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# POLYVINYL ALCOHOL (PVA) FIBER-REINFORCED RUBBER CONCRETE AND RUBBERIZED SELF-COMPACTING CONCRETE

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# POLYVINYL ALCOHOL (PVA) FIBER-REINFORCED RUBBER CONCRETE AND RUBBERIZED SELF-COMPACTING CONCRETE

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# Preface

Part of the experimental specimens were prepared together with Shuaicheng Guo, Ruizhe si, Jiaqing Wang, and Song Han. At the same time, Ruizhe si, Jiaqing Wang, and Song Han collaboratively performed the tests and measured the results. Meanwhile, Dr. Qingli Dai provided the knowledgeable instructions to explain the methods for the performance improvements of rubber-modified concrete. The test data in rubber modified self-compacting were processed by Ruizhe si and Jiaqing Wang. The thesis was wrote under Dr. Dai's supervision.

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# Abstract


POLYVINYL ALCOHOL (PVA) FIBER-REINFORCED RUBBER CONCRETE AND RUBBERIZED SELF-COMPACTING CONCRETE

By Jiaqing Wang

This study experimentally investigates the mechanical performance and durability of Polyvinyl Alcohol (PVA) fiber-reinforced rubber concrete and the rubberized self-compacting concrete. The waste rubber particles were introduced as a partial replacement of fine aggregate in the plain concrete. In addition, the waste tire rubbers were pre-treated with alkali surface treatment method to enhance the performance. The PVA fibers were added to the concrete mixes to enhance the post-failure resistance and thus fracture energy. Rubberized fiber concrete samples were prepared with different fine aggregate replacement ratios and the optimum fiber content. At the same time, the rubber particles had been used to partially replace the fine aggregate in normal self-compacting concrete (SCC). The rubberized self-compacting concrete (RSCC) had also been prepared with different rubber contents. The effects of NaOH treatment method had been evaluated in the self-compacting concrete. For these samples, the mechanical performance including compressive strength, indirect tensile strength, and flexural behavior was measured to compare with control samples. The transport property was also detected by electrical resistivity test. The durability performance such as Alkali-silica reaction (ASR) expansion and drying shrinkage were evaluated and compared with control samples. The test results of the PVA-fiber reinforced rubber concrete showed that it could achieve a high fracture energy and

maintain a high mechanical performance after addition of recycled rubber and PVA-fiber, furthermore, the modified specimens showed a better performance in durability than control samples. At the same time, the results from rubberized self-compacting concrete (RSCC) also indicated that after using of NaOH surface treated rubbers can successfully achieve high-strength requirement and improve durability performance. Overall, the polyvinyl alcohol (PVA) fiber could be considered to improve the mechanical performance and durability in normal rubberized concrete. In addition, the NaOH surface treatment method for rubber particles could improve the performance of rubberized self-compacting concrete (RSCC), thus achieve a high-strength and good durability with the recycled tire aggregate.

# Chapter 1. Literature Review

## 1.1 Significance of development of rubberized concrete

### 1.1.1 Environmental – friendly rubber recycling into concrete

Waste tires induce significant health and environmental issues if not recycled or discarded appropriately [1]. The accumulation of tire rubber can cause many associated environmental hazards such as fires or landfill. The complex composition and structure of tire rubber and its additives make them strongly resistant to natural degradation [2]. Most of the waste tire rubber is discarded in landfills, stockpiled and dumped [3]. The volume of waste tires in landfills is increasing because of the considerable growth of vehicle in the United States. Recycling with the waste tires rubber with reduced environmental impacts are full of challenges all over the world.

In recent 20 years, waste tires have been recycled into civil engineering materials, especially into Portland cement concrete. It is reasonable that using rubber as a fractional replacement of traditional aggregates in Portland cement concrete has reduced environmental impacts.

### 1.1.2 Rubberized concrete properties without surface treatment

The use of waste tire in concrete has been studied for a long term. Many properties of rubberized concrete can be improved by comparing regular concrete, such as heat insulation, sound, and energy absorption, free – thaw resistance, and toughness [4, 5]. Nevertheless, the low stiffness of rubber particles leads to a reduction of compressive strength [6, 7], and the low interface bonding strength between crumb rubber particles and cement paste reduced tensile strength[1, 8, 9]. In general, the recycling of rubber tires into Portland cement concrete can reduce environmental risks and save the natural materials. The performances improved by rubber particles is also a convincing proof of using scrap waste tire rubber to replace fine aggregates in traditional concrete.

## 1.2 The surface treatment methods for rubber particles

Some researchers have studied several pre – modified methods for rubber particles, Segre and Joekes [5] using NaOH solution treated rubber particles, they soaking the rubber particles into the solution for 20 minutes. The investigation of the influence of surface treatment on rubberized concrete was also performed. The fraction of the rubber content using in the test was 10 v/v. % of fine aggregates for both originally received tire rubber and NaOH solution treated tire rubber. The results showed that the samples using NaOH solution pre – treated rubber particles provided a significant improvement in compressive strength compared to the samples only containing originally received rubber particles, which confirms that the bonding strength between cement paste and rubber particles can be increased by using NaOH solution pre – treatment method.

Victor C. Li [10] has studied material design, and performance of polyvinyl alcohol fiber reinforced engineered cementitious composites (PVA – ECC). The research found polyvinyl alcohol (PVA) fiber can be considered as one of the most suitable polymeric fibers to reinforce engineered cementitious composites (ECC). The optimal interface abilities should be in the range of 1.5 Mpa – 2.5 Mpa for frictional stress and lower than

1.5 N/m for interface fracture energy, which is indicated by a parametric study on tensile ductility. However, the bonding strength of PVA fiber with cement paste is far above the suitable value. Thus, oil – treatment method for PVA fiber were introduced to PVA – ECC material. With the addition of oil, both interface fracture energy and frictional stress have a considerable reduction. Finally, the best oil content was determined as 1.2 wt.% of PVA-fiber

## 1.3 Rubberized ordinary concrete

### 1.3.1 Mechanical properties of rubberized concrete

The size, proportion and surface characteristics of the rubber particles can affect the mechanical properties of rubber – modified concrete.

Topcu, Ilker Bekir [11] studied different mechanical properties of rubberized concrete, the compressive strength and splitting – tensile strength of different rubber size replacement was measured in his research. Tire chips or crumb rubber particles replaced the fine or coarse aggregates. The results showed the compressive strength of coarse replacement has an about 30 % reduction compared to fine replacement, which is a considerable reduction in the compressive strength. For fine aggregates replacement, the result shown that the 15% replacement content only reduced about 10% of the compressive strength compared to regular concrete without rubber particles. They also found that the compressive strength of rubberized concrete decrease when the rubber content was increased. Khatib and Bayomy [12] found that the fresh properties like slump was approached to zero and the concrete does not have a good workability when the rubber replacement content get more than 40%.

For tensile strength, the splitting – testing test performed by Topcu, Ilker Bekir [11] shown that fine aggregates replacement samples have 30% reduction compared with the control concrete samples, while coarse aggregates replacement have more than 50% decreasing compared to the normal samples. However, specimens showed high ability of absorbing plastic energy as wanted. The failed specimens had measurable post – failure loads and sustained significant displacement, which was fractionally recoverable. The different performance shown in this result can be explained by the rubber aggregates, which has a high capacity of standing large elastic deformation before its failure point [13].

These studies indicates that using crumb rubber particles replace aggregates will decrease the compressive and tensile strength, the fine aggregates replacement is feasible when rubber content is lower than 25%. At the same time, using rubber particles to replace fine aggregates can reduce the construction cost, which is an eco – friendly method for recycling waste tire rubber.

### 1.3.2 Transport properties

The durability of concrete is mainly affected by the transport properties. Several parameters that mainly govern the transport of fluids in concrete, such as capillary absorption, permeation and diffusion [14]. Thomas, Gupta [15] studied the performance of high strength rubberized concrete, they find when the crumb rubber content is lower than 10% of fine aggregates, the permeability was lesser than or similar to the control mix. The specimens with crumb rubber content 12.5% to 20% have shown a higher permeability depth than control samples.

The transport properties of concrete can be measured by Electrical resistivity test. The electron transmitting capacity can be accessed to reflect the permeability of concrete [16]. Yung, Yung [17] found that the electrical resistance of concrete can be improved by adding rubber particles, the more rubber particles in the concrete, the large electrical resistivity can be presented. At the same time, electrical resistance can be improved about 75% to 105% by adding 5% to 20% rubber powder. Additionally, they found the linear regression relationship between compressive strength and electrical resistance, which means there was a good linear relationship between the surface resistance and the compressive strength of the rubberized concrete.

### 1.3.3 Durability of rubberized concrete

#### 1.3.3.1 Shrinkage

Sukontasukkul and Tiamlom [18] studied the drying shrinkage of rubberized concrete mixed with crumb rubber in various size. In this study, they evaluate the effect of crumb rubber content and size on drying shrinkage. The drying shrinkage of rubberized concrete affected by the rubber particle size as well as crumb rubber content. As the replacement fraction increased, the less fine aggregates in the structure induced a higher reduction of internal resistance and caused the larger shrinkage. Bravo and de Brito [19] studied the durability – related performance of the concrete made with waste tire rubber aggregate. They found that afterward drying shrinkage (caused by water evaporation from concrete) is not influenced using rubber aggregates. Even though the durability – related properties of rubber modified concrete was worse than plain concrete, the use of crumb rubber into concrete can have some advantages, such as excellent damping characteristics, good thermal and acoustic performance of crumb rubber modified concrete. Simultaneously, the environmental advantages produced by recycling waste tires should be counted.

#### 1.3.3.2 Chemical attacks

The durability of concrete can be reduced by the chemical attacks in the concrete structure. The chemical attacks include carbonation of concrete structure, chlorides attacks, sulfates attacks, and alkali – silica reaction (ASR) in concrete structures [20].

Alkali – silica reaction (ASR) is defined, the expansion happened when particular types of aggregates were mixed in concrete with adequate alkalinity and enough moisture, which could cause the loss in strength and elastic modulus of concrete [21]. Youssf, ElGawady [22] found that the crumb rubber contributed to reducing ASR damage when added to normal concrete. The result evidenced that the ASR expansion in mortar samples can be decreased to 43% by adding rubber aggregate to plain concrete. Consequently, the rubberized concrete may have a better ASR expansion resistance.

## 1.4 Rubberized Fiber- reinforced concrete

### 1.4.1 Development of fiber – reinforced concrete

It is noticeable that tire rubber modified concrete has a comparably high toughness. Notwithstanding, the strength and elastic modulus reduced by added rubber particles[23]. Fiber reinforced concrete (FRC) has been well used in various structures such as concrete slabs, shotcrete, architectural panels, precast concrete slabs, ultra-high-performance concrete and many other applications [24, 25]. Based on fracture toughness values, steel fiber is at least 100 times greater than regular Portland cement concrete. The brittleness of concrete often induces cracks in the service period, which are easy accessed routes for deleterious agents resulting in early saturation, freeze – thaw damage, and steel corrosion [24]. Steel fiber reinforced concrete is commonly used in the construction. The low tensile strength and strain ability of high – strength concrete (HSC) can be improved by steel fiber, considering steel fiber has a very high tensile strength [26].

### 1.4.2 The use of PVA – fiber into engineered cementitious composite

In order to improve the strength and stiffness of rubberized concrete, various kinds of fiber have been utilized to the rubberized concrete [22, 27, 28] . In this research, polyvinyl alcohol (PVA) fiber has been used into rubberized concrete, because polyvinyl alcohol (PVA) fiber has very high elastic modulus and tensile strength [29]. The reduction of elastic modulus in rubberized concrete can be increased by polyvinyl alcohol (PVA) fiber. Some research shows that polyvinyl alcohol – engineered cementitious composite (PVA – ECC) has a strain – hardening behavior and the capacity of tensile strain can reach 4% [30]. However, the possibility of using polyvinyl alcohol (PVA) fiber into conventional concrete, especially rubberized regular concrete, still has many properties to be studied.

### 1.4.3 Flexural behavior of rubberized fiber – reinforced concrete

Flexural strength or bending strength is a material property, which is defined as the stress in concrete structures before it yields in the flexural test [31]. The transverse bending test is the most frequently used, in which a specimen was having either a circular or rectangular cross – section is bent until fracture or yielding using a three-point flexural test technique.

The flexural strength indicates the highest strength experienced within the material at its moment of yield. Alhozaimy, Soroushian [32] studied the mechanical properties of polypropylene fiber reinforced concrete, which included flexural behavior. They prepared the specimens with different fiber content as 0.0%, 0.05%, 0.1%, 0.2% and 0.3%. They found that the polypropylene fiber did not have much improvement in the flexural strength. The different fiber fraction volume did not have any impacts on the flexural strength either. However, the flexural toughness was significantly changed by the addition of polypropylene fibers. The improvements in flexural toughness due to the addition of 0.1, 0.2 and 0.3 % polypropylene fibers were 44, 271, and 386% over the control mix. This result indicates that fiber can modify the brittleness of concrete, which could be used into rubberized concrete and improve the flexural toughness together with crumb rubber particles.

The mechanical properties of polyvinyl alcohol (PVA) fiber reinforced engineered cementitious composite (PVA – ECC) has been studied a long time by Li, Wang [29]. The typically tensile strength of polyvinyl alcohol (PVA) fiber is between 1600 and 2500 MPa. The cost of PVA fiber is even lower than that of steel fiber based on an equal volume. However, several types of research represented that PVA fiber reinforced cementitious composites shown relatively low strain capacities, evenly lower than 0.5%. They were not defined as high – performance based on the aforementioned criteria. The reason for this situation can be explained by the sturdy interfacial chemical bond between PVA fiber and cement paste. In order to solve this problem, they introduced an oil agent to modify the extra bonding strength, which improved the performance of PVA – ECC materials.

The flexural behavior of PVA – ECC were studied by Wang and Li [10]. They performed four-point bending test for specimens, which is a refinement of three-point bending test. They prepared the beam specimen with the standard size measures 304.8 mm (length) by 76.2 mm (width) by 25.4 mm (depth), and four-point bending test span configuration is 101.6 mm by 76.2 mm by 101.6 mm.

The bending stress increased continuously when the displacement was enhanced, which shown a significant deflection – hardening behavior. At the same time, the average crack spacing is below 1.5 mm.

However, the PVA –fiber reinforced rubberized concrete properties still need to be studied, especially the flexural behavior under the collective effect by crumb rubber particles and PVA – fiber.

## 1.5 The development of rubberized self – compacting concrete (SCC)

Recently, the durability performance of concrete structures has been studied frequently. The construction of durable concrete structures needs adequate compaction [33]. The labor in American is more expensive than other developing countries. Self- compacting concrete (SCC) is one of the best solutions, as SCC can be compacted into each corner of a formwork, especially only depends on its own gravity. Waste tire rubber can be used to self – compacting concrete (SCC) [34], which is also a good way for recycling waste tire rubber. Because of the low air voids content within self – compacting concrete (SCC), it eliminates the water get through the voids near rubber particles. At the same time, fiber reinforcement can also be employed to self – compacting concrete (SCC) [35]. The durability of the concrete can be highly improved by self – compacting technology in company with fiber reinforcement technique. With the development of urbanization, ultra-high structure, structure with large span and special shape are arising to the world. The difficulties of construct these structures can be solved by using ultra-high-performance concrete [36]. Ultra – high performance concrete (UHPC) are defined as cementitious – based composite materials with discontinuous fiber reinforcement [37], UHPC has a very low water to cement ratio of about 0.20 to 0.25, which provides an extremely dense and strong structure after hardening. The compressive strength of ultra – high performance concrete can reach more than 21.7 ksi (150 Mpa) after 28 days companying with the great improvement in durability [38]. Crumb rubber from waste tires also can be used to replace fine aggregates in UHPC to overcome the high cost, and keep the excellent properties.

