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The Impact On Mechanical Properties of Different Geometric Shapes On recycled HDPE (rHDPE) Reinforcement in Concrete Structures

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Abstract: This research was carried out to develop a reinforcing structure with different geometrical shapes and patterns from recycled HDPE motor oil containers to be embedded in concrete structures. The reinforcing structure was prepared by dimensioning, cutting and joining of waste HDPE. In this study, different basic engineering shapes of rHDPE were used to investigate the mechanical properties of produced concrete composites based on split tensile test. These reinforcement shapes consist of square tubing, round tubing, I beam, X-shaped beam, square perforated tubing, round perforated tubing, I-perforated beam, and X-shaped perforated beam were embedded parallel into the concrete structure. Based on the overall tensile strength, concrete with round tube (1.508 MPa), round perforated tube (1.323 MPa), X-beam (1.443 MPa), X-perforated beam (1.489 MPa) and square tube (1.641 MPa) had fulfilled the minimum required tensile strength of reinforced concrete. In comparison, the overall performance of the solid structure reinforced concrete increased 14.9% tensile strength when compared to the perforated structure reinforced concrete. It was seen that, concrete with square tubing (1.641 MPa) and round tubing (1.508 MPa) had the highest tensile strength among other reinforced concretes.

Keywords: High Density Polyethylene, mechanical properties, reinforcement, geometrical shape

1. Introduction

Composites are strong heterogeneous materials. The properties of a composite vary considerably from point to point in the material, depending on which material phase the point is located (Kutz, 2006). Many artificial composites, especially those reinforced with fibres, are anisotropic, which means their properties vary with direction (the properties of isotropic materials are the same in every direction). The heterogeneous nature of composites results in a complex failure mechanism, which impart toughness. Fibre-reinforced materials were found to produce durable and reliable structural components in countless applications. The unique characteristics of composite material, especially anisotropy, require the use of special design methods. One of the composite classes is the concrete structure. It is commonly used in the building and construction sector to make light structural and decorative components, while in civil engineering, it is applied as adhesives, modifiers and matrix materials (Nair & Thachil, 2010).

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Durability is one of the main concerns for reinforced concrete structures, in which steel-concrete composite structures are often exposed to severe environments (Wang & Yang, 2010). Examples of deterioration include corrosion of steel in structures exposed to marine environments (Castro, Véleva, & Balancán, 1997; Cramer et al., 2002) and salt crystallisation-induced concrete corrosion of structures in saline environments (Fujiwara Y, Maruya T, 1992). Currently, billions of dollars are spent annually for repairing deteriorated structures worldwide.

Nowadays, cement composites of thermoplastics are used to increase the durability of concrete structures that are exposed to chemical pollution. Modification by thermoplastics influences the properties of a fresh concrete mixture as well as its hardened version properties (Foti & Paparella, 2014). It is believed that polymer is used to prevent leachability in water-soluble components, and thereby enhancing the durability of the composite when exposed to external chemicals (Nair & Thachil, 2010). The reinforcement also has the advantage to be less corrosive and less expensive than reinforcement that consists of steel wire nets (Foti & Paparella, 2014).

2. HDPE as A Reinforcement

Polyethylene plastics are lightweight, semicrystalline thermoplastics that are prepared by the catalytic polymerisation of ethylene. Depending on temperature, pressure, catalyst, and use of comonomer, three basic types of polyethylene can be produced (HDPE, LDPE, LLDPE). Most PEs are functions of their density and molecular weight. As density is decreased, the strength, modulus, and hardness will decrease, and flexibility, impact, and clarity will increase. Therefore, HDPE exhibits greater stiffness, rigidity, improved heat resistance, and increased resistance to permeability than LDPE and LLDPE (Kutz, 2006).

Since the last century, polyethylene copolymer coatings have been used to protect the external surface of onshore and offshore pipelines (Punj B. M., 1990). The anti-corrosion characteristic of HDPE was proven to be outstanding (Wang & Yang, 2010) as compared to steel. Some HDPEs can also be used as a protective layer against mechanical damage caused by severe environment. Finally, the service life of HDPE pipe is longer than 50 years. Moreover, with the mechanical support of the core concrete, HDPE can serve longer as a protective layer for the concrete structure (Wang & Yang, 2010). The physical properties of HDPE are given in Table 1.

Table 1 - Physical properties of HDPE (Wang & Yang, 2010)

No.	Parameter	Value
1	Density	0.954 g/cm^3
2	Elastic modulus (short-term:1 min)	1.0×10^3 MPa
3	Ultimate tensile strength	26 MPa
4	Breaking elongation	750%
5	Brittle temperature	≤–94°F (–70°C)
6	Working temperature	–112°F (–80°C) ~ 212°F (100°C)
7	Thermal conductivity	0.29 kcal/m.hr°C
8	Service life	>50 years

Note: 1 g/cm^3 = 62.4 lb/ft^3; 1 MPa = 145 psi.

3. Research Significance

The primary purpose of this research is to investigate how the shapes of the rHDPE reinforcing structure affect the strength of concrete composites. Therefore, solid waste of HDPE that was chosen in this study was scientifically related to design suitability for the reinforcement that were planted into the cement concrete structures. The ability to fabricate complex shape allows consolidation of parts, which reduces machining and assembly cost (Kutz, 2006), and thus improving the mechanical properties (Aslani & Nejadi, 2012; Santos, 2016). By this means, special geometrical design for the reinforcement of rHDPE will be emphasised. The relative ease of smooth shapes is a significant factor of using reinforcement in concrete structures, in which more aerodynamic considerations are important.

The shapes of rHDPE reinforcing structure were designed based on the basic engineering shapes for structure. The rHDPE reinforcements were formed in particular profiles with specific geometric characteristics, which determined the mechanical properties of the reinforced concrete. This is because the geometrical difference in rHDPE reinforcement inside the concrete structure will produce different mechanical strengths. The reinforcement shapes were comprised of square tubing, round tubing, I beam, X-shaped beam,square perforated tubing, round perforated tubing, I-perforated beam, and X-shaped perforated beam.

4. Reinforcing Materials Preparation

The waste motor oil containers were cleaned and washed with soap so as to remove residue oil. Then the containers were cut into sheets when they were completely dried. The rHDPE sheets were joined by adhesive (hot glued) to form different shapes of reinforcing structures. In this research, there were eight designs of rHDPE reinforcing structures produced in order to compare the loading effects in concrete structures. All shapes of rHDPE reinforcing structure were designed based on the basic engineering shapes for structure. The rHDPE reinforcing structures were manufactured in hollow shapes with a constant width of 30 mm for all shapes and the length of the reinforcing structure was 150 mm.

