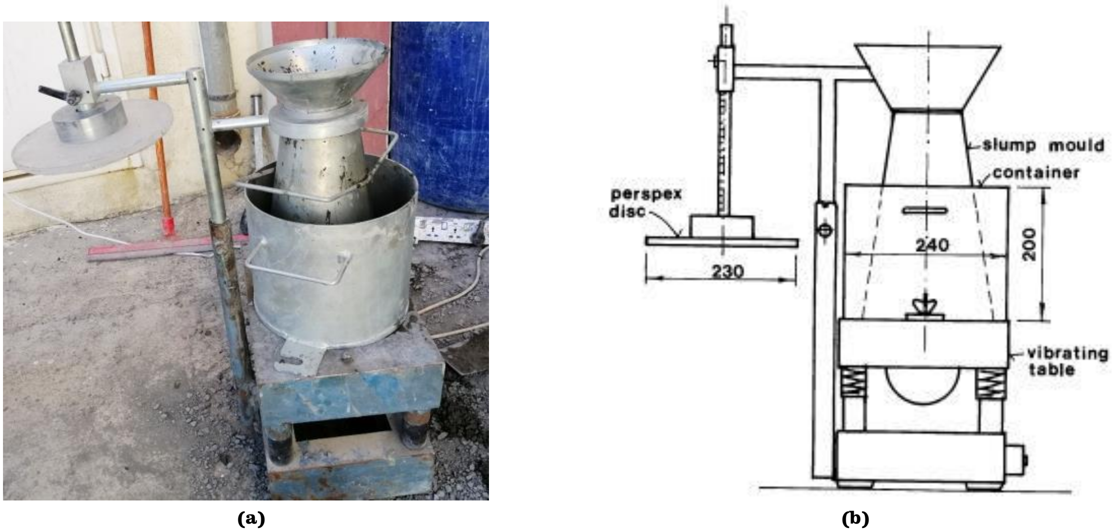

Fig. 5: Vebe test apparatus; a) Vebe meter, b) Vebe meter detail (Bartos *et al.* 2002 p. 105)

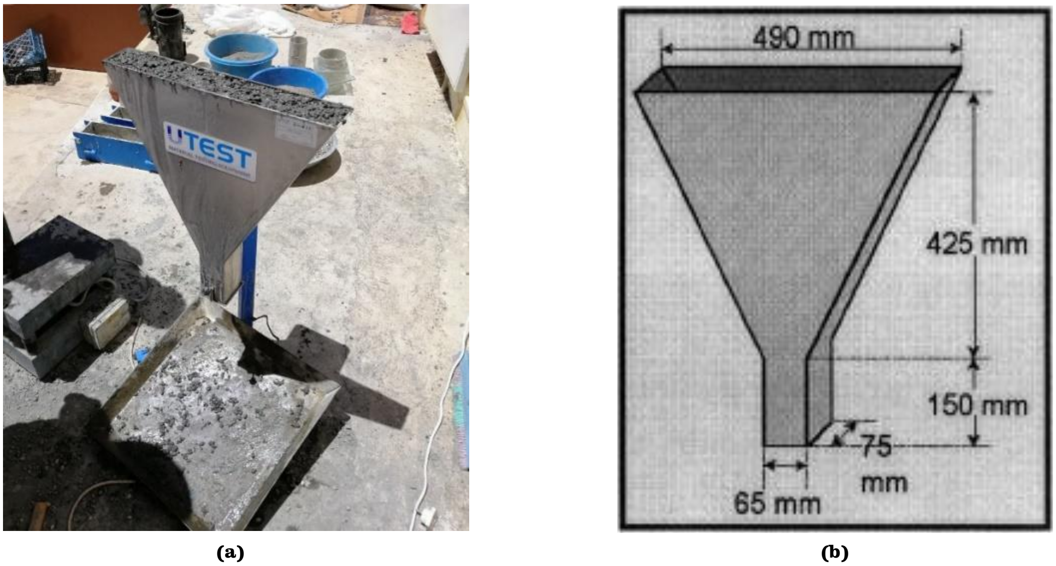

Fig. 6: V-funnel test apparatus; a) V-funnel and container, b) V-funnel detail (Bartos *et al.* 2002 p. 111)