## 1.6 Research Objective

1. Evaluate the mechanical and durability performance of PVA fiber-reinforced rubberized concrete

In this research, waste tire rubbers were added into PVA – fiber reinforced concrete. Rubberized concrete contains an excellent durability, but the elastic modulus and the strength of concrete are reduced. To improve the mechanical properties of rubberized concrete, PVA-fibers were added for the reinforcement. The rubber particles were used to replace the fine aggregate in different volume ratios. The amount of PVA-fiber content have been optimized as 0.5 v/v.% based on concrete volume.

The prepared specimen for this objective study will include five groups,  plain concrete (CO), concrete with 0.5 v/v.% PVA –fiber reinforcement (FCO), PVA – fiber reinforced concrete with 15 v/v.% rubber (FR – 15), with 20 v/v.% rubber (FR – 20) and 25 v/v.% rubber (FR – 25).

The mechanical properties will be measured in this research. Electricity resistance will also be used to measure the transport properties of rubberized concrete. At the same time, the durability was evaluated by shrinkage, ASR expansion and free- thaw test. Then, the mechanical properties were assessed, compressive test, indirect tensile test, and flexural test were performed. Finally, finite element simulation was operated to verify the three-point bending test result of flexural behavior. According to posted results, the rubberized PVA fiber – reinforced normal concrete has a good durability and relatively good mechanical performance.

2. Evaluate the mechanical and durability performance of rubberized self-compacting concrete

Self – consolidating concrete (SCC) is defined as high-performance concrete (HPC). SCC has a better workability company with high strength than normal concrete. However, the cost of SCC is much higher than plain concrete. Hence, in this research, the waste tire rubbers are considered as the cost – effective replacement of fine aggregate in SCC. Nevertheless, the high-performance may be affected by added rubber particles.

In this research, a small amount of rubber particle was added into SCC. The mechanical properties, such as compressive strength, indirect tensile strength were tested. The results of these tests shown the feasibility of using waste tire rubbers to replace the fine aggregate in SCC. Meanwhile, the cost and environmental impacts can be subsided by making use of waste tire rubbers.

# Chapter 2. Experimental investigations of rubberized PVA-fiber reinforced concrete

## 2.1 Research significance

Although the properties of PVA-ECC have been studied exhaustively in last few years [10, 27, 29, 30, 32], there is a great deal of work that needs to be discovered in the field of normal concrete, especially using PVA-fiber in rubberized concrete. Hence, the extensive experimental research was carried out to produce rubberized concrete incorporating with polyvinyl alcohol (PVA) fiber. Transport properties (such as electricity resistance, ultrasonic wave transmission speed), strength (compressive, splitting tensile and flexural), flexural toughness of specimens with a various volume percentages of fiber and rubber were evaluated.

## 2.2 Production of samples

### 2.2.1 Material properties and gradation of aggregates

The experiment used ASTM Type I Portland cement (as per ASTM C 150 [39]) as binder. The chemical and physical characteristics are introduced in Table 1 Properties of cement.

Figure 1 Type of the cement

Table 1 Properties of cement

| Chemical analysis (%) | Cement |
|---|---|
| Silicon dioxide $SiO_2$ | 19.8 |
| Aluminum oxide $Al_2O_3$ | 5.5 |
| Ferric oxide $Fe_2O_3$ | 2.49 |
| Calcium oxide CaO | 63.0 |
| Magnesium oxide MgO | 2.4 |
| Sulphur trioxide $SO_3$ | 4.5 |
| Potassium oxide $K_2O$ | - |
| Sodium oxide $Na_2O$ | - |
| $C_3S$ | 52.3 |
| $C_2S$ | 17.4 |
| $C_3A$ | 10.4 |
| $C_4AF$ | 7.6 |
| Total alkali | 1.0 |
| Loss on ignition | 2.0 |

The fiber we used in this investigation is polyvinyl alcohol (PVA) fiber, the properties of PVA-fiber are shown in Table 2.

Table 2 Properties of PVA-fiber

| | |
|---|---|
| Diameter (mm) | 0.04 |
| Length (mm) | 8 |
| Tensile strength (MPa) | 1400 |
| Elongation (%) | 7 |
| Young's modulus (GPa) | 32 |
| Density ($kg/m^3$) | 1300 |
| Chemical stability | Stable |
| Color | White |

The photograph of PVA-fiber is shown below:

Figure 2 Original PVA-fiber

The gradation of aggregates are following the requirements in ASTM C33 [40]. The gradation of coarse aggregates are presented in Table 3 Gradation of coarse aggregates.

Table 3 Gradation of coarse aggregates

| Sieve Size | Weight percent (%) | Dry weight |
|---|---|---|
| 3/4 | 5 | 7.02 |
| 1/2 | 25 | 35.1 |
| 3/8 | 25 | 35.1 |
| No. 4 | 20 | 28.08 |
| No. 8 | 16 | 22.47 |
| No. 16 | 9 | 12.64 |

Superior Sand&Gravel Inc, provides all aggregates in this project. The fine aggregates are well graded by the company. The preparation of the aggregates is shown in Figure 3 Weighted aggregates.

Figure 3 Weighted aggregates

## 2.2.2 Surface treatment of scrap rubber particles and PVA-fiber

### 2.2.2.1 Pre-treatment of rubber particles

The previous studies indicated that the use of waste tire rubber in concrete leads to a reduction in compressive strength, the weak interfacial link between rubber particles and cement paste is the primary reason. The poor adhesion of rubber particles to cement paste is attributed to the existence of zinc, which stearate migrates and diffuses to the rubber surface and create a soap layer that resists water [22]. Surface treatment of rubber particles by using a Sodium Hydroxide (NaOH) solution can remove the zinc stearate covers [41]. In addition, it increases the hydration at the interface, which enhances the bonding.

In this project, the size of rubber particles has been chosen as mesh #10 to mesh #30 and premixed together with a good gradation. The rubber particles were treated in 1N NaOH solution for 30 minutes in a tub. Then, the rubber particles were washed by using clean water until the PH value became 7. Finally, flattened the rubber particles in a flat tray and waited until the rubber particles were air dry.  The figures below shows the mechanisms for the method of treating rubber aggregate.

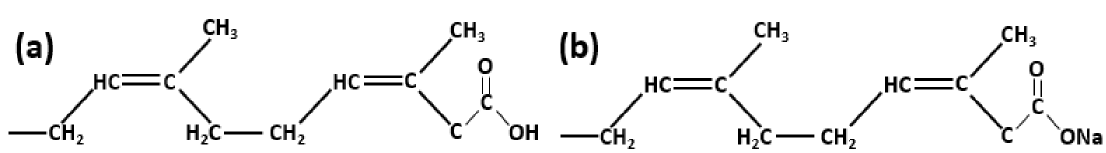



Figure 4 Mechanisms for the method of NaOH solution treatment. (a) The chemical structure of cis-polyisoprene with the carboxylic acid group (b) The chemical structure of the compound of NaOH solution with cis-polyisoprene with the carboxylic acid group

### 2.2.2.2 Oil-coating of PVA-fiber

Polyvinyl alcohol (PVA) fiber have a strong bonding to cemnet paste, the PVA-fiber tends to rupture instead of pullout in a cementitious matrix [30]. In the previous studies by Victor C Li, he found the oil-coating can provide a good solution to the overstrong interfacial bonding. The oil layers on the PVA-fiber surface can decreased the adhension to cement paste, which provided a possibility of pullouting from the cement paste. Consequently, the 1.2% oil content by weight of fibers were used to treated PVA-fiber in this investigation. The PVA-fibers were abundantly mixed with oil before adding to concrete mixture. The photograph of oil-treated PVA-fiber are shown in Figure 5 Fiber with oil coating.

Figure 5 Fiber with oil coating

### 2.2.3 Mixture design

Five groups of samples were prepared in this investigation. The samples without rubber and fiber (CO) and samples with only 0.5 v/v.% PVA-fiber (FCO) were produced as two control group to compared the performance with other variable groups. In this study, the fine aggregates were partially replaced by crumb rubber aggregates. The replacement ratio of rubber aggregates were based on the total fine aggregate volume. The specimens with 15 v/v.% rubber and 0.5 v/v.% PVA-fiber (FR-15) and specimens with 20 v/v.% rubber and 0.5 v/v.% PVA-fiber (FR-20), and specimens with 25 v/v.% rubber incorporated with 0.5 v/v.% fiber (FR-25), were defined as variable groups. Consequently, the mixture design were came up with the difference in rubber content.

Table 4 Mixture design of rubberized PVA-fiber concrete shows the mixture design for two control groups as well as each group with different rubber content. The concrete were producing by using the barrow electrical concrete mixer. Three different types of molds (twenty two 4 in. × 8 in. cylindrical mold, three 3 in. × 4 in. × 15 in. steel beam mold, and three 2 in. × 2 in. × 15.75 in. wood beam mold) were applied to cast the specimens in this investigation, the design volume of each batch is 0.06 cubic yard/ 0.045 $m^3$.

Table 4 Mixture design of rubberized PVA-fiber concrete

| | Coarse Aggregate (kg/$m^3$) | Fine Aggregate (kg/$m^3$) | Portland Cement (kg/$m^3$) | Water (kg/$m^3$) | Rubber (kg/$m^3$) | PVA-fiber (kg/$m^3$) | HRWR (kg/$m^3$) |
|---|---|---|---|---|---|---|---|
| CO | 1404 | 936.2 | 423.1 | 187.5 | 0 | 0 | 0.88 |
| FCO | 1404 | 936.2 | 423.1 | 187.5 | 0 | 7.87 | 0.88 |
| FR-15 | 1404 | 795.6 | 423.1 | 187.5 | 60.6 | 7.87 | 0.88 |
| FR-20 | 1404 | 717.7 | 423.1 | 187.5 | 81.2 | 7.87 | 0.88 |
| FR-25 | 1404 | 655 | 423.1 | 187.5 | 101.2 | 7.87 | 0.88 |

In this investigation, in order to receive the comparable results, the same contents of high-range water reducer were applied to each group. Casting and curing of concrete samples was based on the ASTM C192 [42]. The compressive strength were measured in 3 days, 7 days, and 28 days. The splitting tensile strength and flexural behavior were evaluated in 28 days. In addition, the transport properties and ultrasonic wave transmission speed were accessed in 3 days, 7 days, 14 days, and 28 days.

## 2.3 PVA-fiber reinforced rubberized concrete properties

### 2.3.1 Fresh concrete properties

The fresh concrete properties always related to the workability of concrete mixture. The slump, air content, and unit weight were evaluated during the casting process. The results are presented in Table 5 The fresh concrete properties. With the introducing of PVA-fiber, the slump in FCO group was reduced by CO group. The reduction in slump and unit weight was found in those samples that contains rubber particles. Rubber particles brought air into concrete mixture during the mixing procedure, those air were contained in the rough surface of rubber particles. As the lower specific gravity that rubber particles have, the increasing in rubber aggregates replacement ratio reduced the unit weight. After adding rubber particles, the slump was decreased as well, the situation can be explained by the rough surface of rubber particles, the friction between the components in the fresh concrete mixture were enhanced. The workability of fresh concrete was undermined after adding more rubber particles, since the low content of high-range water reducer, the FR-25 only had 10 mm slump. In addition, the w/c ration and water reducer content were also contributed to the workability of fresh concrete. The FR-15, after adding 5 v/v.% PVA-fiber and 15 v/v.% rubber particles can still remain 15 mm slump value. Since the PVA-fiber has a high capacity of water absorption, the slump of FCO group was also lower than CO group. According to the results, the workability of fresh concrete will reduced by adding PVA-fiber and rubber particles. The slump test in this investigation were lower than the suggested value which used in construction. Not only the water to cement (w/c) ratio we used in this investigation was relatively small, but also the amount of high range water reducer (HRWR) that we used in this project were lower than field construction design. Nevertheless, the workability can be improved in the field pavement construction by adding more water reducer or air entertainer in order to relieve the difficulties on fabrication.

Table 5 The fresh concrete properties

| | CO | FCO | FR-15 | FR-20 | FR-25 |
|---|---|---|---|---|---|
| Slump (mm) | 32 | 20 | 14 | 12 | 10 |
| Air content (%) | 3.9 | 4.4 | 4.6 | 4.9 | 5.1 |
| Unit Weight ($kg/m^3$) | 2375 | 2310 | 2250 | 2195 | 2130 |

### 2.3.2 Compressive strength

The unconfined compressive strength test was performed followed the ASTM C39 [43], 4 in. by 8 in. cylindrical specimens were applied to this investigation. The specimens were evaluated in 3 days, 7 days, and 28 days. The test results were calculated by taking the average value of three samples in each group for corresponding curing periods. The results met the anticipation shown in Figure 6 Compressive strength of different rubber content. The compressive strength decreased after adding more rubber particles. In addition, the application of PVA-fiber also contributed to the reduction in compressive strength. All five groups shows the relatively same compressive strength at 3 days curing. However, the increasing rate of compressive strength in CO and FCO group were accelerated, especially in CO group. This situation can be explained by the different elastic modulus between rubber particles and hardened concrete mixtures. The elastic modules were enhanced during the curing period in cement paste, but kept the same value in rubber particles. After 28 days curing, the FR-25 group shown the lowest strength value.

The compressive strength of FR-15 group can reach 5715 psi (39.4 MPa) after 28 days curing, which is similar to the result gained from the control samples, the results can be an evidence of NaOH-treated method. The pre-treatment method do have an improvement on interfacial bonding. However, comparing the results between CO group and FCO group, the PVA-fiber reduced some compressive capacity in concrete specimens but do not have much impact on compressive strength like rubber aggregate.

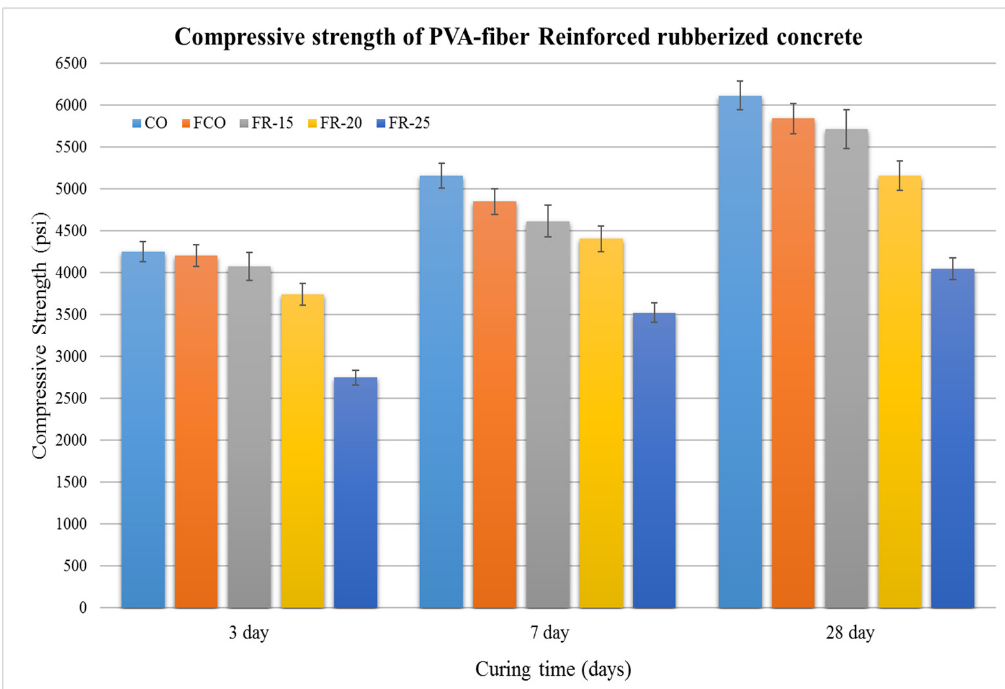



Figure 6 Compressive strength of different rubber content

The strength developed faster in CO and FCO group than other various groups. For 3 days curing data, comparing to CO group, the compressive strength of FR-15 group only has a 6.7% decrease. However, after adding 25% rubber aggregate, the compressive strength was dramatically undermined about 33% capacity. Consequently, the 15% replacement ratio reached an ideally compressive capacity, which indicates that the compressive strength of PVA-fiber reinforced concrete can keep the relatively same performance after adding rubber particles lower than 15%. Added PVA-fiber and rubber particles introduced more air voids and weak interface inside the specimens, which was the dominated effect on compressive performance. At the other hand, the low flowability of fresh concrete after adding fiber and rubber may contribute to the reduction in compressive capacity.