Among the eight designs, there were four designs of rHDPE reinforcing structures with perforated holes. The function of the holes was to provide greater interfacial adhesion, whereby no sliding phenomena can occur at the same time (Foti & Paparella, 2014) and as a bridging system between the rHDPE plastic and cement paste. The diameter of the hole was 6 mm and the distance between two holes was 15 mm. Each surface of the reinforcing structure was designed with 10 holes for a 150 mm long reinforcing structure. Figure 1 shows the shapes and patterns of the rHDPE reinforcing structure.

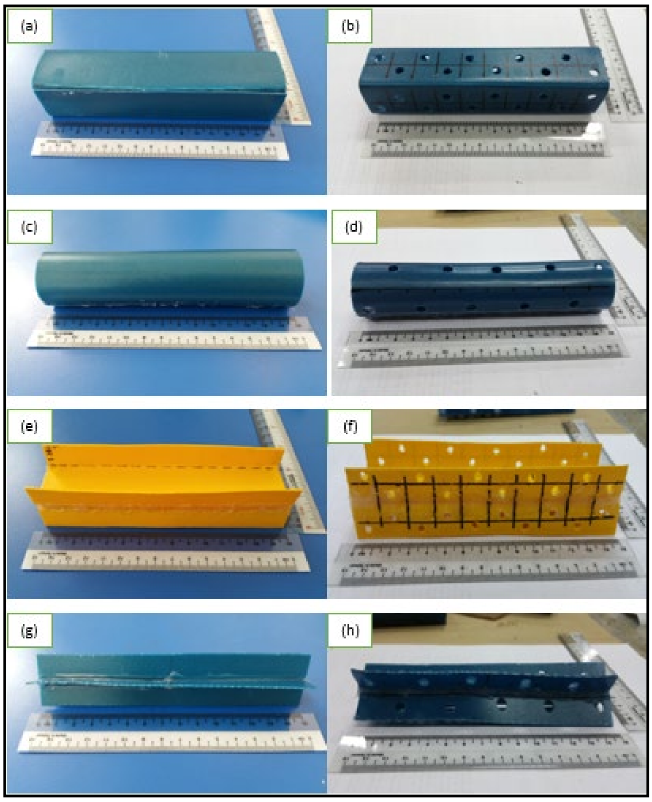

Fig. 1 - Designs and shapes of rHDPE reinforcing structure: (a) square tube; (b) square perforated tube; (c) round tube; (d) round perforated tube; (e) I-beam; (f) I-perforated beam; (g) X-shaped beam; and (h) X-perforated beam

5. Specimens Preparation

Portland cement is the most important raw material used as a cementitious material in this experiment as. Portland cement is a dry, fine and grey powder that contains calcium, silicon, and aluminium. Cement was mixed with water and fine aggregate to form a paste, which hardened and will bind the aggregates to form a concrete.

For the preparation of concrete, the ratio for cement, sand, water was set at 1:2:0.5 in weight basis and the water-to-cement ratio was 0.50. This mixture proportion was based on previous research studies and some of them were invented and suggested in this study.

Then, the reinforcing structure of rHDPE was placed at the centre or symmetry of the concrete structure. There were 27 test cylinder beams prepared for mechanical testing, including a controlled beam (without rHDPE reinforcement). Each type of rHDPE reinforcement was moulded into three test cylinder beams. The specimens were kept in a place that was free from vibration and kept in moulds at ambient temperature for about 24 hours to harden before being demoulded and transferred to the outside environment (direct sunlight) for curing at specific time periods. Once demoulded, each concrete specimen was noted with an identification code. Finally, the hardened concrete specimens were tested for split tensile.

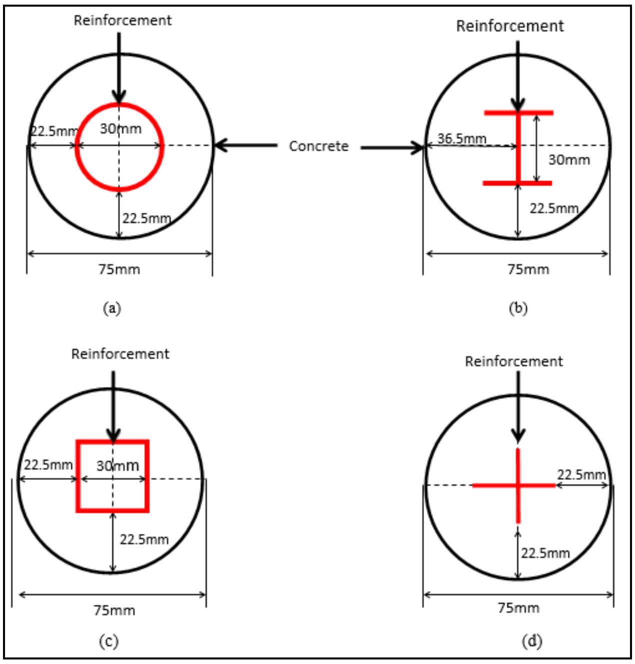

Fig. 2 - Location of rHDPE reinforcement in fresh concrete: (a) round; (b) I-beam; (c) square; and (d) X-beam

6. Split Tensile (Brazilian) Test Setup

Split tensile testing is a tensile strength test where the cylindrical specimen is loaded to failure in diametral compression applied along the entire length, in which the specimen will split across the vertical diameter. In this research, the split tensile strength test was conducted on a cylindrical specimen of 75 mm diameter and 150 mm long in accordance to BS 1881-117:2013 (Figure 3). Three cylindrical concrete specimens for each types of rHDPE reinforcing design were tested for split tensile strength. The test specimen was located at the centring jig with packing strips and loading pieces thoroughly positioned along the top and bottom of the loading specimen plane. The jig was located in the machine so that the specimen was centrally located. The upper platen was parallel to the lower platen. The initial load that is applied to the test specimen should not exceed 20% of the failure load. After the initial load was engaged, the load was applied attentively and without shock such that the stress was raised at a rate within the range of 0.04 MPa/s and 0.06 MPa/s. Once adjusted, the rate was maintained at ± 10 % until failure. The tensile splitting strength f_{ct} in MPa was given by Equation (1):

$$f_{ct} = \frac{2F}{\pi \times L \times d} \qquad (1)$$

Where;
F is maximum load (N),
L is average measured length (mm), and
d is average measured diameter (mm).