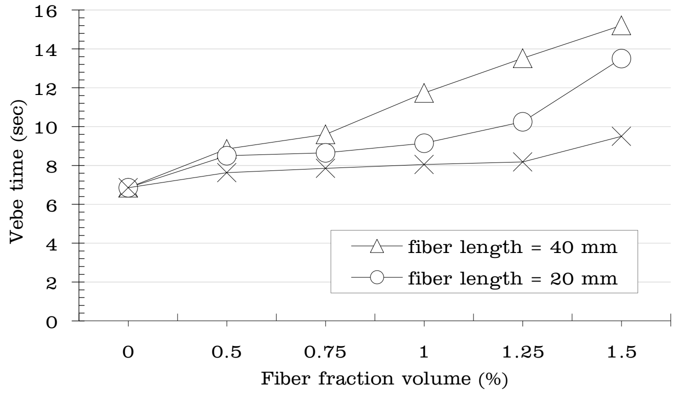

Figure 7: Vebe time change versus fiber content.

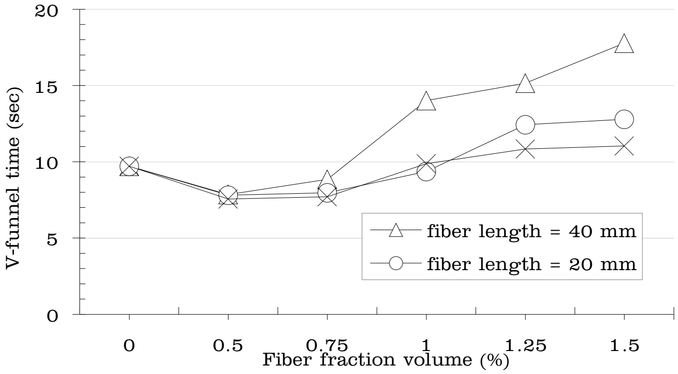

Figure 8: V-funnel time change versus fiber content.

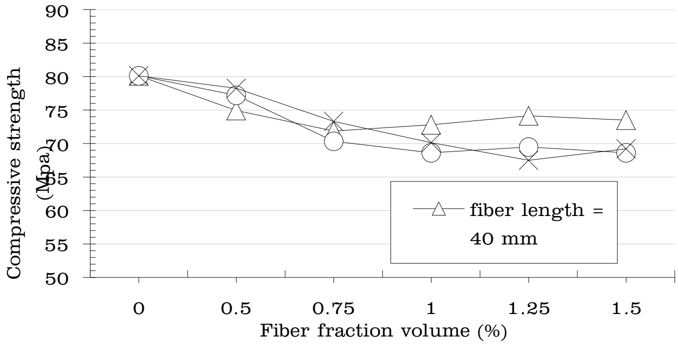

Figure 9: Variation in compressive strength with fiber length and fraction volume.

(a) **(b)**

Figure 10: failure modes under compression, a) control sample, b) fibrous samples.

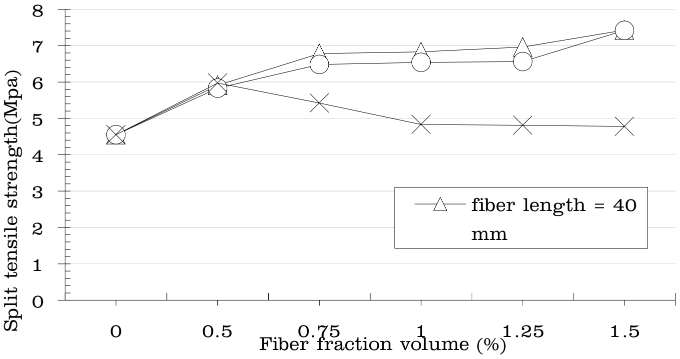

Figure 11: Variation in split tensile strength with fiber length and fraction volume.

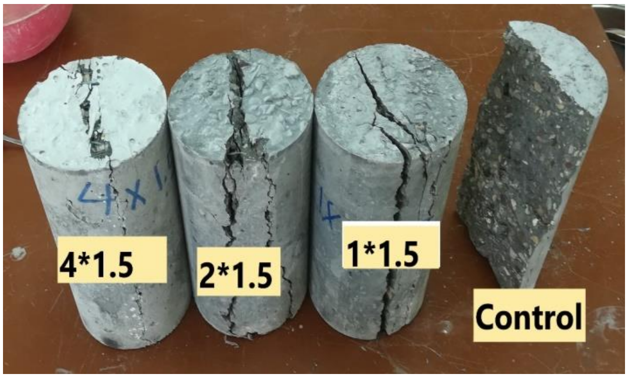

Figure 12: Failure modes under split tensile load.