### 2.3.3 Flexural behavior of PVA-fiber reinforced rubberized concrete

The flexural behavior is one of the most important investigations in assessing the performance of fiber reinforced concrete. In this investigation, the different performances after adding various content rubber were evaluated by flexural test. Three-point bending test method was applied to this investigation. Preparation of specimens and test procedure were corresponding to ASTM C31/C31M and ASTM C1609/C1609 [44]. The concrete beams were prepared in 2 by 2 by 15.75 inches. After 28 days curing, the specimens were notched a crack at the midpoint of the bottom. The depth of the crack is 8 mm (0.3 in.). To measure the crack mouth opening displacement, a clip gauge attached to knife edges glued to the specimen was connected to a data collection system in order to record the test results, Figure 7 (a) The depth of the notched crack; (b) glued knife chips below show the prepared specimens.

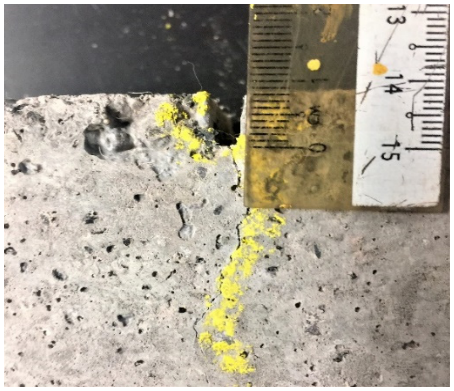
(a)  (b) 

Figure 7 (a) The depth of the notched crack; (b) glued knife chips

#### 2.3.3.1 Flexural strength

The flexural test was performed on prismatic specimens with dimensions of 50×50×400 mm (2×2×15.75 in). The load was located at the center point of the prepared beam. The span under the concrete beam is 250 mm (9.85 in). Before starting to load, the clip-on gauge was calibrated to make sure the accuracy of the results. The MTS machine recorded the load change during the test, and the clip-on gauge captured the displacement curve in the notched crack. The Figure 8 (a) Three point bending test set up; (b) Development of the crack below show the establishment of the test.

(a) (b)

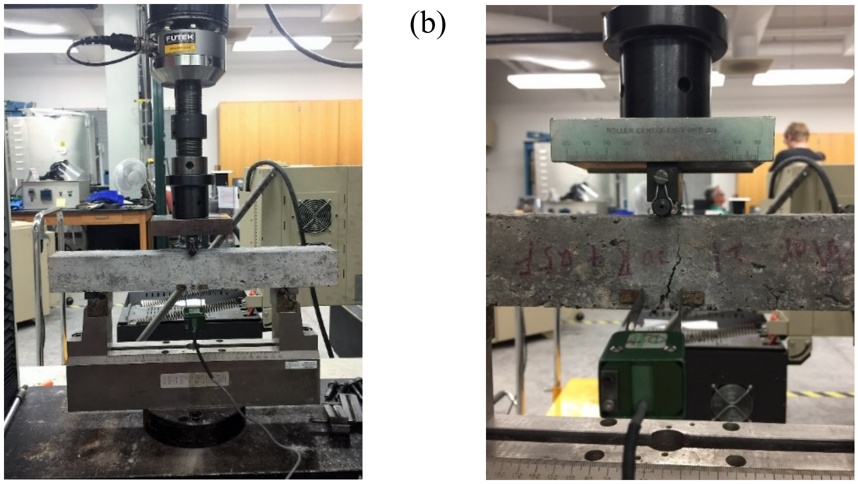


Figure 8 (a) Three point bending test set up; (b) Development of the crack

The test results of different rubber content (15%, 20%, and 25%) with same volume of PVA-fiber, the control group without PVA-fiber and rubber particles, and another control group with only PVA-fiber were recorded. The peak load of each group can be observed in Figure 9. From the test results, the flexural strength reduction was observed after adding more rubber particles. The load capacity of 15% rubber content can still reach 1.8 kN, but after more aggregates were replaced by rubber particles, the flexural strength reduced dramatically. The result of 25% rubber content decreased about 32.21% capacity of flexural strength based on fiber reinforced control group. The flexural strength of 20% rubber content did not show too much improvement when compared to 25% aggregate replacement ratio. The rubber particles not only reduced the compressive strength of concrete, but also undermined the flexural capacity. Thus, the replacement rate of rubber particles were suggested to be lower than 20% in this evaluation.

However, the displacement developed in the notched crack were displayed an opposite results from flexural strength. The 20% and 25% rubber content groups represented a higher number on developed displacement than 15% replacement fraction. Consequently, the toughness of PVA-fiber reinforced rubber concrete should be much higher than plain concrete. This kind of concrete will absorb large impact energy and keep the damaged structure together when it is broken. The displacement in the crack mouth were recorded in Figure 9.  The broken surface showed the distribution of PVA-fiber and rubber particles as Figure 10 (a) Broken samples of the flexural test; (b) The cross-section perspective. The rubber particles were distributed on the surface, some of the PVA-fiber were not dispersed very well, but the PVA-fiber can be still observed all over the fracture surface. At the same time, the PVA-fiber contained the original shape and did not broken around the surface. Hence, the oil-treatment contributed to decrease the exceeded interfacial bonding between the PVA-fiber and cement paste.

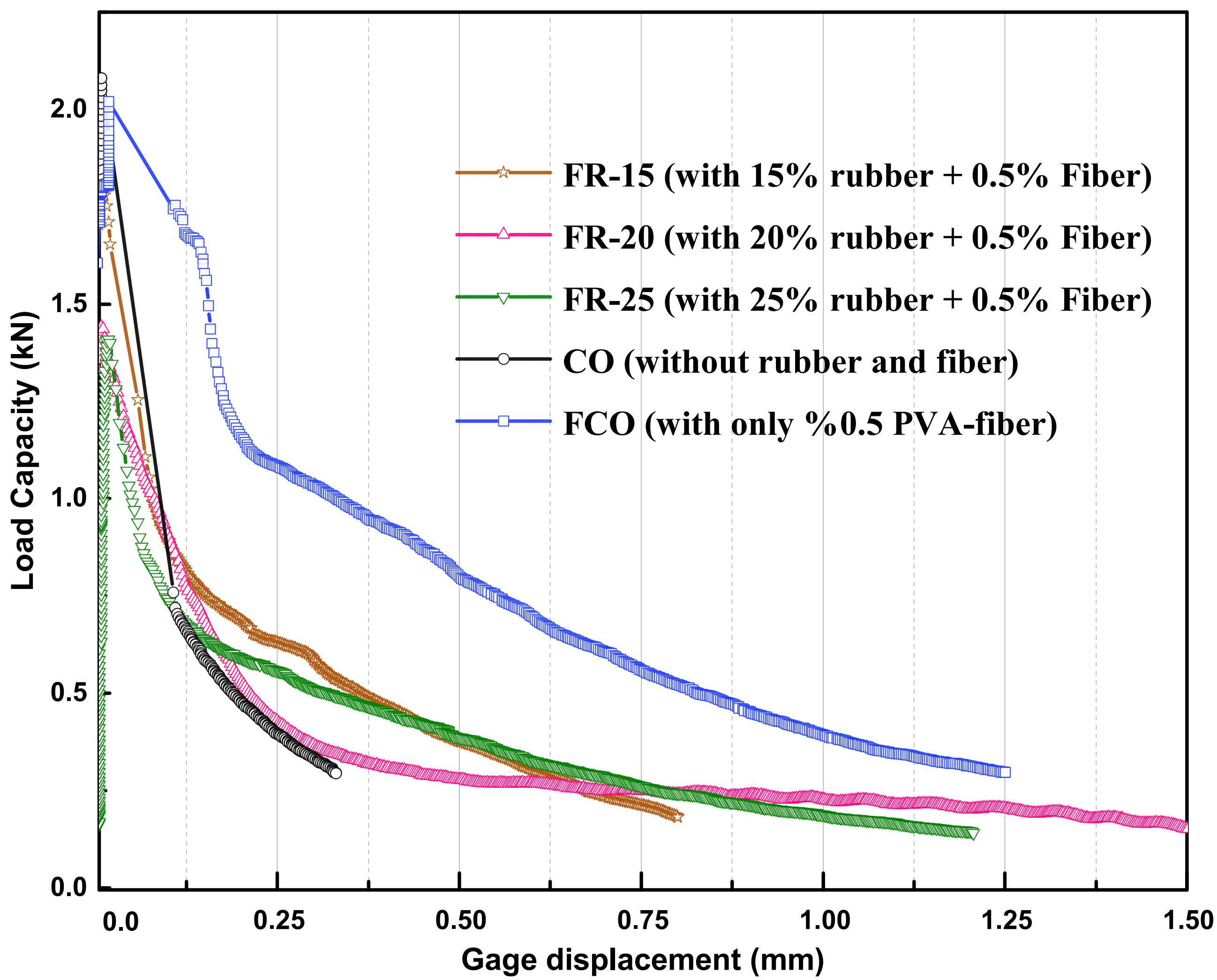



Figure 9 Load-CMOD curves

(a) (b)

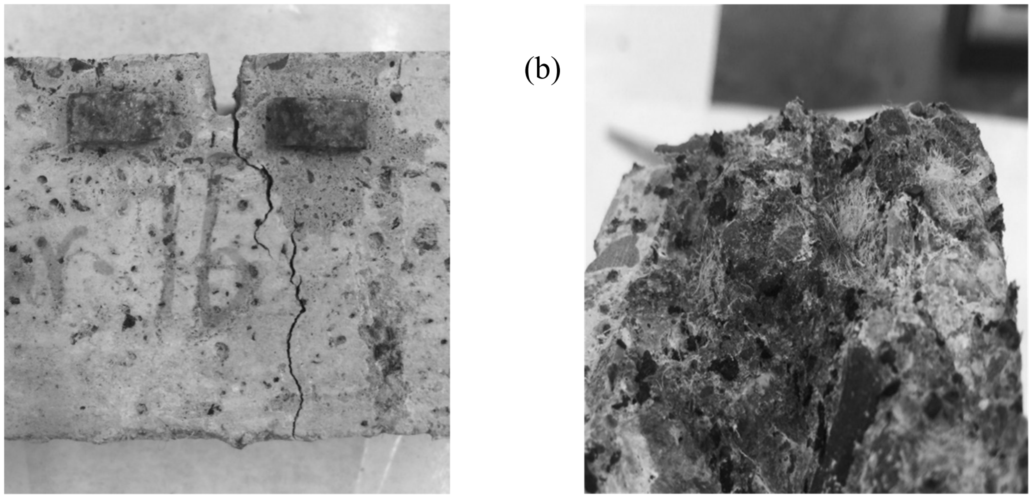


Figure 10 (a) Broken samples of the flexural test; (b) The cross-section perspective

#### 2.3.3.2 Post-crack behavior

The flexural toughness can also be determined using three-point bending test. The first-crack at the notch tip was formed when the gauge displacement changed from zero point on the load-displacement curves. The load capacity at the point of crack occurring can be defined as first-crack strength following the ASTM C1018 [45] in Figure 9 Load-CMOD curves. In the previous study about rubberized concrete, the first-crack strength can be diminished by adding more rubber particles. However, a better deflection behavior were found in the specimens which contain rubber particles. The main crack in rubberized beams, both the width and depth decreased with increasing rubber content [46]. The first-crack strength were undermined by replacing more rubber aggregate. The rubber particles had a relatively lower interfacial bonding with cement paste, hence, the first-crack may occurred early in the specimens which contains more rubber particles. The flexural strength can reach 1.8 kN in FR-15 group. The flexural strength reduced dramatically when the specimens with rubber content over 15%. The first-crack strength in FR-20 and FR-25 were decreased when comparing with FR-15. However, the gauge displacement value were enhanced in FR-20 and FR-25, which indicates that addition of rubber can improve the post-crack performance of plain concrete under bending load. This phenomenal occurred when the tip of the main crack touched the scrap rubber, part of the energy giving rise to further propagation was absorbed by the crumb rubber, which reduced the speed of crack growth, similar to a damper [47].

In this investigation, after adding PVA-fiber to the control group, the flexural strength of the specimens keep the similar value compared with the control group. However, the post-crack behavior displayed a definitely different result. The cracks developed in the notch reached a high value than specimens without PVA-fiber. The displacement in the notched crack can reach about 1.2 mm after increasing rubber content that more than 20%. Furthermore, the addition of PVA-fiber in rubberized concrete resulted in a positive synergetic effect with rubber. The introduction of PVA-fiber not only restrained cracking but also provided significant residual post-peak strength [48]. In this investigation, the feasibility of adding PVA-fiber in rubberized concrete has been proved. The flexural behavior of plain concrete can be improved by both PVA-fiber and rubber aggregates. The fracture energy was calculated followed the load-CMOD curve, the results were shown in the Table 6, the fracture energy was calculated based on the Japan Concrete Institution Standard-001-2003 [49]. From Table 6, after addition of PVA-fiber, the fracture energy of the specimen was increased about 290%, which means the PVA-fiber could provide a considerable improvement in the fracture energy of plain concrete. After introduction of rubber aggregate, the fracture energy was reduced when compared with FCO group. The fracture energy was improved with the increase of rubber content that below 20%, and the value was trended to slowly reduce when the rubber content was over than 20%. However, the fracture energy can still achieve about 2 times higher in FR-15, FR-20, and FR-25 than control specimens.

Table 6 Fracture energy of PVA-fiber reinforced rubber concrete

| Mix ID | Fracture Energy (N/mm) |
| --- | --- |
| CO | 0.0783 |
| FCO | 0.306 |
| FR-15 | 0.136 |
| FR-20 | 0.162 |
| FR-25 | 0.148 |

The equations of the calculation are shown as below:

$$G_F = \frac{0.75W_0 + W_1}{A_{lig}}$$

$$W_1 = 0.75(\frac{S}{L}m_1 + 2m_2)g \cdot CMOD_c$$

Where,

$G_F$ = fracture energy (N/mm); $W_0$ = area below CMOD curve up to rupture of specimen (N*mm); $W_1$ = work done by dead weight of specimen and loading jig (N*mm); $A_{lig}$ = area of broken ligament (b*h) ($mm^2$); $m_1$ = mass of specimen (kg); S = loading span (mm); L = total length of specimen (mm); $m_2$ = mass of jig not attached to testing machine but placed on specimen until rupture (kg); g = gravitational acceleration (9.807 $m/s^2$); and $CMOD_c$ = crack mouth opening displacement at the time of rupture (mm).

The fracture surface of the specimens were observed under microscope. The PVA-fiber were almost pull-out as shown in the Figure 11 Pull-out PVA-fiber captured under microscope.