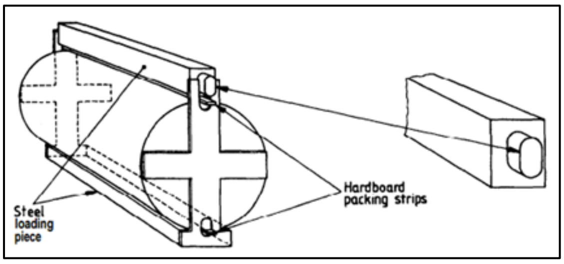

Fig. 3 - Jig for tensile splitting strength test

7. Analysis of Split Tensile Property

The purpose of tensile testing is to evaluate the interaction between cement paste and reinforcement structure. The results of the tensile test were directly inter-related with the interfacial bonding established from this matter. The constitutive response of the standard control normal concrete and the rHDPE reinforced concrete can be evaluated further by performing this test. From the tests, the splitting tensile strength of the rHDPE reinforced concrete composite can be measured based on the physical structural failure (Figure 4).

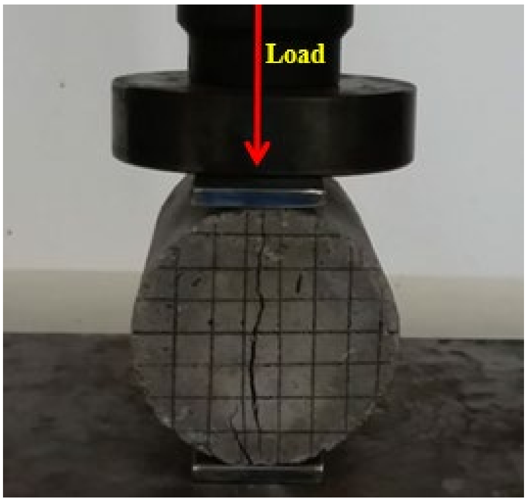

Fig. 4 - Split tensile test of cylinder concrete

Figure 5 depicts the splitting tensile strength of the fabricated composites incorporated with various shapes of rHDPE reinforcing structure addition. The indicated results were the mean made on three specimens. The results showed a significant reduction of 59% in performance, for any substitution pattern of reinforcement. From Figure 5, it can be seen that the overall splitting tensile strength (1.289 MPa) of the reinforced concretes decreased with the addition of rHDPE reinforcement, regardless of the reinforcing structure shapes with respect to control concrete (3.142 MPa).

However, if we compare the tensile strength between the concrete containing solid rHDPE reinforcement with concrete containing perforated rHDPE reinforcement, the reinforced concrete with the addition of solid structure had a higher tensile strength of 1.379 MPa than that of perforated structure reinforced concrete with 1.20 MPa. Therefore, the overall performance of the solid structure reinforced concrete had about 14.9% increment in tensile strength as compared to the perforated structure reinforced concrete. Based on the overall tensile strength of the reinforced concrete of 1.289 MPa, the concrete with round tube (1.508 MPa), round perforated tube (1.323 MPa), X-beam (1.443 MPa), X-perforated beam (1.489 MPa) and square tube (1.641 MPa) had fulfiled the minimum required tensile strength of reinforced concrete. It was seen that concrete with square tubing and round tubing had the highest tensile strength among other reinforced concretes.

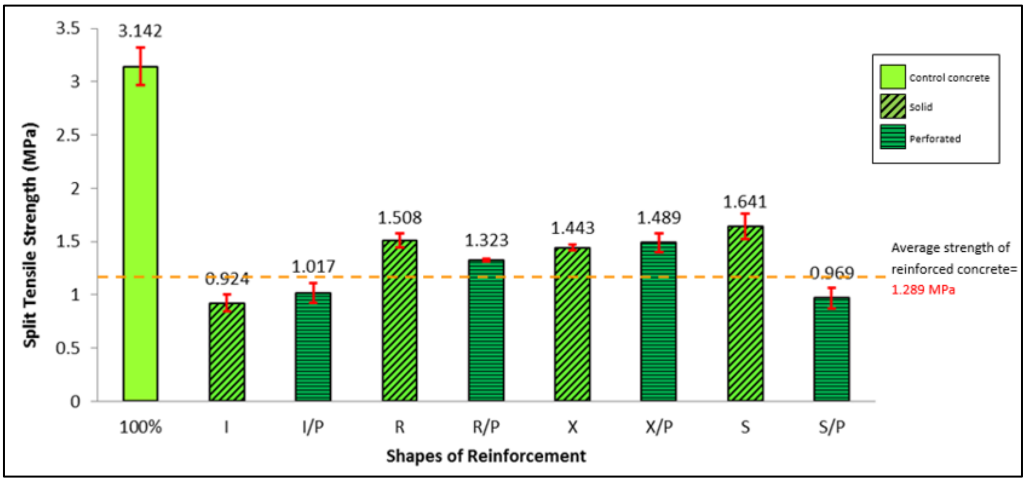

Fig. 5 - The effect of split tensile strength by different shapes of rHDPE reinforcement addition in cylinder concrete after 28-day

From Figure 5, the worst performance was observed for concretes that contained I-beam rHDPE reinforcement with tensile strength of 0.924 MPa, which was about 71% and 44% reduction in strength as compared to the control concrete and square tube reinforced concretes. The reduction in strength of concrete with I-beam reinforcing structure was due to the orientation of the I-beam towards applied stress and weak adhesion of the structure itself, as shown in Figure 6. Therefore, when the load was applied to the direction of the weakest part of the reinforcing structure, the concrete failed with a smaller force, whereby the tensile strength was decreased. From the figure, it is observed that there is a good physical adhesion between the smooth surface rHDPE plastic and cement paste. The rHDPE plastic was not debonded from the cement matrix although the concrete was split into two fractions. Therefore, a stronger adhesive or a different adhesion method is necessary to build the I-beam reinforcement to improve the tensile strength of the concrete.

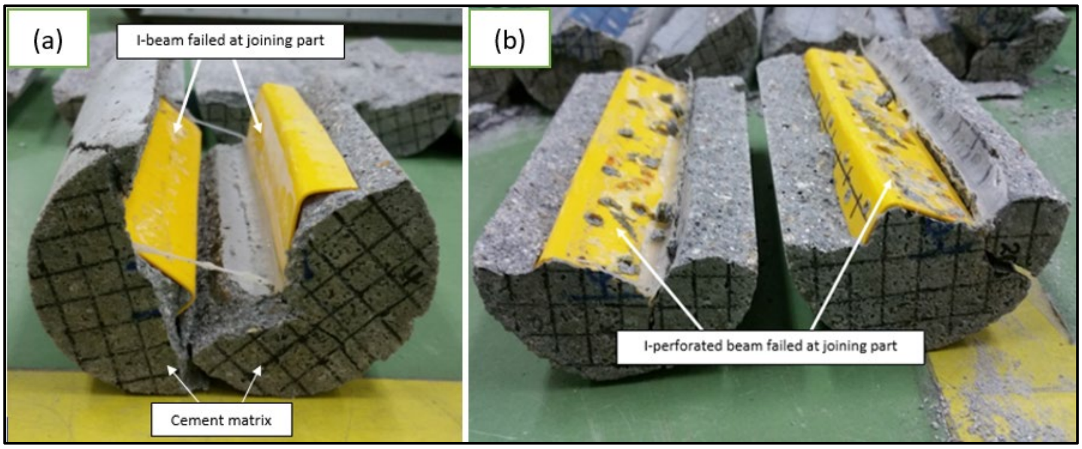

Fig. 6 - Failure mode of the concrete cylinder containing (a) I-beam and; (b) I-perforated reinforcement

Based on the tensile strength results as depicted in Figure 5, concrete containing perforated rHDPE structure showed a decrease of 13% in strength as compared to the solid rHDPE structure. From Figure 7 (a), it was found that the cement paste did pass through the perforated holes and created a bridging system between the plastic and cement matrix. This bridge effect can be seen from the fractured surface (Figure 7(b)) of the reinforced concrete. The rHDPE reinforcement was adhered to one side of the concrete after the concrete was split into three fractions after the tensile test as shown in Figure 4.5a. This scenario was also observed in all concrete specimens that contained perforated rHDPE reinforcing structure. The bridging action between the plastic and cement paste is expected to provide a better strength to the produced concrete due to the interlocking relation between cement paste and plastic. This bridging action tends to create a better bond strength between the hydrophobic rHDPE plastic and cement matrix. However, the results indicated that the perforated rHDPE reinforcing structure did not improve the tensile strength of concrete with respect to concrete containing solid rHDPE reinforcing structure.

The decrease in strength of concrete involving perforated structure can be explained after observing the fractured surface under optical microscope as illustrated in Figure 7 (b) and Figure 7 (c). The reduction in concrete strength was induced by the presence of micro-cracks, cavities and pores found around the fractured surface of the perforated hole. Based on the Balshin's model, stress concentration are present around the pores and is define by pore geometry and pore orientation with the direction of applied force (Mydin, 2014). When porosity increased, the load bearing area was reduced, and thus caused a stress concentration around the pores (Chen, Wu, & Zhou, 2013). Cavity is formed when the cement paste does not fully flow through the plastic perforated holes due to the weak workability of cement paste that causes weak compaction during casting, while micro-cracks are the effect of shrinkage. All these defects will concentrate stress and act as a stress raiser that will initiate and propagate crack in the direction of the applied stress. Therefore, the defects will influence the mechanical performance of the concrete. From Figure 7 (b) and Figure 7 (c) microscopic analysis, intergranular cracking can be observed from the fractured surface. The crack propagated along the path of least resistance through the cement matrix and interface boundary of aggregates at a constant strain rate.

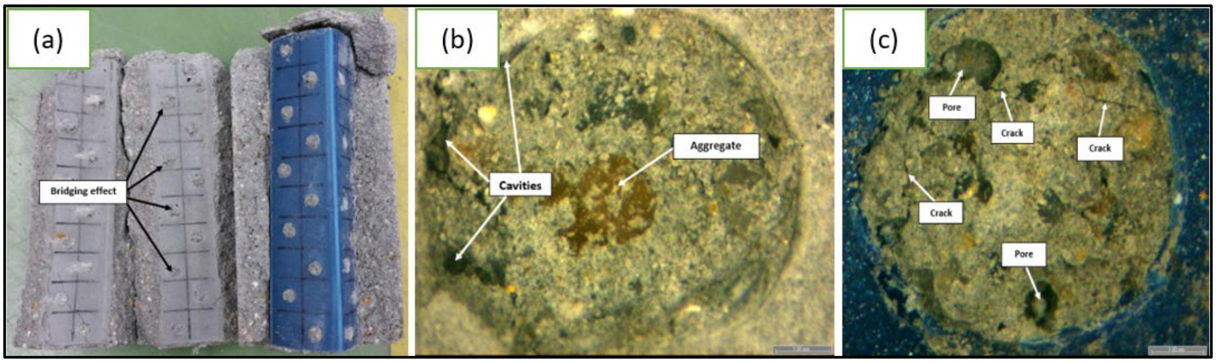

Fig. 7 - (a) Fractured surface of the concrete containing square-perforated tube; (b) Micrograph of bridging effect on cement-rHDPE interface; (c) Micrograph of cement paste in perforated hole

Besides, the orientation of the rHDPE structure also affects the concrete tensile strength. For example, imagine placing a hollow rHPDE structure horizontally during the tensile test, the rHPDE structure only has two points because the centre is a hollow section. Then, the perforated rHDPE structure was compressed and had higher strain. The compressed rHDPE structure will create stress at the holes and transfer the stress to the bridging cement paste. When the applied load is continued, the cement bridge will fail due to stress that was concentrated within limited area.

Figure 8 depicts the fractured surface of round and square solid tube reinforced concretes. The splitting tensile strengths for concrete containing square hollow and round hollow rHDPE reinforcement were 1.641 MPa and 1.508 MPa, respectively (Figure 5). The results showed that the square hollow rHDPE tube reinforced concrete had the highest strength among other reinforced concretes, which was 52% of the strength of the controlled concrete. The better strength of reinforced concrete containing solid structure can be explained by the uniform transferred stress from the cement matrix to the entire surface of rHDPE plastic as compared to the perforated structure.