(a) (b)

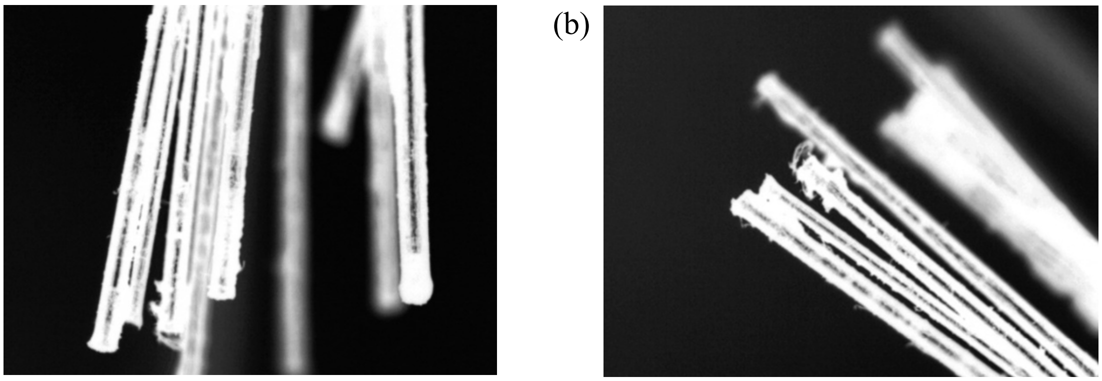


Figure 11 Pull-out PVA-fiber captured under microscope

### 2.3.4 Transport properties of rubber concrete

The electrical resistivity test was performed to investigate the transport properties of PVA-fiber reinforced rubber concrete. The durability of concrete can be affected by electrical resistivity. A higher resistivity value equal to a better durability of the concrete [50]. In this research, the electrical resistivity was evaluated at 3 day, 7 day, 14 day, and 28 day ages with the 4 in×8 in cylindrical specimens. The results of concrete samples incorporating different rubber contents are shown in Figure 12 Electrical resistivity results. As shown in Figure 12, the addition of rubber particles in concrete increased the electrical resistivity of concrete. The FCO group with added only PVA-fiber represented the lowest electrical resistivity in this investigation, the addition of PVA-fiber can contribute to the reduction of resistance. The CO group without PVA-fiber and rubber particle shows the relatively higher value than FCO group. Comparing to CO group, the electrical resistivity was reduced about 6% at 28 days curing. However, the addition of rubber particles dramatically improved the electricity of concrete specimens. In the group FR-15, the resistivity was increased about 31.7% comparing to control samples. The concrete specimens with rubber particles were all performed a better performance of electrical resistivity compared with specimens without addition of rubber aggregates. From the results, the decrease in durability performance of PVA-fiber reinforced concrete can be overcame and improved manifestly by adding rubber particles. In addition, the results revealed that the mounting rubber content under 25% could lead to a better performance on electricity resistivity in PVA-fiber reinforced concrete.

According to the previous results, with addition of PVA-fiber, the workability of the fresh concrete was reduced, which leaded to more air voids and weak surface and finally contributed to the reduction of resistance in specimens. Nevertheless, rubber is a non-porous material, when the rubber particles were used to replace the fine aggregates in concrete, the connection between cement pastes were blocked by rubber particles.

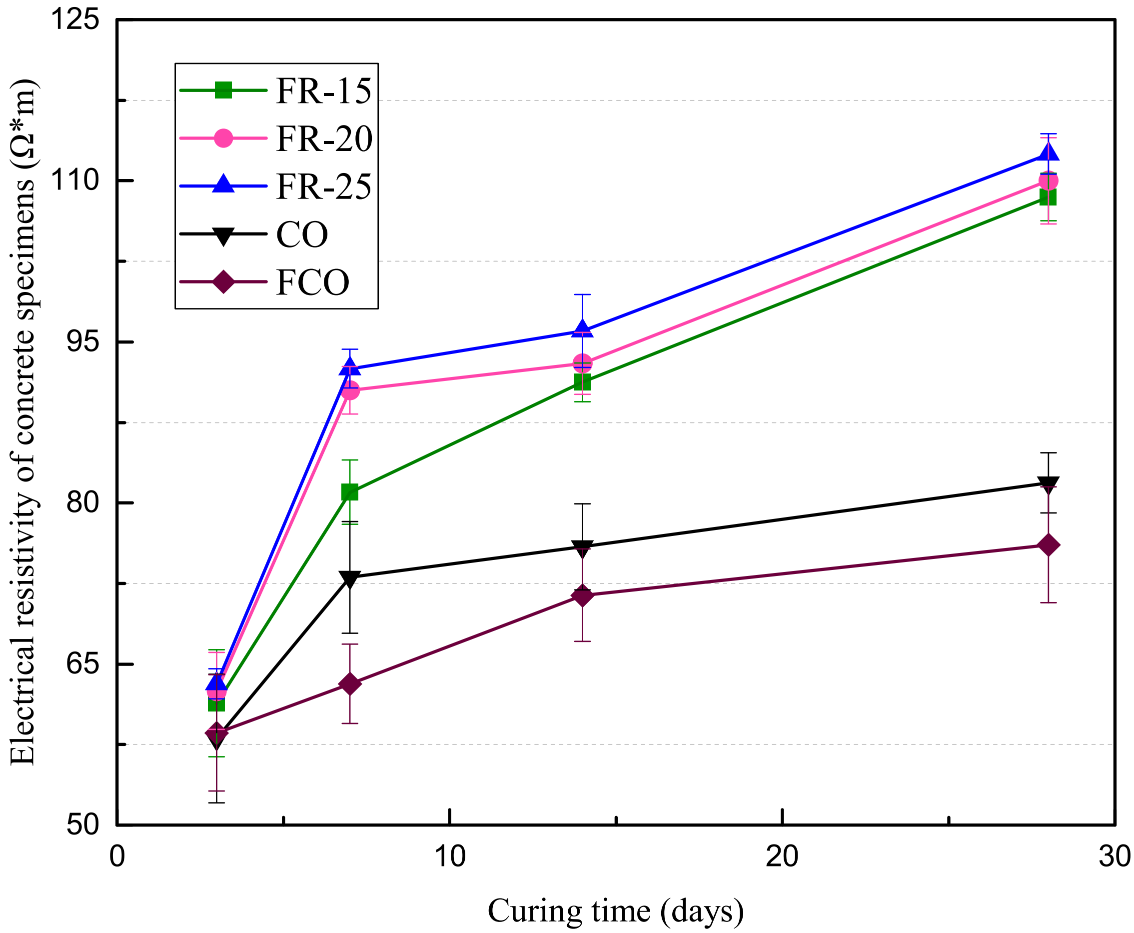



Figure 12 Electrical resistivity results

### 2.3.5 Measurement of Ultrasonic transmission speed

Ultrasonic wave transmission speed is corresponding with the stiffness of a specific material. In this study, the ultrasonic transmission speed has been measured based on the methods of Guo, Dai [51]. The specimens were measured during the curing period at 3 days, 7days, 14days, and 28 days. The ultrasonic wave transmission speed can be used to evaluate the elastic modulus of the concrete specimens with different curing ages and mixture designs. Figure 13 Ultrasonic transmission speed of different rubber contents shows the results of ultrasonic transmission speed test, in which we found that the different replacement ratio of fine aggregate lead to various results of ultrasonic transmission speed. The wave transmission speed was decreased by addition of rubber particles, which indicated that the elastic modulus of concrete specimens could be reduced by addition more rubber particles. It is all known that the elastic modulus of rubber particles are much lower than that in traditional gravel aggregates. This difference is the mainly reason that caused the reduction in elastic modulus of rubberized concrete. The lower elastic modulus of rubberized concrete can produce a better absorption capacity of impact energy. The structure with rubberized concrete can resist massive impact power with the lower elastic modulus, which can be applied to improve the impact resistance. Moreover, rubber aggregate can absorb the energy when suffering an impact like earthquake. Hence, the impact damage could be minimized by addition of rubber particles, comparing to plain concrete. In case of FCO and CO groups, the application of PVA-fiber reduced the wave transmission speed, the lower workability in FCO, which caused more air voids in the specimens and contributed to the reduction on elastic modulus. However, comparing to the effects that caused by rubber particles, the PVA-fiber only had a minor influence on the ultrasonic wave transmission velocity. After 28 days curing, the transmission speed was reduced about 17.5% when comparing to the CO control group. In this part of the investigation, the effects on elastic modulus were observed by evaluating the ultrasonic wave transmission speed, the rubber particles can be used as “damper” in the concrete structure, which will perform better than plain concrete when suffering the impact risk.

Furthermore, with addition of PVA-fiber, the reinforcement can hold the structure together so that resist the impact energy.

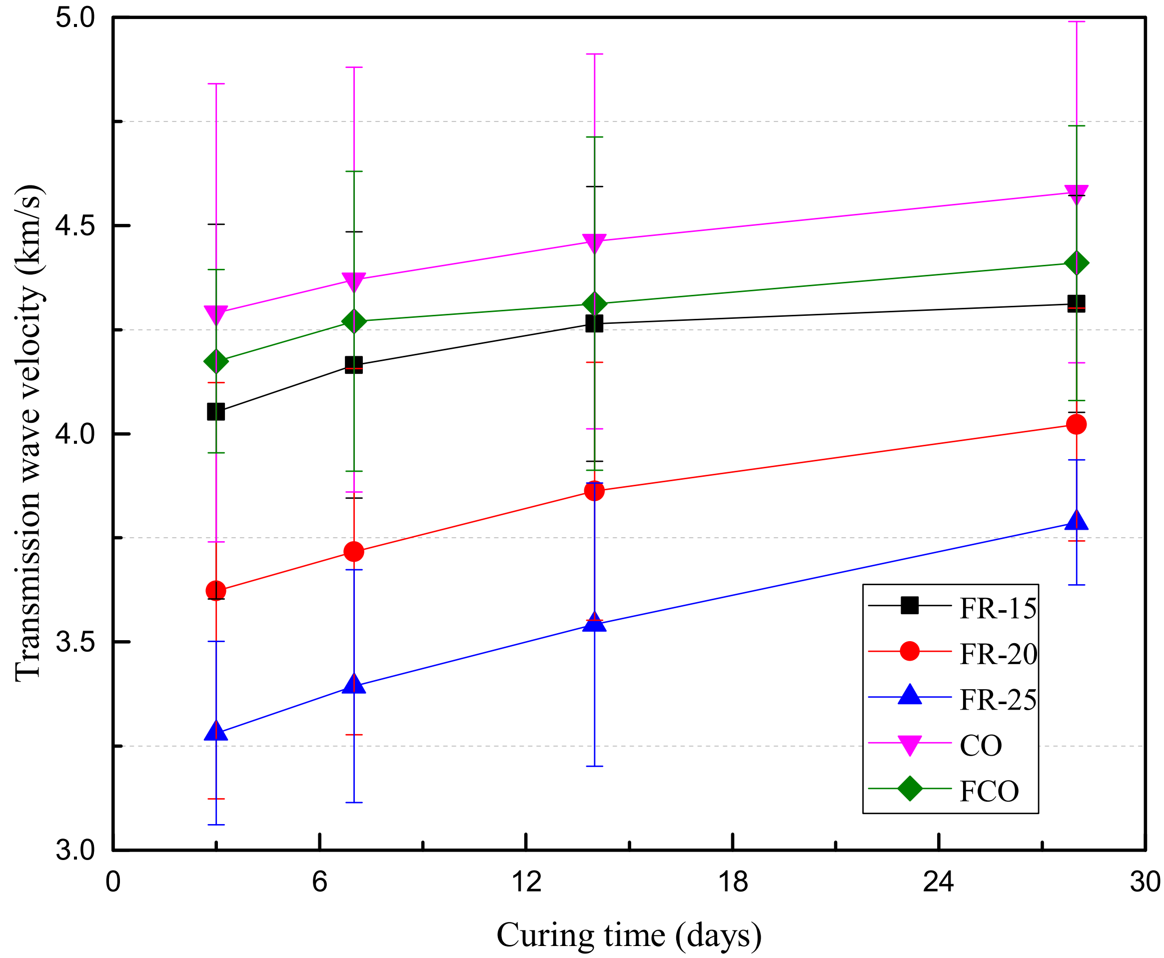



Figure 13 Ultrasonic transmission speed of different rubber contents

## 2.4 Durability of PVA-fiber reinforced rubberized concrete

The durability of PVA-fiber reinforced rubberized concrete were evaluated in this investigation. Shrinkage test, ASR expansion were performed to obtain the results. In this investigation, the specimens were prepared to compare the different performance after applying reinforcement and rubber replacement method. The good durability of concrete means a good ability to resist damage caused by abrasion, weathering, chemical rush [52]. It is universally known that the long-term performance is very important when evaluate a concrete related material. The durability is the main factor, which can affect the long-term service ability of a concrete structure. As we all know, the concrete pavement should have a good durability to make sure the structure keep the work ability under different temperature, humidity, repeated load and freeze-thaw cycle. The maintenance cost of concrete structure can be reduced if there is a good durability. Thus, the drying shrinkage and Alkali-silica reaction resistance were measured in this investigation.

The Alkali-silica reaction was first recognized as a problem in USA in 1940. Alkali-silica reaction (ASR) in concrete is a reaction between certain silicious constituents in the aggregate and the alkali-sodium and potassium hydroxide which are released during the hydration of Portland cement [53]. ASR gel has dramatically hydrophilic properties. The gel can absorb the water and expand during the reaction. Furthermore, the ASR gel can easily transfer to hard component like calcium silica gels. Finally, when the stresses created by the expansion of Alkali-silicate gel exceed the tensile strength between the cement paste and the aggregates. The concrete structure can be damaged by the stresses caused by the expansion of silica gels, the micro-cracks will form and develop. After adding rubber particles, the elastic property of rubber can provide a deformation space under internal stress, the pressure caused by expansion can be absorbed and limit the development of micro-cracks. At the same time, the PVA-fiber can reinforce and hold the cement paste together to resist the micro-cracks. In this investigation, in order to evaluate the ability of ASR expansion resistance, the mortar specimens with or without rubber particles and PVA-fiber were casted. The accelerated ASR expansion test for mortar bars were performed to get the results.

Cement concrete will shrink when the water existed in the capillary pores or CSH gel pores of cement mixture are lost in the air. When the concrete structures expose in the air, the evaporation will occur, and the inner moisture are lost. The tensile capillary stress onto concrete walls surrounding the pores will be increased by the declined vapor pressure in the capillary pores. The tensile stiffness of surrounding cement paste tends to balance the increased tensile stress. Finally, the drying shrinkage of concrete or mortar were caused by internal capillary stress [54]. The drying shrinkage test was performed in this study, the mortar samples were prepared to evaluate the drying shrinkage performance of the PVA-fiber reinforced rubberized concrete. The PVA-fiber were added to the rubberized mortar bar samples. The effects that caused by the PVA-fiber and rubber particles were measured by the length changes. The different performance of drying shrinkage can defined as a factor to evaluate the durability performance of cement related concrete materials. Thus, the drying shrinkage performance of PVA-fiber reinforced rubber concrete can be assessed.

### 2.4.1 Mixture design and sample preparation of mortar bars

In this study, the mortar bar with the 1 in × 1 in dimension of the cross-section were prepared to evaluate the durability performance. The mixture design was based on the ASTM C1260-14 standard [55], the graduation of aggregates was followed the standard. Type I cement was applied in this test. For the fine aggregate replacement, the NaOH treated rubber particles were introduced to the matrix. The rubber content used in this investigation is 15% by the total volume of the fine aggregates. There are four different groups in this evaluation, control group I without PVA-fiber or rubber particles (CO-I), control group II with only rubber aggregates replacement (CO-II), control group III with only addition of PVA-fiber (CO-III), and the last group with PVA-fiber reinforcement and rubber particles (F-R). Three specimens were casted for each group. Consequently, twenty-four mortar bars were prepared for ASR expansion and Shrinkage length change test.