Based on Figure 8, it is observed that the interfacial zone displayed a smooth surface as compared to the rough texture of concrete fractured surface. It can be seen from the figure that the non-perforated (solid) rHDPE reinforcement was completely removed or debonded from the cement matrix after the tensile test. This was due to the properties of interfacial transition zone (ITZ) between cement matrix and rHDPE plastic that affected the splitting tensile strength of the concrete (Frigione, 2010; Kou, Lee, Poon, & Lai, 2009; Ponmalar, 2018). The smooth interfacial zone and hydrophobic nature of rHDPE plastic promotes weaker bonding with cement paste because the free water in cement paste accumulated at the surface of the rHDPE reinforcing structure (Gu & Ozbakkaloglu, 2016). Therefore, the ITZ promotes the weakest bonding and strength limiting phase in the reinforced concrete. Besides, free water that accumulated at the interfacial zone will generate pores, which also affect the final properties of concrete.

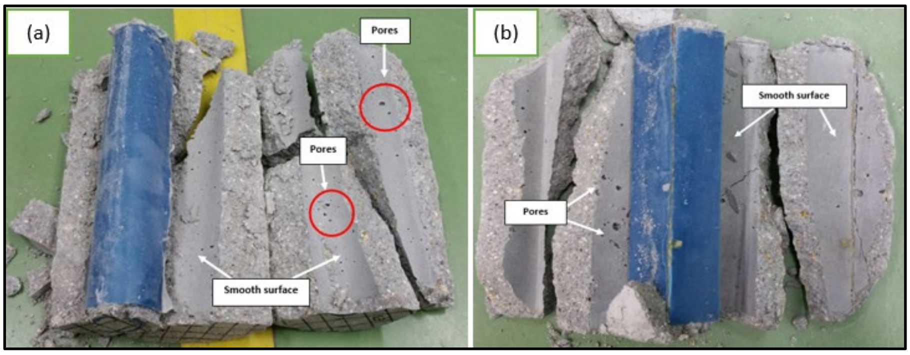

Fig. 8 - Fractured surface of (a) round tube and; (b) square tube reinforced concrete

Based on Figure 5, the splitting tensile strength of the concrete containing X-shaped beam was 1.443 MPa, which was about 46% of the controlled concrete tensile strength. From Figure 9, the reinforced concrete did not split into two fractions after the tensile test. The concrete failed due to the joining failure of the X-shaped structure itself. As a result of the weak adhesion of reinforcing structure, the reinforcement will act as a bridge that connects the two split concrete pieces. Therefore, this bridging effect will indirectly improve the tensile strength of the concrete. It was noticed that the X-shaped reinforcement had good bonding with the cement paste because the reinforcing structure was still embedded in the concrete after determination of tensile strength. This observation was also applied to X-shaped perforated beam reinforced concrete. From Figure 5, concrete containing X-shaped perforated beam had the highest split tensile strength of 1.489 MPa as compared to the three other shapes of perforated structures. The strength was about 47.4% of the strength of the controlled concrete. It was also found to be the third highest tensile strength among all reinforced concretes.

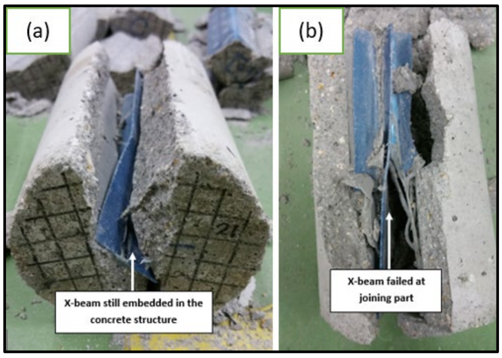

Fig. 9 - Fracture mode of concrete containing X-shaped reinforcing structure

8. Fracture Mechanism of Split Tensile Concrete Cylinder

According from the recent research, the first crack will open at about 70 % of the maximum load. It was reported that the crack did not initiate at the centre of the cylinder cross section but the maximum tensile stresses were found in the loading plane, at one third of the cylinder height (Malárics & Müller, 2010). Besides, a wedge fric was observed below the load bearing strips, which was the result of a secondary cracking.

Figure 10 depicts the failure pattern of rHDPE reinforced concrete during the split tensile testing. The failure pattern of controlled concrete was different from rHDPE reinforced concrete. It was observed that all concrete specimens showed that the crack did not initiate at the centre of the cylinder cross section but initiated at one third of the cylinder height, regardless of the shapes of reinforcing structure incorporated in the concrete structure. For the normal controlled concrete, there was only one longitudinal crack line that propagated down the concrete surface. However, for reinforced concrete, there was a secondary crack line initiated from the diametral and propagated towards the centre to combine with the main crack. For concrete containing I-beam and X-shaped reinforcements as shown in Figure 10 (a) and Figure 10 (b), the crack pattern was almost similar to the controlled concrete but with the presence of a secondary crack due to the sharp edge of the structure that acted as a stress raiser that initiated a crack. The crack growth observed in the reinforced concrete containing square and round tubes will follow the shape or cross section of the reinforcing structure, as shown in Figure 10 (c) and Figure 10 (d).

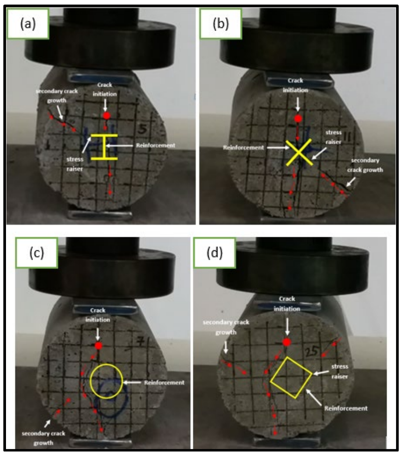

Fig. 10 - Failure pattern of concrete containing (a) I-beam; (b) X-shaped beam; (c) round tube and; (d) square tube rHDPE reinforcing structure

9. Fracture Surface Morphology

Micrograph in Figure 11 shows the fractured surface of the normal concrete and the interfacial transition zone between the rHDPE reinforcement and cement matrix. The fractured surface, as shown in Figure 11 (a), displays a rough surface due to constant strain rate of 5 mm/min. It can be seen that the coarse aggregates still remained as a whole structure without being broken along the fractured surface. Due to shrinkage effect on hardened concrete, micro-cracks were present in the unloaded concrete primarily at the interface boundaries between the cement matrix and aggregates. At low strain rate, micro-cracks are normally shown after reaching the maximum stress. In addition, micro-cracks in the cement matrix were restricted by the aggregates from growing further. Therefore, they were originally stable and required higher energy for further propagation. The area around the micro-cracks continued to carry load until it reached a critical crack width, which was unstable and failed. The fracture surface grew gradually to the path of least resistance, which was the matrix-aggregate interface boundaries and resulted in matrix failure. Figure 11 (b) shows the smooth flattened surface of the interfacial zone (ITZ). It was observed that the ITZ was the result of excess cement water accumulated at the surface of the rHDPE reinforcement and the generation of pores from water evaporation. This was due to the hydrophobic nature of plastic that impeded the cement hydration reaction near the plastic surface by inhibiting water movement (Gu & Ozbakkaloglu, 2016). Therefore, the ITZ promoted the weakest bonding and strength limiting phase in the reinforced concrete.

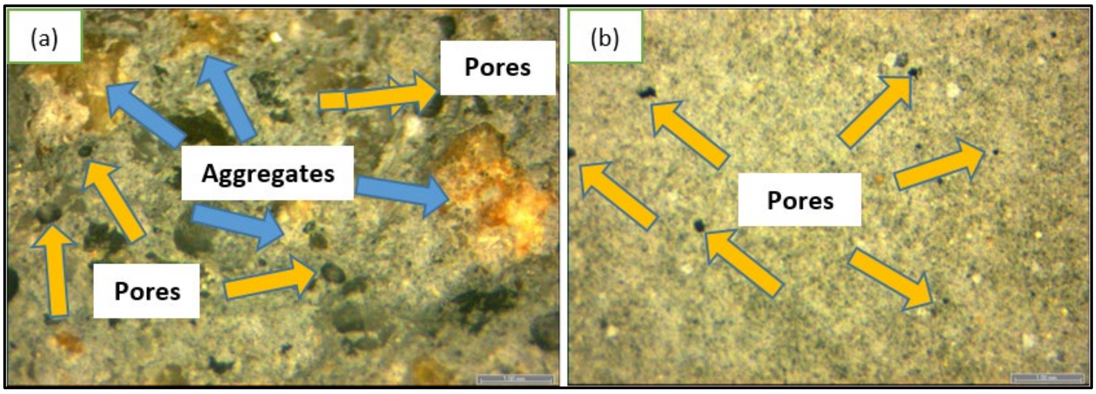

Fig. 11 - Surface morphology of fracture surface: (a) normal concrete; (b) interfacial zone between rHDPE and cement matrix

10. Summary Discussion

After analysing the overall obtained experimental data, it can be concluded that the addition of rHDPE reinforcing structure tends to enhance the properties of the produced concrete composites. However, the properties of the interfacial transition zone (ITZ) between the cement matrix and rHDPE plastic affected the mechanical strength of the reinforced concrete composites. Due to the hydrophobic nature of rHDPE plastic, the plastic tends to impede cement hydration reaction near the plastic surface by inhibiting water movement. Therefore, the excess cement water will accumulate at the surface of the rHDPE reinforcing structure and promotes weaker bonding between the cement matrix and rHDPE reinforcement, as shown in Figure 12.

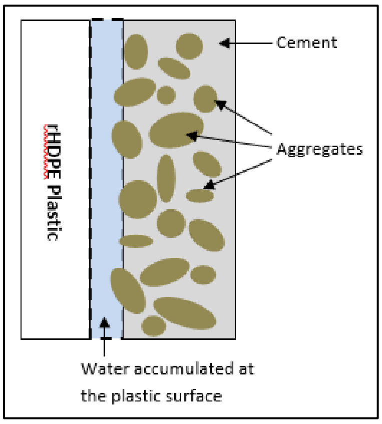

Fig. 12 - Illustration of the interfacial zone between cement matrix and rHDPE plastic

By designing the rHDPE reinforcing structure with perforated holes, the cement paste will pass through the holes and create a bridging system between the plastic reinforcement and cement matrix. This bridging action tends to promote better interfacial bonding between the rHDPE plastic and cementitious materials due to the formation of interlocking between rHDPE reinforcement and cement matrices, as shown in Figure 13. Therefore, a better interfacial bonding will enhance the bond strength between reinforcement and matrix, and thus improved the mechanical properties of the concrete composites.

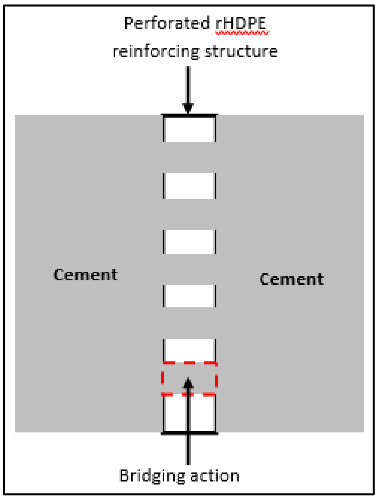

Fig. 13 - Illustration of the cement bridging between perforated rHDPE reinforcing structure

Besides, the mechanical strength of the concrete composites also depended on the orientation of the rHDPE reinforcing structure embedded in the concrete structure. For split tensile test, the rHDPE structure was placed horizontally or perpendicular to the applied stress. This was because when the concrete structure was placed horizontally or perpendicular to the applied load, the reinforcement only had two points (double wall) to support the entire load, as shown in Figure 14 (a). However, if the concrete structure was placed vertically or parallel to the applied load, the reinforcement was supported by its entire body from top to bottom, as shown in Figure 14 (b). Therefore, the orientation of rHDPE reinforcement in concrete structure will result in higher strength and is more stable in resisting the load if the best orientation position is considered for this matter. This scenario should be applied to concrete structure containing hollow and perforated reinforcement regardless of the shapes of the reinforcing structure. The concrete structure will be easily weaken in resisting the load; thus, reduced the mechanical strength if the reinforced orientation is ignored.