#### 2.4.1.1 Selection of aggregate

The gradation of the aggregate used for the sample production is shown in Table 7 Gradation of aggregates for mortar bar test. The gradation achieved the requirement in the ASTM C1260-14 standard. Crushed sand were used in this project. All sand had been washed by water spray to remove the dust from aggregates. After cleaning, all aggregates were dried in a clean container with a cover.

Table 7 Gradation of aggregates for mortar bar test

| Passing | Retained on | Mass, % |
|---|---|---|
| 4.75mm (No.4) | 2.36 mm | 10 |
| 2.36mm (No.8) | 1.18 mm | 25 |
| 1.18mm (No.16) | 600 um | 25 |
| 600 um (No.30) | 300 um | 25 |
| 300 um (No.50) | 150 um | 15 |

**2.4.1.2 Mixture proportion of each group**

After determining the aggregates gradation, the different weights of each component in the mixture were calculated in Table 8. The rubber replacement ratio used in this study is 15%. At the same time, the PVA-fiber had been oil treated before adding to mixture, the pre-treated oil content was 1.2 wt. % of fiber. The weight was based on the volume of making three mortar bars. For ASR expansion test and drying shrinkage test, three mortar bars were made incorporating with each group, respectively. The water to cement ratio was determined as 0.44 in this study, which was same as the water to cement ratio in the previous concrete mixture design.

Table 8 Weights of each component

| | Water (g) | Cement (g) | Sand (g) | Fiber/ Rubber (g) |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| CO-I | 300 | 666.5 | 1500 | |
| CO-II | 300 | 666.5 | 1275 | Rubber: 97.5 |
| CO-III | 300 | 666.5 | 1500 | Fiber: 7 |
| F-R | 300 | 666.5 | 1275 | Rubber: 97.5，Fiber: 7 |

*1.The fiber need to be pre-treated with 0.1g oil 2. Using NaOH treated rubber particles

#### 2.4.1.3 Sample preparation of mortar bars

After determining the mixture proportions of each group. The samples were prepared follow the same procedure, the fibers were added after matrix was well mixed. The mortar-bar wood molds were applied to cast the specimens. All molds were covered with a plastic film after the molds were fulfilled to make sure the moisture did not evaporate to the air. 12 specimens were prepared for ASR expansion test and eight specimens were prepared for shrinkage test. Figure 14 Prepared mortar-bars shows the process.


Figure 14 Prepared mortar-bars

### 2.4.2 ASR expansion test results

As we know, the durability of concrete can be influenced by ASR expansion, the cracking will undermine the concrete structure, which is hard to fix. The accelerated ASR expansion test were performed in this investigation to detect the different potential alkali reactivity of the mixtures. The mortar-bar method was introduced to this study follow the ASTM C1260 [56] standard. The lengths of different groups were measured in specific curing time. All specimens were demolded 24 hours after remaining in the molds. Those samples were put into a container with distilled water. Then, the container had been sealed and placed in an oven at 80.0 C° for 24 hours. After that, the length of each sample was measured as the initial value. Finally, all specimens were placed into 1N NaOH solution and returned to the oven at 80.0 C°. After that, the length of specimens were measured and recorded in 3 days, 7 days, 11 days, and 14 days. The length changes were calculated and ploted in the figure below. The different results were showed in the Figure 15 ASR expansion test results, from the figure, the largest expansion happened in control-1 group. The expansion rate in control-1 group always keeps higher than other groups. After addition of NaOH solution treated rubber-particles, the ASR expansion rate was reduced in control-2 group. Furthermore, the application of PVA-fiber had a dramatically reduction in the ASR expansion rate, which means the PVA-fiber can improve the resistance of the Alkali-silica reaction. During the first 7 days, the C-3 group with 0.5% PVA-fiber reinforcement had the lowest ASR expansion rate. Comparing C-2 group with only rubber particles with F-R group with rubber and fiber, the similar increasing trends were found from the results. After 11 days curing in the 80 C° NaOH solution, the groups with addition of PVA-fiber shown a better ASR expansion resistivity than those which without fiber. The control-3 fiber-reinforced group with PVA-fiber showed a better ASR damage resistance than control-2 group which was without reinforcement. The excepted results also shown in results at 14 days. From the ASR expansion test, the PVA-fiber do have an improvement on controlling the ASR damage in the mixture, which means PVA-fiber reinforcement can help the resist the deformation caused by Alkali-silicate reaction, the PVA-fiber were randomly separated in the mixtures, the good bonding strength can help tight the cement paste and reduce the expansion by ASR.

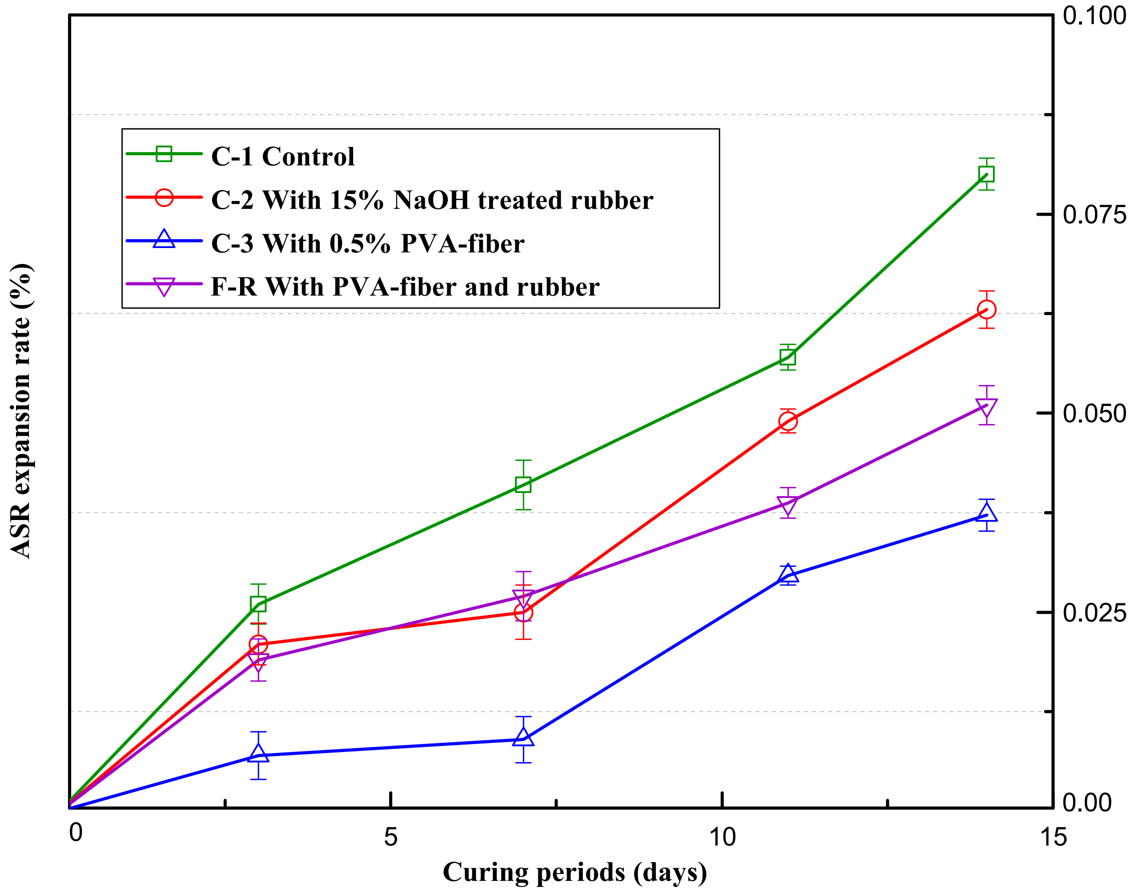



Figure 15 ASR expansion test results

### 2.4.3 Shrinkage test results

In this investigation, the drying shrinkage test was applied to evaluate the free shrinkage behavior in the PVA-fiber reinforced rubber concrete. The drying shrinkage test was performed following the ASTM C157/C157M [57]. Five different test groups were prepared to compare the different performance of drying shrinkage behavior. The control group (C-1) without rubber particles and PVA-fiber, the control group (C-2) with only rubber particles, the control group (C-3) with only fiber reinforcement, and the group (F-R) with PVA-fiber and rubber particles. The all specimens were produced and demolded after 24 hours. The specimens were stored in the curing room, which had the humidity controller. The humidity of the room was settled up as 50%. All specimens were measured at 3 days, 7 days, 14 days. The effects of different mix designs on free shrinkage can be determined by measuring the shrinkage strain in concrete. The results were recorded in Figure 16 Test results of drying shrinkage length changes. From the results, the specimens with only PVA-fiber had the lowest length change during the curing period. However, the introduction of partially replacement of fine aggregate using rubber particles increased the strain in the specimens (C-2), comparing to control (C-1) group, was increased about 13%. After addition of PVA-fiber, the length change caused by free drying shrinkage had been reduced about 21.1% comparing to C-2 group. Obviously, the application of PVA-fiber dramatically improved the performance of drying shrinkage resistance. The PVA-fiber itself has a good chemical stability, and a good ability in alkaline resistance. The relatively high drying shrinkage behavior in rubberized concrete can be controlled by using PVA-fiber as reinforcement. The PVA-fiber has a good adhesion to cement matrix, in alkaline environment, calcium hydroxides are easy to absorb to PVA molecule due to their affinity [58]. The good bonding strength between fibers and cement paste can resist the internal stresses caused by shrinkage.

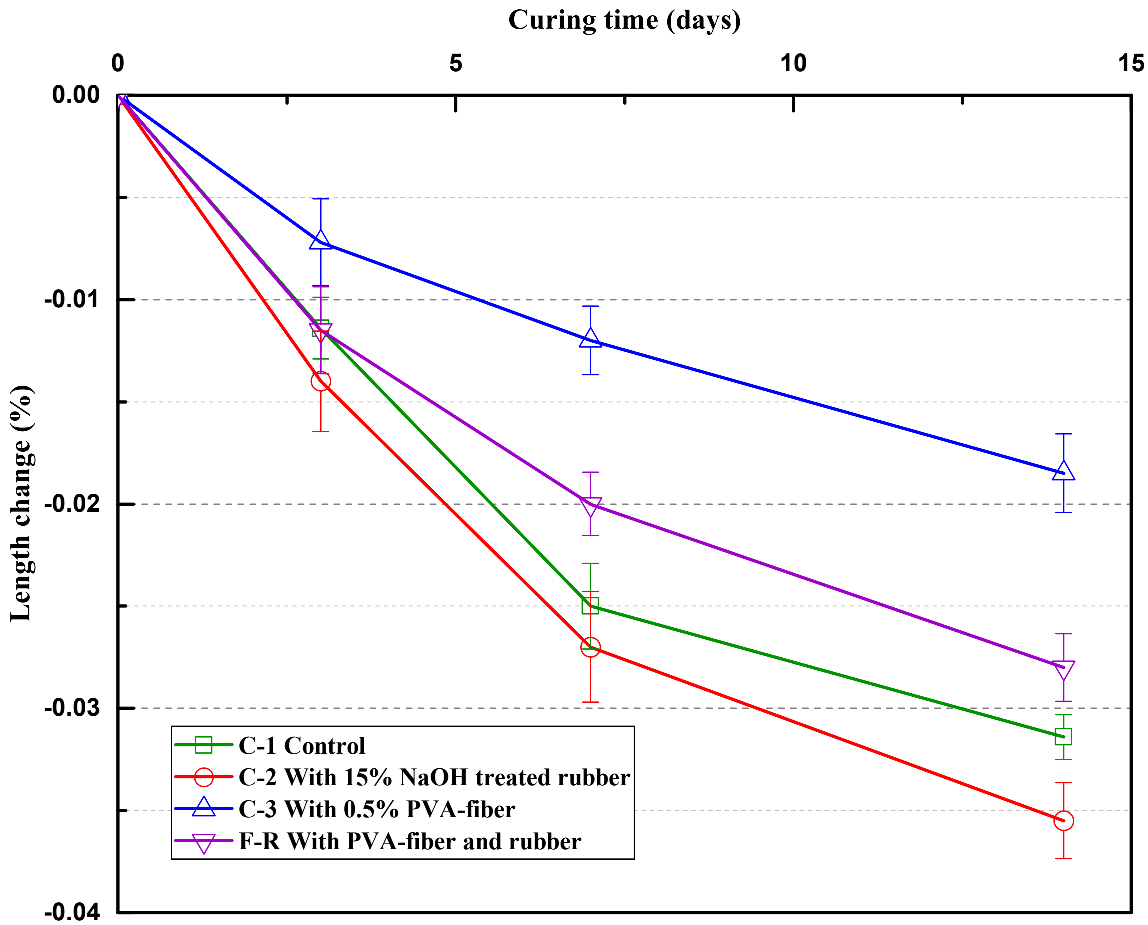



Figure 16 Test results of drying shrinkage length changes

## 2.4 Conclusion

In this investigation, the PVA-fiber was introduced to rubberized concrete to enhance the mechanical and durability performance. NaOH solution and oil agent were used to pre-treat the rubber aggregate and PVA-fiber. The concrete samples containing different rubber content were reinforced by PVA-fiber, two control groups and three various groups were prepared in this investigation. The mechanical properties, transportation properties, and longitudinal dynamic modulus were measured to evaluate the PVA-fiber reinforced rubber concrete.

In the compressive test, the strength after applying of PVA-fiber had a tiny reduction. After addition of PVA-fiber, the workability of fresh concrete was reduced a lot, which induced more pore structure in the concrete matrix. As expected, the FR-15 group, with partially substitute of fine aggregates by 15% rubber particles, still maintained a high strength (5704 psi (39.4 Mpa), 28days) even with the application of PVA-fiber and rubber. At the same time, the compressive strength showed a decreasing trend when the rubber content was increased as expected. However, the compressive strength still reached the standard strength (4000 psi (27.6 Mpa), 28 dys) after addition of 25% rubber particles in company with PVA-fiber. From this test, the PVA-fiber reinforced rubberized concrete can obtained a relatively high compressive strength after adding rubber particles and the PVA-fiber can keep the broken parts together instead of separating.

The addition of PVA-fiber showed a positive promotion on flexural performance. Even though the flexural strength were reduced by addition of rubber particles, the specimens shows a good ductility. The cracking behaviors were observed after flexural test. The relatively lower elastic modulus of rubber particles improved the flexural toughness in company with the high tensile strength of PVA-fiber. The displacement of the cracked notch can reach a higher value before broken after adding PVA-fiber and rubber aggregates. The specimens can maintain the original shape and do not rupture under the bending load because of the fiber reinforcement. From Figure 11, the specimens with PVA-fiber showed a better post-crack behavior than the control group that without reinforcement, since the PVA-fiber can easily distribute in the concrete mixture, the fiber tighten up the cement paste when the hardened specimens were suffering a tensile force. The flexural toughness of the specimens also improved by PVA-fiber, the relation between the load capacity and the gage dis placement showed a large area under the curve, which means the specimens, could absorb more energy under the loading. The transport properties were influenced by the PVA-fiber, however, the addition of rubber particles represents a substantial improvement on the transport performance, and finally offsets the effect that caused by PVA-fiber.