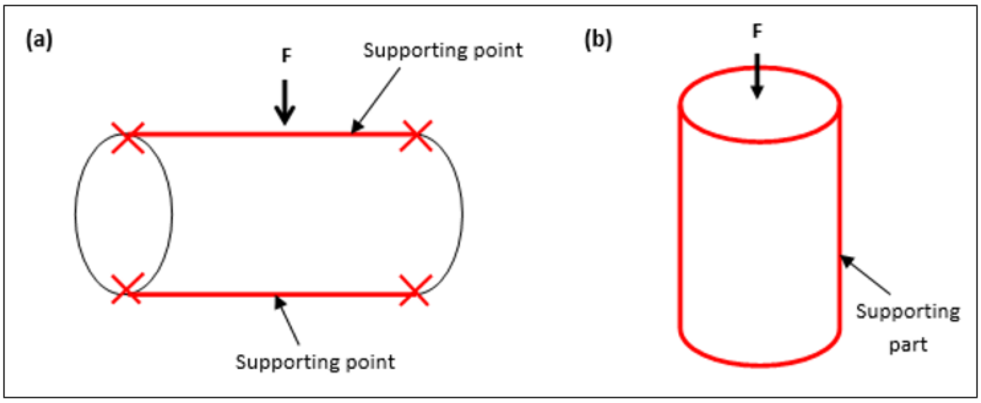

Fig. 14 - Load supporting point (a) horizontally and (b) vertically placed hollow reinforcement in concrete composite

Apart from that, for concrete containing I-beam and X-beam, the orientation, as shown in Figure 15, affected the split tensile performance of the reinforced concrete. From Figure 15, the orientation shown in (a) and (d) will give higher strength because it was more stable in resisting the load as compared to the orientation shown in (b) and (c). The reinforcing structure orientation shown in (b) and (c) will be easily deflected and was weaker in resisting the load, and thus reduced the strength of the reinforced concrete.

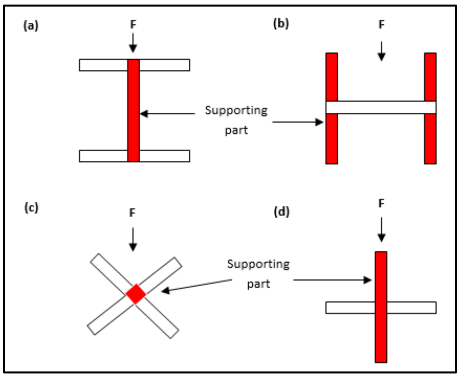

Fig. 15 - Illustration of the orientation of rHDPE reinforcing structure (a) I-beam, (b) inverted I-beam, (c) X-beam and (d) inverted X-beam

For the split tensile test, it was observed that all the concrete specimens had similar crack initiation point at one third of the height of the cylinder, as shown in Figure 16. Then, the crack will propagate down the vertical diameter of the cylinder as the applied stress was continued. For concrete without reinforcement, the crack pattern showed a longitudinal line down the vertical diameter of the cylinder specimen, as shown in Figure 16 (a). This meant that the stress was transferred directly from the upper to the bottom part of the concrete cylinder. However, for concrete with the addition of reinforcement, the crack propagated based on the orientation and shapes of the rHDPE reinforcing structure. This meant that the stress or crack line was diverted following the shapes of the rHDPE structure rather than being propagated in a straight line down the vertical diameter of the cylinder as shown in Figure 16 (b). Besides, the edges of the rHDPE structure acted as a stress raiser that initiated secondary crack lines when the load was applied. These secondary crack lines initiated from the diametral and grow towards the centre and combined with the main crack and propagated down the vertical diameter of the concrete cylinder, as shown in Figure 16 (c). All concrete cylinders will split into two halves or two fractions after the test.

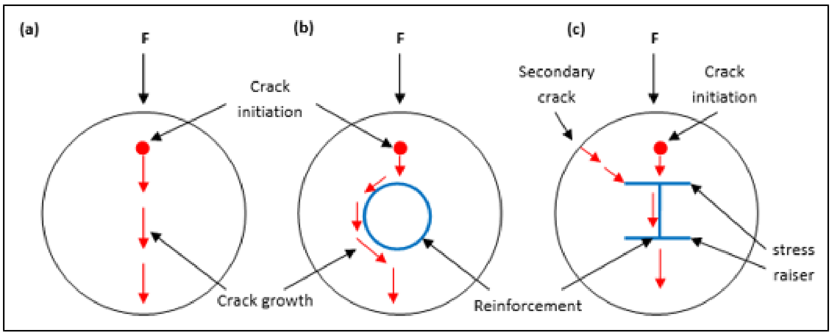

Fig. 16 - Illustration of crack pattern of concrete cylinder (a) without reinforcement; (b) hollow reinforcement and; (c) I-beam

Finally, the study carried out and described in this paper can be considered as an approach for further investigations on the use of reinforcement based on its orientation and design structure. The ability to fabricate complex shape allows consolidation of parts, which reduces machining and assembly cost, in addition improving mechanical properties of the materials. The relative ease with smooth shapes can be made and considered as a significant factor for use in today's construction applications. Size effect based on the specimen size and shape difference affected the properties of concrete. The incorporation of reinforcement in terms of content, length, aspect ratio and shape played an important role in controlling workability and improves engineering performance of structural and non-structural of the concrete (Aslani, 2013; Foti, 2011; Fraternali, Ciancia, Chechile, Rizzano, & Feo, 2011; Frigione, 2010; Khalid, Juki, Othman, & Wan Ibrahim, 2017; Ochi, Okubo, & Fukui, 2007). It is believed that, the reinforcement is a very important parameter that affects the performance and behaviour of concrete, especially the ratio of longitudinal reinforcement (Yang & Tang, 2011). Based on the observation, the crack propagated based on the shapes of the rHDPE reinforcing in concrete structure. This means that the stress or crack line was diverted following the shapes of the rHDPE structure rather than propagating in a straight line down the vertical diameter of the cylinder. Besides, the edges of the rHDPE structure acted as a stress raiser, which initiated secondary crack lines when the load was applied. These secondary crack lines initiated from the diametral and grew towards the centre and combined with the main crack, propagating down the vertical diameter of the concrete cylinder.

11. Conclusions

This paper proposed a new kind of composite material by using different geometric shapes of reinforcement, which were obtained by embedding post-consumed rHDPE plastic into concrete structure. Eight designs of rHDPE reinforcing structures with specific geometric characteristics were successfully created with some highlights were as the followings.

(i) The average split tensile strength of the rHDPE reinforced concrete was 1.289 MPa, whereas the tensile strength of the control concrete was 3.142 MPa. The tensile strength of the rHDPE reinforced concrete showed a 59% reduction in strength.

(ii) The average split tensile strength of concrete containing solid rHDPE reinforcing structure was 1.379 MPa, while 1.20 MPa was for concrete that contained perforated rHDPE reinforcing structure. The tensile strength of the solid rHDPE reinforced concrete was about 14.9% better than the perforated rHDPE reinforced concrete composites.