# Chapter 3. Rubberized self-compacting concrete (RSCC)

Nowadays, the concrete structures become more complicated and artistic. The construction of these kinds of concrete structure looks like more difficult than what that was before. The ordinary concrete materials are not suitable for the developing construction industry. Consequently, the self-consolidating concrete (SCC) was introduced to the world in 1988. The studies on SCC developed rapidly in the past 20 years [33]. Many investigations has been performed to improve the properties of SCC, and has been used into construction industry all over the world. Since SCC has a good workability in the fresh stage, the material can be compacted itself, which could help on saving labor and time in the construction. The previous investigations found that the cost of SCC was normally higher than traditional concrete materials. In order to decrease the costs of SCC, some recycled materials have been applied to replace partial components of the mixtures. In this investigation, the crumb waste tire aggregates were added to SCC mixture. The fine rubber particles (Mesh size 7-13) was chosen to replace the fine aggregate. Rubberized self-compacting concrete (RSCC) were prepared with volumetrically 15% untreated rubber particles and 15% NaOH solution treated rubber particles based on the total volume of the mixture. In addition, the control SCC group without replacement of crumb rubber was prepared to compare the different properties. The RSCC properties were evaluated during the curing periods. The fresh-stage properties were measured with V-funnel, U-box, and slump tests. In addition, the compressive strength, splitting tensile strength, transport properties, and electricity resistance were investigated. In this study, the durability performances of RSCC were also observed, ASR and drying shrinkage test were operated.

## 3.1 Mixture design

### 3.1.1 Mixture design of RSCC

In this investigation, the RSCC samples were prepared in three different groups, incorporated with one SCC control group. The different RSCC specimens were prepared with different rubber content and rubber treatment method. Crumb rubber (size, 1.44mm-2.83mm) volumetrically replaced the fine aggregates in the mixture. The specimens with 15% (RSCC-OH15) and 25% (RSCC-OH25) NaOH-solution treated rubber particles were prepared to compare the effects of different rubber replacement contents. In order to assess the pre-treatment method, the specimens with 15% as-received rubber particles (RSCC-15) were prepared. In addition, the control samples (CO) were prepared without rubber particles. In this investigation, the cement were partially replaced by fly ash as binder in the mixture. HRWR was also introduced to achieve the required SCC fresh properties. The mixture design shown in the Table 9 Mixture proportions of RSCC (kg/m$^3$)

Table 9 Mixture proportions of RSCC (kg/m$^3$)

| Specimens | CA | Sand | Rubber | HRWR | Cement | Fly ash | Water |
|---|---|---|---|---|---|---|---|
| CO | 777 | 790 | 0 | 2.42 | 430 | 120 | 215 |
| RSCC-15 | 777 | 671.5 | 51.23 | 2.42 | 430 | 120 | 215 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| RSCC-OH15 | 777 | 671.5 | 51.23 | 2.42 | 430 | 120 | 215 |
| RSCC-OH25 | 777 | 592.5 | 85.39 | 2.42 | 430 | 120 | 215 |

### 3.1.2 Mixture design of RSCM

In this research, the durability performances of rubberized self-compacting concrete were evaluated by mortar specimens (RSCM), the RSCM specimens were prepared in four different sets. The specimens include 15% as-received crumb rubber (RSCM-15), 15% NaOH treated rubber (RSCM-OH15), and 25% NaOH treated rubber (RSCM-25OH). In order to compare the different performance with plain concrete, the control samples (MCO) without rubber particles were prepared as well. The components of each types were shown in Table 10 Mixture proportions of RSCM (Unit: kg/m$^3$).

Table 10 Mixture proportions of RSCM (Unit: kg/m$^3$)

| Group | w/p | Water | HRWR | Cement | Fly ash |
|---|---|---|---|---|---|
| MCO | 0.42 | 256 | 3 | 435 | 174 |
| RSCM-15 | 0.42 | 256 | 3 | 435 | 174 |
| RSCM-OH15 | 0.42 | 256 | 3 | 435 | 174 |
| RSCM-OH25 | 0.42 | 256 | 3 | 435 | 174 |

The aggregate gradation of the mixture was followed ASTM 1260-14, which was shown in Table 11 Aggregate gradations and rubber replacement content (Unit: kg/m$^3$). In this investigation, the rubber particles were used to replace the No.16 sand in the aggregates based on the total volume of sand.

Table 11 Aggregate gradations and rubber replacement content (Unit: kg/$m^3$)

| No.8 | No.16 | No.30 | No.50 | No.100 | Rubber |
|---|---|---|---|---|---|
| 138 | 346 | 346 | 346 | 208 | 0 |
| 138 | 138 | 346 | 346 | 208 | 90 |
| 138 | 138 | 346 | 346 | 208 | 90 |
| 138 | 0 | 346 | 346 | 208 | 150 |

## 3.2 Samples preparation

### 3.2.1 Mixing procedure

After determining the mixture proportions of different samples. The specimens were prepared and casted in the same procedure. For RSCC, all mixtures were prepared with an electrical concrete mixer with a maximum capacity of 6.0 $ft^3$. Coarse aggregates, fine aggregates (with rubber particles), and other components were weighted before the mixing procedure. All aggregates were firstly mixed in the mixer for 1 min. Half of the mixing water was then added into the mixer and combined with aggregates for 30 s. Then, the binder (cement, fly ash) were added for mixing another 1 min. The HRWR was distributed in the remaining water, and then added into the mixture. At last, the concrete was mixed for 3 min, rest for 2 min, and then mixed for another 2 min. In addition, the mortar samples were mixed by the small mixer, which has a capacity of 0.67 $ft^3$.

### 3.2.2 Casting of specimens

The different molds were filled after testing the fresh properties of RSCC. In this investigation, the hardened performance were evaluated in several directions, compressive strength, splitting tensile strength, and transport properties were conducted. All specimens were stored in the curing room after demolding. The compressive strength were test at 3 days, 7days, and 28 days. The splitting tensile strength were measured at 28 days. The electrical resistivity and ultrasonic wave transmission speed were evaluated at 3 days, 7 days, 14 days, and 28 days. For RSCM, mortar prisms with the dimension of 1 by 1 by 11.25-in were prepared for durability test.

## 3.3 Experimental operation

### 3.3.1 Fresh concrete tests

Since self-consolidating concrete has high flowability, the traditional workability tests for ordinary cement concrete mixture are not sufficient to evaluate the workability of SCC [59]. Some methods for evaluating the fresh properties of SCC such as filling ability, passing ability, and segregation resistance can be investigated by different experiment methods such as slump-flow, V-funnel, U-box, etc. In this study, slump-flow test, V-funnel test and U-box test were operated to assess the fresh properties of SCC and rubber modified SCC.

#### 3.3.3.1 Mini Slump-flow and slump-flow test

The measurement tools used in this study were based on EFNARC SCC guidelines [60]. A mini slump cone with the height 60 mm and a slump cone with height of 300 mm were used to measure the flowability of RSCM and RSCC mixtures. In addition, a stiff non-absorbing plate with the dimension of 1 × 1 m was used as the measurement base in the test. At first, the surface of base plate and slump cone, or mini slump cone, were moistened. The cement mixture was filled to the slump cone or mini slump cone without tamping. Then the extra concrete or mortar above the top of the cone and around the base of the cone was removed. The slump cone or mini slump cone were pulled up to allow the concrete or mortar mixture to flow out due to its own weight. At last, the final flow diameter of the mixture was measured in two perpendicular directions. For RSCC mixtures, the time that the fresh concrete reach the 500 mm spread circle after raising the slump cone was recorded as $T_{50}$ flow time [60].

#### 3.3.3.2 Mini V-funnel and V-funnel test

The mini V-funnel and V-funnel tests were conducted in this investigation to evaluate the filling ability and restricted deformability of RSCM and RSCC mixture, respectively [35]. The procedure of the tests were described in the EFNARC SCC guidelines was used for RSCM or RSCC, respectively. The inside surface of the mini V-funnel or V-funnel should be moistened before the test. Before filling, close the trap door of the funnel. The fresh mixture was filled to the top of the funnel without tamping or vibrating. The trap door was opened 10 sec after the mini V-funnel or V-funnel was filled. The discharge time of the

RSCM and RSCC mixtures from the mini V-funnel and V-funnel, respectively, was recorded as the flow time. For RSCC mixture, the V-funnel was refilled instantly after the flow time was recorded again as the flow time at $T_{5minutes}$ to evaluate the segregation resisitance of RSCC mixture. Similar test operations were applied for the RSCM mixture with the mini V-funnel.

#### 3.3.3.1 U-box test

U-box tests were used for evaluating the passing ability of rubber modified self-compacting concrete. Before filling the mold, the sliding gate of the U-box was closed and the inside surface was moistened. 20 liters of fresh mixture was added into the U-box and keep in the U-box for 1 minute. Then, the sliding gate was removed and the height of the two compartments were measured as $H_1$ and $H_2$. The difference between these two heights is the filling height [60].

### 3.3.2 Hardened concrete tests

#### 3.3.2.1 Compressive strength test

The compressive strength test was conducted based on the ASTM C39 standard [43]. The concrete samples were cast in the cylindrical molds with the dimension of 4 by 8-inches. The samples were removed from the molds after 24 hours. The samples were cured in water at room temperature. Compressive strength of the samples was obtained at day 3, 7, and 28. For each type of mixture, three samples were used to conduct the compressive strength. The average tested value of these three samples were considered as the compressive strength of the mixture.

### 3.3.2.2 Splitting tensile strength test

Cylindrical samples with a diameter of 4 inches and length of 8 inches were used to conduct the splitting tensile strength test according to ASTM C 496 standard [61]. The samples were taken out from molds after 24 hours casting. Those specimens were cured in water at room temperature. Splitting tensile strength test were carried out at day of 28. The average value of three samples was obtained for each type of SCC or RSCC.

### 3.3.2.3 Electrical resistivity test

The surface electrical resistivity of concrete mixture was measured by Giatec Surf$^{TM}$ according to AASHTO TP 95 standard [62]. The Wenner array was applied in these test in which 4 electrodes are placed in a straight line with equal distance. The tow exterior electrodes inserted an alternating current into concrete mixture, while the tow inner electrodes inserted an alternating current into concrete mixture, while the tow inner electrodes measured the electrical potential created by the exterior electrodes. The surface electrical resistivity can be calculated by using Equation 1:

$$\rho = 2\pi a \frac{V}{I}$$

Where $\rho$ is electrical resistivity, a is the distance between two electrodes, V is electrical potential, and I is the alternating current.

The samples used for surface electrical resistivity were 4 by 8-inches cylindrical samples. The samples were placed inside the sample holder. The signal frequency of 13 Hz and the voltage of 25 V was applied during the test according to the requirements of AASHTO TP 95 standard [62].

#### 3.3.2.4 Ultrasonic transmission speed measurement

The ultrasonic transmission speed of the samples was evaluated in this investigation. The 4 by 8-inch cylindrical samples were cut into thin cylinder with a diameter of 4 inches and a thickness about 1 inch. The emitter transducer generated ultrasonic waves and the receiver transducer received the signal, respectively. These transducers wre placed on the two sides of the concrete slides. Both transducers have 500 KHz resonant frequencies. The ultrasonic wave frequency of 0.5 MHz was generated with a function generator. The receiver transducer could detect the first transmission wave signals, and the ultrasonic wave travel time was captured by the system. The ultrasonic wave transmission speed can be calculated by Equation 2 [51]:

$$V = \frac{L}{T}$$

Where V is the velocity of the transmission wave, L is the wave travel distance between the emitter and receiver transducers, and T is the wave travel time.

#### 3.3.2.5 ASR expansion test

The ASR expansion test were conducted on the RSCM specimens. The specimens were prepared with the dimension of 1 by 1 by 11.25. The same procedures were performed as PVA-fiber reinforced concrete did. The length of the specimens were measured at day 3, 7 11, 14, and 21.

#### 3.3.2.6 Drying shrinkage test

Drying shrinkage test were operated to observe the free shrinkage behavior of the rubber modified self-compacting concrete. The measurement methods were same as the PVA-fiber reinforced concrete. The length comparator reading of the specimens were obtained at day 3, 7, 14, 21, and 28.

## 3.4 Test results and discussion

### 3.4.1 Fresh-stage properties

#### 3.4.1.1 Fresh properties of RSCM

The measurements of mini V-funnel flow time with different mixture designs were presented in Table 12 Flow properties of rubber modified self-compacting mortar.

Table 12 Flow properties of rubber modified self-compacting mortar

| Type | Mini Slump flow (in) | Mini V-funnel (s) |
|---|---|---|
| CO | 11.25 | 4.72 |
| RSCC-AS 15 | 9.25 | 4.47 |
| RSCC-OH 15 | 9.88 | 4.22 |
| RSCC-OH 25 | 8.575 | 4.75 |

From Table 12, the introduction of rubber particles did not perform significantly impacts on the results of mini slump flow, with the increasing of rubber particles replacement ratio, the distant of mini slump flow only reduced 2.675 in comparing to CO group. In addition, the results were based on the same dosage of HRWR and w/b ration. From Table 11, with the NaOH-treated method, the fresh concrete had a lightly improvement on mini slump flow results than as received rubber particles. From Table 11, the similar results were observed in the mini V-funnel test, from Table 11, the mini V-funnel results in RSCC-OH 15 showed a slight decrease when comparing to RSCC-AS 15, which containing the rubber particles without NaOH treatment. Form Table 11, after addition of rubber particles, the distance of the mini slump flow was reduced. The mini V-funnel speed was increased with the crumb rubber. After the application of NaOH treated method, the mini slump flow obtained a larger distance with the same rubber replacement dosage, as well as the mini V-funnel test.

According to the results, the NaOH treatment method could provide better fresh properties in the RSCM, the flowability of the concrete. The results showed that the introduction of rubber particles did not have many effects on the fresh properties of the RSCM. The application of HRWR and the NaOH treatment method could help to provide a feasible fresh workability after the replacement of fine aggregate with crumb rubber in RSCM.

**3.4.1.2 Fresh properties of RSCC**

The fresh properties of RSCC mixtures were also investigate in this study. The different results were showed in the Table 13. The fresh properties test set up are shown in Figure

17 (a) Measurement of flow time; (b) Slump test overview. In this investigation, the different properties of RSCC mixtures were evaluated, the ability of filling and passing were determined by the V-funnel, slump flow, and U-box test. The fresh properties of RSCC were decreased with the increasing of rubber content. However, the mixtures still meet the requirement in EFNARC that the value of slump flow are higher than 650 mm, with 15% rubber particles. In addition, the time of slump flow $T_{500}$ was also observed, the results were also reach the values in EFNARC, which was between 2s and 5s. Obviously, the NaOH treated 15% rubber modified mixtures had a high slump flow distance and lower $T_{500}$ than as-receive rubber particles, which indicated that the NaOH solution treatment method has contributed to the improvement of the fresh properties of RSCC mixtures. With 25% rubber particles, the RSCC mixture was failed in the requirements in slump flow test, which was mainly caused by the workability was dramatically reduced by the rough surface of rubber particles. Therefore, the reduction in the fresh properties of RSCC can be partially counteracted by NaOH pre-treat method.

(a)

(b)

Figure 17 (a) Measurement of flow time; (b) Slump test overview

Table 13 The fresh properties of different RSCC mixtures

| Mixtures | Slump flow | | V-funnel | | U-box |
|---|---|---|---|---|---|
| | Spread (mm) | $T_{500}$ (s) | Flow time (s) | $T_{5\,min}$ (s) | $H_2 - H_1$ (mm) |
| CO | 700 | 2.06 | 5.02 | 5.19 | 5 |
| RSCC-AS 15 | 662 | 2.59 | 5.75 | 6.06 | 14 |
| RSCC-OH15 | 665 | 2.3 | 5.41 | 5.61 | 13 |
| RSCC-OH25 | 600 | 1.78 | 7.04 | 7.13 | 14 |

From Table 13, the V-funnel flow time were all lower than 6 s in CO, RSCC-AS 15, and RSCC- OH 15, except RSCC-OH25, which means the mixtures can be qualified as self-compacting concrete followed by Khayat [63]method. In addition, the RSCC-OH 25 can also meet the requirement in the EFNARC standard, which recommended that the V – funnel time result of SCC mixtures should be less than 12 s. Therefore, all of the various mixture designs in this investigation could reach the requirements of V-funnel test. Furthermore, the NaOH treated rubber particles can contribute to the improvement of performance in V-funnel flow time, the V-funnel flow time of RSCC-OH15 was decreased 0.34s compared to the replacement that used original rubber particles. The results indicated that with the NaOH solution treatment, the viscosity of the mixture was reduced. From the results of $T_{5min}$, all of the different mixtures still maintained a good flowability (the increasing of the V-funnel flow time were lower than 3s [60]). Normally, the segregation of SCC mixture was observed by $T_{5min}$, the results form Table 12 can be an evidence that the RSCC mixture has a good ability to resist segregation, even the rubber content was added up to 25%.