(iii) Square tube rHDPE reinforced concrete had the highest tensile strength of 1.641 MPa among other reinforced concretes, while the I-beam rHDPE reinforced concrete showed the weakest in tensile strength of 0.924 MPa. The square tube reinforced concrete showed about 44% increment in strength as compared to the I-beam reinforced concrete.

(iv) Based on the average tensile strength of 1.29 MPa for reinforced concretes, the concrete containing square tube (1.641 MPa), round tube (1.508 MPa), X-perforated beam (1.489 MPa), X-beam (1.443 MPa) and round perforated tube (1.323 MPa) had fulfilled the minimum required tensile strength of reinforced concretes.

The fracture surface morphology of the rHDPE reinforced concretes was observed through optical microscope in order to meet the last study objective. It was interesting to note the following findings so as to highlight the success of this research.

(i) From the optical microscope, it showed that the pores, cavities and microcracks were clearly presented in the observed samples. This observation had supported the resulted properties diminishment as gathered in the previous part of research. This was because these defects acted as stress concentration points that may result in early premature failure that will decrease the performance of the concrete composites.

(ii) The cement paste bridging action through rHDPE perforated structures were contributed in the betterment of the interfacial bonding between the cement matrix and rHDPE plastic that resulted in a better compression properties of the produced reinforced concrete structure. This was because the bridging effect will lead to more effective load transfer due to the interlocking between reinforcement and matrix.

(iii) Shrinkage effect, weak compaction of cement paste, smooth surface or hydrophobic nature of the HDPE plastic that impeded cement hydration reaction and high water-to-cement ratio were among the various factors which impeded the quality of rHDPE reinforced concrete composites which defined the unpredictable resulted performances of produced concrete composites.

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References

Aslani, F. (2013). Effects of Specimen Size and Shape On Compressive and Tensile Strengths of Self-Compacting Concrete with or Without Fibres. *Magazine of Concrete Research*, *65*(15), 914–929.

Aslani, F., & Nejadi, S. (2012). Bond Behavior of Reinforcement in Conventional and Self-Compacting Concrete. *Advances in Structural Engineering*, *15*(12), 2033–2051.

Castro, P., Véleva, L., & Balancán, M. (1997). Corrosion of Reinforced Concrete in A Tropical Marine Environment and in Accelerated Tests. *Construction and Building Materials*, *11*(2), 75–81.

Chen, X., Wu, S., & Zhou, J. (2013). Influence of Porosity On Compressive and Tensile Strength of Cement Mortar. *Construction and Building Materials*, *40*(March), 869–874.

Cramer, S. D., Covino, B. S., Bullard, S. J., Holcomb, G. R., Russell, J. H., Nelson, F. J., … Soltesz, S. M. (2002). Corrosion Prevention and Remediation Strategies for Reinforced Concrete Coastal Bridges. *Cement and Concrete Composites*, *24*(1), 101–117.

Foti, D. (2011). Preliminary Analysis of Concrete Reinforced with Waste Bottles PET Fibers. *Construction and Building Materials*, *25*(4), 1906–1915.

Foti, D., & Paparella, F. (2014). Impact Behavior of Structural Elements in Concrete Reinforced with PET Grids. *Mechanics Research Communications*, *57*, 57–66.

Fraternali, F., Ciancia, V., Chechile, R., Rizzano, G., & Feo, L. (2011). Experimental Study of the Thermo-Mechanical Properties of Recycled PET Fiber-Reinforced Concrete. *Composite Structures*, *93*(9), 2368–2374.

Frigione, M. (2010). Recycling of PET bottles as Fine Aggregate in Concrete. *Waste Management*, *30*(6), 1101–1106.
Fujiwara Y, Maruya T, O. E. (1992). Degradation of Concrete Buried in Soil with Saline Ground Water. *Nuclear Engineering and Design*, *138*(2), 143–150.

Gu, L., & Ozbakkaloglu, T. (2016). *Use of Recycled Plastics in Concrete: A Critical Review*. *51*, 19–42.
Khalid, F. S., Juki, M. I., Othman, N., & Wan Ibrahim, M. H. (2017). Pull-Out Strength of Polyethylene Terephthalate Bottle Fibre in Concrete. *Malaysian Construction Research Journal*, *21*(1), 75–85.

Kou, S. C., Lee, G., Poon, C. S., & Lai, W. L. (2009). Properties of Lightweight Aggregate Concrete Prepared with PVC Granules Derived from Scraped PVC Pipes. *Waste Management*, *29*(2), 621–628.

Kutz, M. (2006). *Mechanical Engineers' Handbook Materials and Mechaical Design* (3rd ed.; Myer Kutz, ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Malárics, V., & Müller, H. S. (2010). Evaluation of the Splitting Tension Test for Concrete from A Fracture Mechanical Point of View. *Fracture Mechanics of Concrete and Concrete Structures-Assessment, Durability, Monitoring and Retrofitting of Concrete Structures-B.H. Oh, et Al., Eds, Seoul*, pp. 709–716.

Mydin, M. A. O. (2014). Models for Prediction the Strength and Stiffness of Foamed Concrete at Ambient Temperature. *European Researcher*, *67*(1–2), 124–129.

Nair, P. S., & Thachil, E. T. (2010). Microstructural Studies of Cement Composites of Thermoplastics. *Polymers and Polymer Composites*, *18*(2), 75–83.

Ochi, T., Okubo, S., & Fukui, K. (2007). *Development of Recycled PET Fiber and Its Application As Concrete-Reinforcing Fiber*. *29*, 448–455.

Ponmalar, S. (2018). Bond Behavior of Self Compacting Concrete Bond in General Mechanism of Bond. *Journal of Civil Engineering*, (March), 95–105.

Punj B. M., S. G. (1990). Current Trends in Pipe Coating Technology and Applications. *Proceedings of the 8th International Conference: Internal and External Protection of Pipes*, 49–64.

Santos, A. C. P. (2016). Bond Behavior of Self Consolidating Concrete. *Journal of Construction*, *15*(3), 9–16.
Wang, J., & Yang, Q. (2010). Experimental Study on Mechanical Properties of Concrete Confined with Plastic Pipe. *Aci Materials Journal*, *107*(2), 132–137.

Yang, P., & Tang, J. (2011). A Study on Parameters Affect Seismic Behavior of Reinforced Concrete Specially Shaped Columns. *Advanced Materials Research*, *163–167*(February), 1300–1306.