The U-box test was also performed in this study. The U-box test was used to evaluate the passing ability of SCC mixtures. From Table 13, the results of U-box test showed that the filling height of the rubberized self-compacting concrete kept the almost same value with the increasing of rubber content and NaOH treatment method. The filling height was increased by adding rubber particles when compared to control group. However, the values still reached the requirement (less than 30mm). Therefore, the fresh properties of RSCC mixtures was feasible and possible to use in the construction.

### 3.4.2 Mechanical properties

#### 3.4.2.1 Compressive strength

In this investigation, the compressive strength of the normal self-compacting concrete and rubber-modified concrete were evaluated. The results were showed in Figure 18.

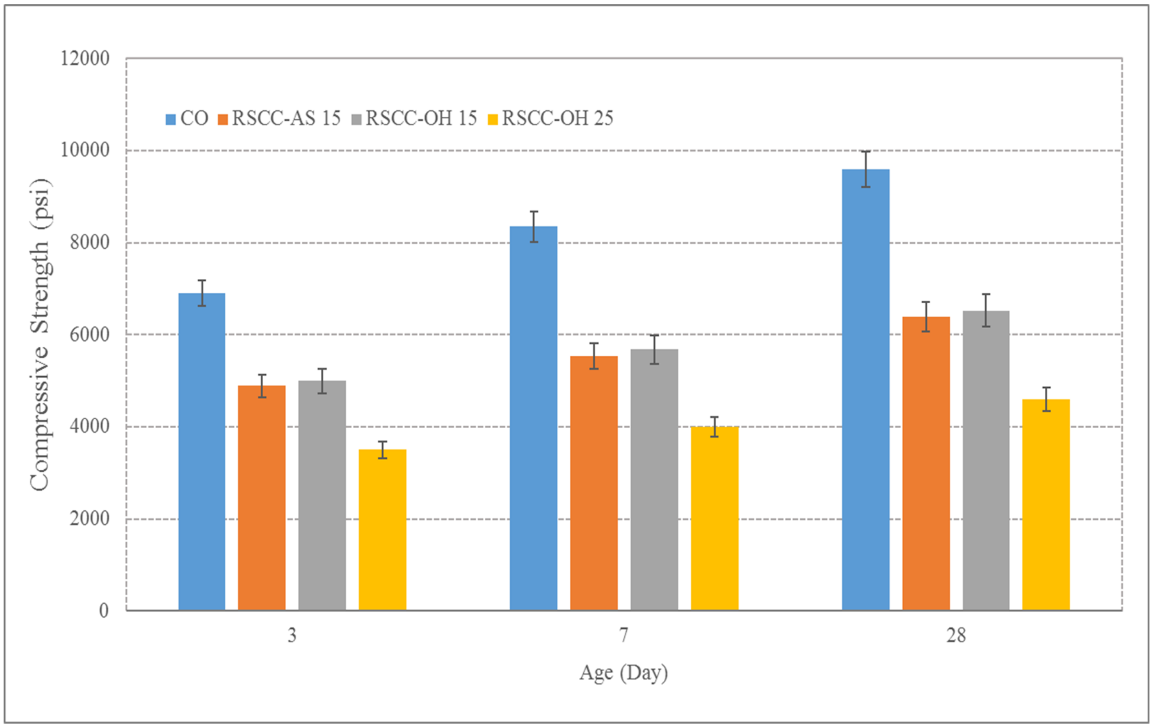



Figure 18 Compressive test reults of RSCC

From Figure 18 Compressive test reults of RSCC, the compressive strength of the rubber modified concrete were reduced when compared with the SCC control group. As previous study shown that the compressive strength of the RSCC mixtures were almost reduced by the lower stiffness of the added rubber particles and the lower bonding strength between the rubber particles and the cement paste. In this investigation, the compressive of the RSCC-AS 15 with 15% replacement of fine aggregate was decreased 33% after 28 days curing based on the value of the SCC control group. At the same time, the more rubber particles in the RSCC-OH 25 caused the more reduction in compressive strength up to 51.5% at 28days.

The introduction of NaOH surface treatment method, the compressive strength in RSCC-OH 15 was increased about 2% based on the results of untreated RSCC-AS 15 group. After the treatment of the rubber aggregate, the bonding strength between the rubber particles and the cement paste was modified. Finally, the modification of the bond may lead to the improvement in the compressive strength.

#### 3.4.2.2 Indirect tensile strength

In this study, the splitting tensile test, which is known as the indirect tensile test was performed to evaluate the tensile capacity of the cylinder specimens. The specimens with increasing rubber content and the specimens with or without surface treatment were tested to compare the various behavior under tensile force. RSCC-AS 15, RSCC-OH15, RSCC-OH 25, and the CO group were involved in this experiment. The results shown that the splitting tensile strength of the specimens was reduced after addition of more rubber particles. In addition, the surface treatment using NaOH solution on the rubber particles did have some contribution to the improvement of the indirect tensile strength. The results of the test were presented in Figure 19 28 days splitting tesnile strength.

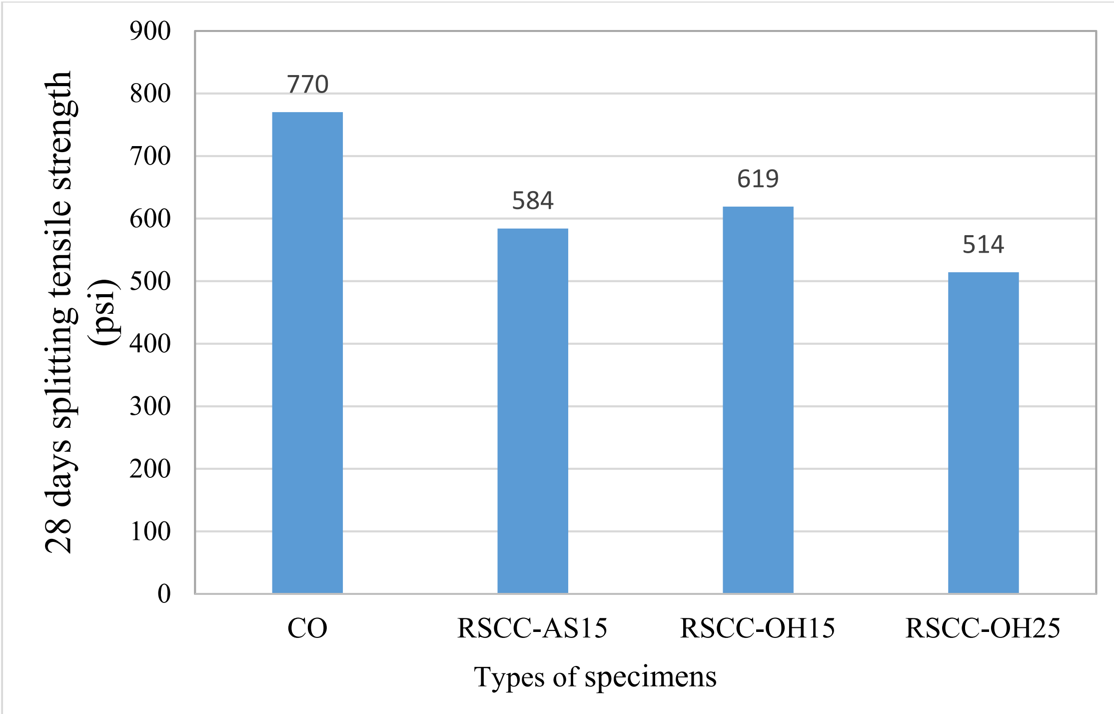



Figure 19 28 days splitting tesnile strength

From the Figure 19, the splitting tensile strength of the specimens were reduced after application of rubber aggregate, 24.1%, 19.6%, and 33.2% reductions were observed in RSCC-AS 15, RSCC-OH 15, and RSCC-OH25, respectively. These reductions may cause by the lower bonding strength between the rubber and cement paste, which is much higher between the traditional aggregate and the cement paste. The same thing was observed in this test, the NaOH treatment method could increase the splitting tensile strength as well as the compressive strength. The splitting tensile strength of RSCC-OH 15 group was increased 6%, comparing to RSCC-AS 15 group. The reduction in splitting tensile strength was lower that it was in compressive strength, from the previous study, this situation can be explained as the rubber particles could absorb the tensile energy and thus prevent the development of the cracks around the rubber particles in the cement paste [64]. In addition, the splitting tensile strength is almost controlled by the large aggregates in the samples, the replacement of fine aggregates by rubber particles may not have much impacts in strength like what it is in the compressive behavior.

#### 3.4.2.3 Transport properties (Electrical resistivity)

The transport properties of concrete can be evaluated by the electrical resistivity test. The concrete specimens contain a lot of pore water under the saturated condition, in which the electrical current is passed mainly by the movement of ions [65]. The capacity of resistance can be defined as the ability to prevent the corrosion. The addition of waste tire rubber do have some effects on it. Thus, the electrical resistivity test was operated to observe the transport properties of the concrete specimens with increasing rubber content as well as the surface treatment method. The test result are shown in Figure 20 Electrical resistivity test results.

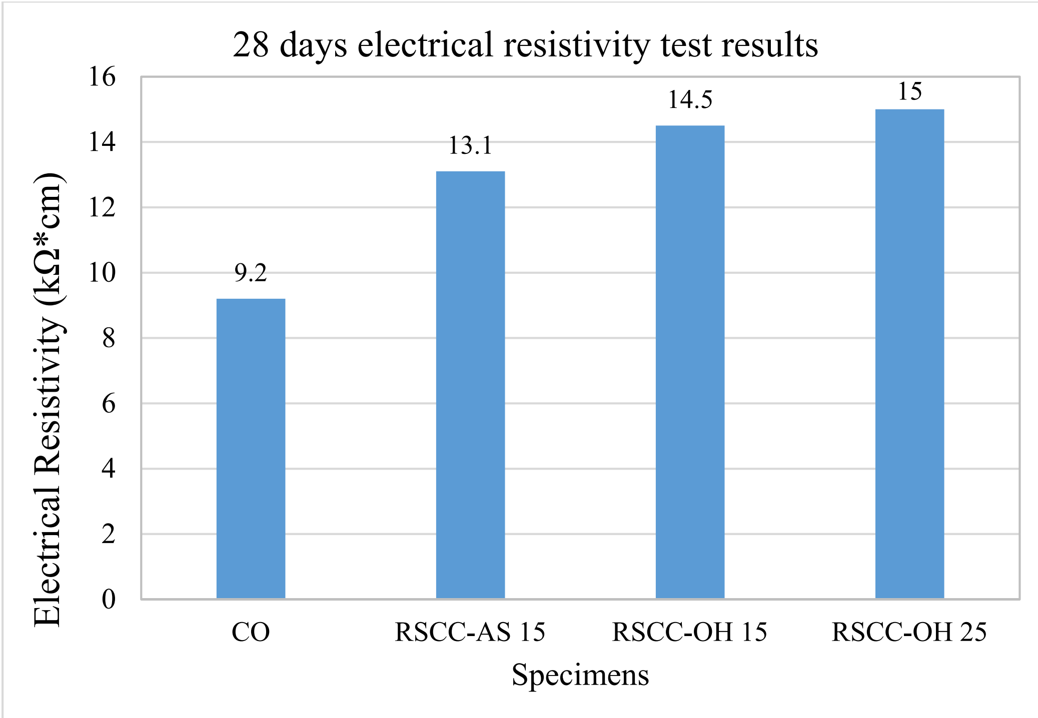



Figure 20 Electrical resistivity test results

From Figure 20, the electrical resistivity had been increased with the increasing rubber content. The rubber particles are nonconductive and nonporous materials. In addition, comparing to the traditional fine aggregate, the size of rubber aggregate is larger, thus the soft rubber particles can fill in the voids that may provide the passageway for the electrical current. From the results, the resistance of electricity was increased 42.3%, 57.6%, and 63.0% in RSCC-AS 15, RSCC-OH 15, and RSCC-OH 25, respectively. The rubber particles in the specimens certainly had a positive effect on the electrical resistivity, which means the transport properties in the concrete can be reduced by addition of rubber aggregates, the specimens could also get a better ability to prevent the corrosion at the same time. The NaOH solution treatment method also provided more resistance. The result of electrical resistivity was increased 10.68% in RSCC-OH 15 when compared with the group that contained the original rubber aggregates. The better bonding strength after surface treating may provide the extra electrical resistivity. However, the increasing rubber content did not shown much effect on the electrical resistivity, the increasing replacement ratio of the fine aggregate by scrap rubber under 25% may not have an exact relation with the electrical resistivity.

### 3.4.3 Durability performance

#### 3.4.3.1 ASR expansion test

The mortar specimens were prepared for the ASR expansion test. Alkali-silica reaction in the concrete can be measured to evaluate the different behavior between the normal self-compacting concrete and the rubber modified self-compacting concrete. From the previous study of fiber-reinforced rubber concrete, the ASR expansion can be decreased by addition of rubber aggregates as well as the fiber reinforcement. The results of the ASR expansion of the SCC and RSCC mortar were shown in Figure 21 ASR expansion result of RSCM.

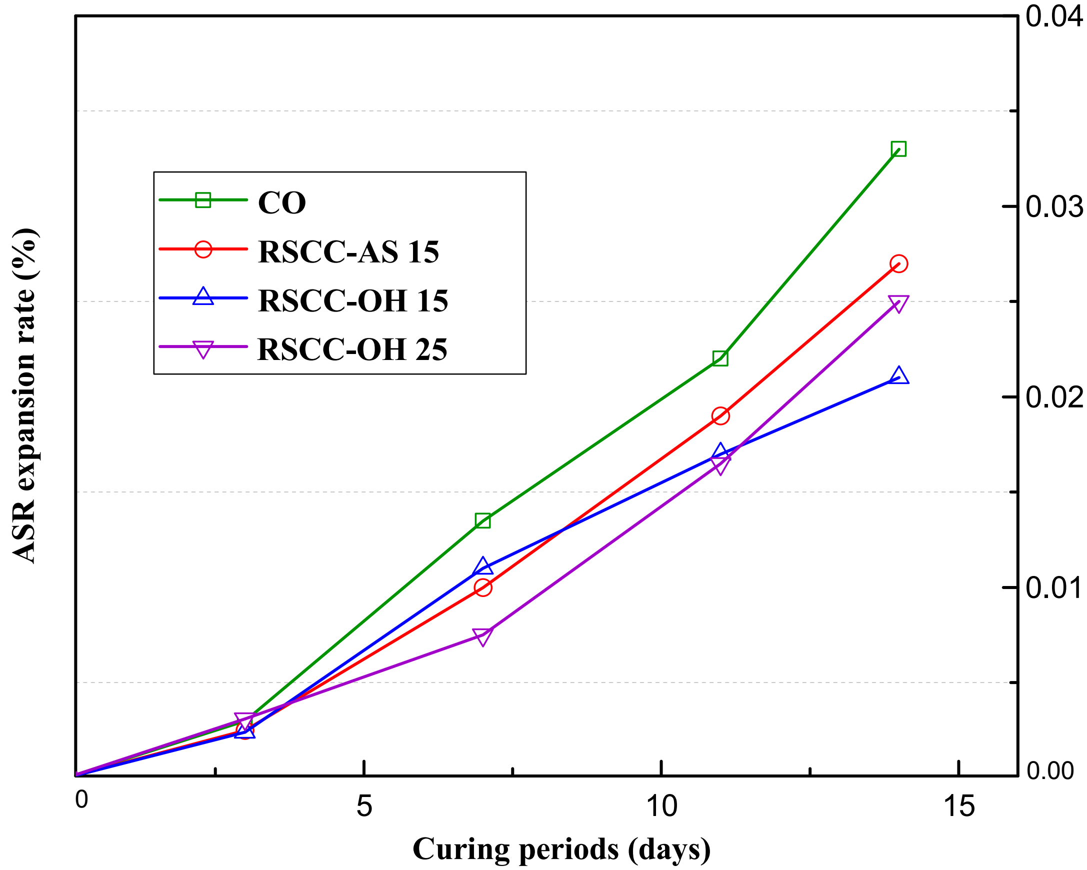



Figure 21 ASR expansion result of RSCM

From Figure 21, the ASR expansion of the mortar bars had been measured within different groups. Obviously, the introduction of rubber particles reduced the ASR expansion rate of the specimens in all three groups that contained partially fine aggregate replaced by rubber particles. The RSCC-AS 15 group had a 36.36% reduction on ASR expansion rate in 14 days curing time. The results presented the same trend like fiber-reinforced rubber concrete. The soft rubber particles can absorb the internal force caused by the Alkali-silica reaction. The deformation can be reduced when the rubber particles were extruded, comparing to the specimens without rubber particles. Meanwhile, the application of surface treatment method also provide some improvement on the resistivity of ASR expansion. The expansion rate in RSCC-OH 15 group had been reduced about 22.22% based on the RSCC-AS 15 group, which contained the original rubber particles without NaOH solution treatment. However, the increasing of rubber content shown some impacts on the ASR expansion rate. From Figure 21, the results presented that the group with 25% rubber particles had a higher ASR expansion rate than the group with only 15% rubber particles. The results shown in previous study on fiber-reinforced concrete shown that the increasing of rubber particles could reduce the expansion rate under ASR procedure. This different behavior between the normal concrete and self-compacting concrete can be discovered in the future.

#### 3.4.3.2 Drying Shrinkage

In this investigation, the drying shrinkage behavior of the self-compacting concrete were measured. The drying shrinkage shown some differences between the normal self-consolidating concrete and the rubber modified self-consolidating concrete. The results of the test were shown in the Figure 22 Length change of drying shrinkage in RSCM.

From the figure 22, the drying shrinkage of the normal self-compacting concrete shown a lower length change than all of the groups that contained rubber particles. This result was similar as the observation in fiber-reinforced rubberized mortar test. The rubber particles in the specimens were softer than the ordinary fine aggregates, which were much easier to be deformed. At the same time, the drying shrinkage of the mortar bar was increased with the increasing rubber replacement ratio. The length change of the specimens was increased about 26.19% in 14 days when the rubber content was increased from 15% to 25% in RSCM-OH 15 and RSCM-OH 25, respectively. The more rubber particles leaded to the lower elastic modulus of the test samples, the samples were easier to shrink. However, the surface treatment method by using NaOH solution had reduced the length change in the specimens from the test results.

The length change rate had been decreased about 7.9% in the same rubber replacement content after introduction of treated rubber aggregate in 14 days, based on the result from the untreated group. The situation could be explained as the introduction of surface treatment to the rubber particles, the transport properties of the specimens was reduced, which provided a better condition for keeping the moisture from evaporating.

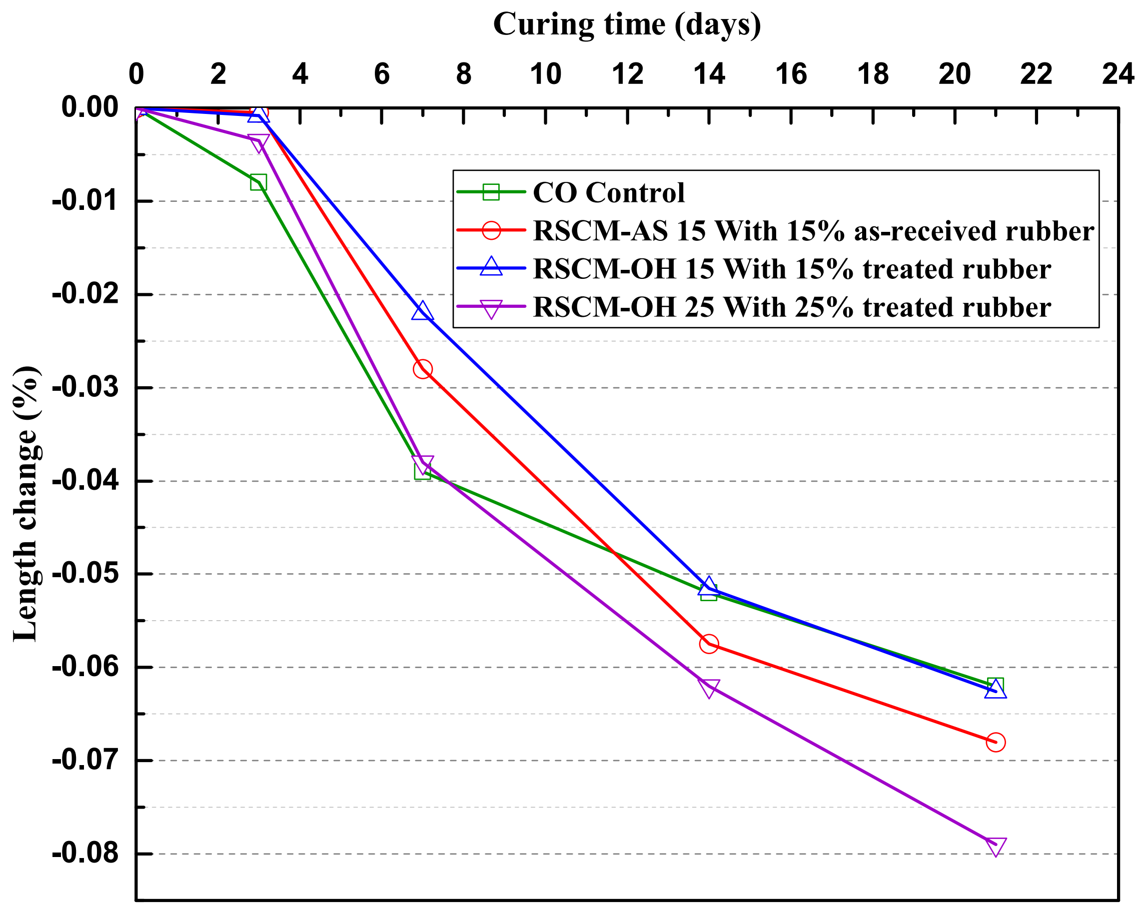



Figure 22 Length change of drying shrinkage in RSCM

## 3.5 Conclusion

In this investigation of the rubber modified self-compacting concrete, the fresh properties can almost keep the same level as the normal rubber modified concrete after addition of rubber aggregate. The workability was not effected much by replacing the fine aggregate by rubber particles. The mechanical properties can still maintain in a high value after addition of 15% rubber aggregate. The compressive strength can still reach 6,000 psi in

RSCC-AS 15 and RSCC-OH 15 groups. The introduction of NaOH treatment method also improved a lot performance of the rubberized self-compacting concrete, such as compressive strength, splitting tensile strength, and durability behavior. The high-strength rubber modified concrete can be used in the concrete structure and provide a considerable reliability. The self-compacting concrete can provide a good fresh workability in order to reduce the cost of labor. At the same time, the fine aggregate can be partially replaced by recycled waste tire rubber. The structures that constructed by this kind of material could save money and protect the environment. Meanwhile, the durability of the rubber modified self-compacting concrete is also better than the normal concrete. The structures that contain RSCC could have a good ability to resist the corrosion and the ASR damage, which provide a long-term service life and save money from maintenance. This kind of concrete material can be considered to use in pavement construction, the high compressive strength and the good durability can provide a better performance for repeated loading, the road paved by RSCC could also reduce the labor cost and save time.

In a word, using rubber particles as partially replacement of fine aggregate in self-compacting concrete is an environmental friendly way to recycle the waste tire rubber in civil engineering construction.

# Chapter 4. The field construction of rubber modified concrete

## 4.1 Introduction of the sidewalk field construction

In this investigation, the rubber-modified concrete has been used in the sidewalk construction in Cliff Drive, Michigan Technological University, Houghton, Michigan. All of the sidewalks through this road were replaced by the rubber modified concrete to evaluate the field performance. The facilities management in Michigan Tech University managed the construction. The concrete mixing and transportation were provided by the superior sand & gravel, Inc in Hancock. The rubber aggregate was treated by Dr. Dai's research group. Three different types of rubberized concrete were poured in the construction site, normal rubberized concrete, rubber concrete with meshed fiber, and rubber concrete with steel fiber, respectively.

## 4.2 Rubber treatment

The rubber particles were prepared and treated by Dr. Dai's research group. The process of treating rubber are shown in Figure 23 The process of treating rubber aggregate. The rubber particles were packaged in 50 lbs/bag. The NaOH solution was prepared for the surface treating. The rubber particles first immersed in the NaOH solution with PH value of 12 for 20 min, then moved to the container with the tap water and washed for several times until the PH value was blow to 9. At last, the rubber particles were dried in air after the extra water in bags was removed. The treated rubber was used for the sidewalk construction with the content of 10% by the volume of fine aggregate. In this project, totally 9,000 lbs rubber aggregate had been treated and mixed with concrete.

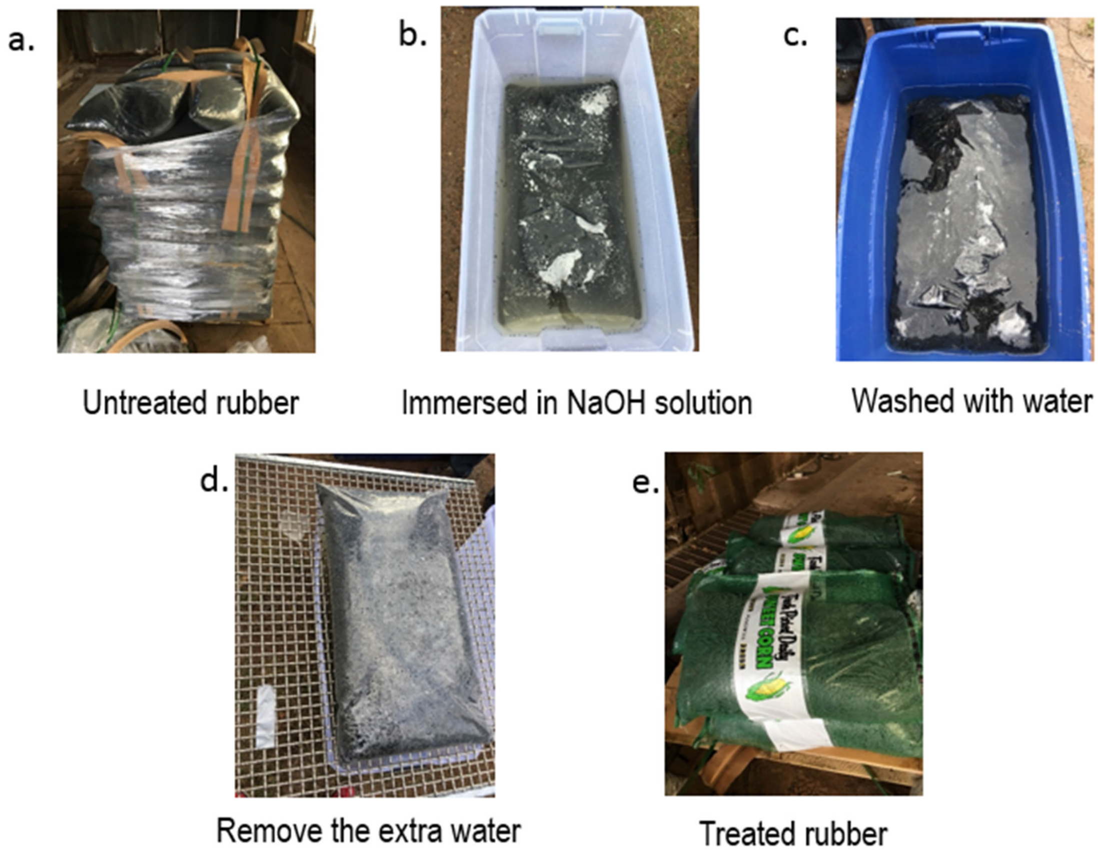



Figure 23 The process of treating rubber aggregate

## 4.3 Field construction and experimental performance

### 4.3.1 Field construction procedure

The concrete pouring were scheduled and finished within 6 months, the construction procedure is shown in Figure 24 The procedure of concrete pouring. The different types of rubberized concrete materials had been pouring in the job site. The most parts of the sidewalk were finished by the normal rubberized concrete, and the rest parts were finished by meshed fiber reinforced rubber concrete or steel fiber reinforced one. The field materials had been collected and the specimens had been made for experimental performance tests.


Figure 24 The procedure of concrete pouring

### 4.3.2 Experimental performance

The cylinder specimens were prepared to evaluate the compressive strength of the field mixture. The 4in by 8in cylinder specimens were made and cured in the water tank for 28 days. The fresh properties were measured and the compressive strength in 3 days, 7 days, and 28 days were tested and recorded. The prepared specimens are shown in Figure 25 Prepared concrete specimens.

Figure 25 Prepared concrete specimens

#### 4.3.2.1 Fresh concrete properties

The results of the fresh properties tests of filed concrete are shown in Table 14 Fresh properties of field rubber concrete. The slump of the fresh field concrete was tested during the process of the construction as showing in Figure 26 Slump test of fresh field concrete. As the results shown in Table 14, the slump of fresh field concrete was 9.8 cm which ensure the adequate workability of the concrete for sidewalk pouring process. In addition, the unit weight and air void of the field concrete have no significant difference with the plain concrete which we prepared in lab before. It indicated that 10% replacement of fine aggregate by rubber particles did not influence the fresh concrete properties and has no negative effect on concrete pouring process.

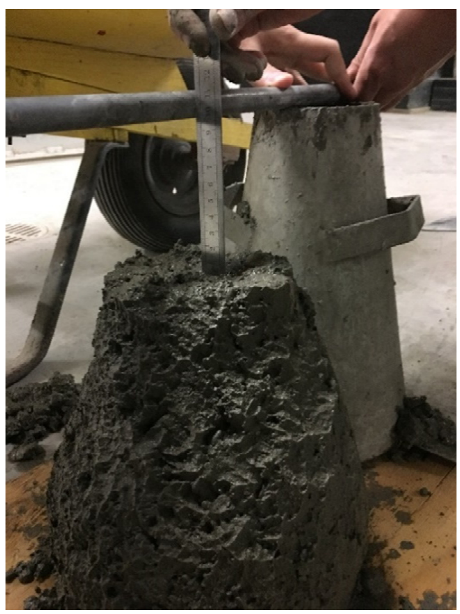


Figure 26 Slump test of fresh field concrete

Table 14 Fresh properties of field rubber concrete

| Mixtures | Slump (cm) | Unit weight (Kg/m$^3$) | Air void (%) |
|---|---|---|---|
| Normal batch | 9.8 | 2353 | 6.0 |
| With meshed fiber | 7.6 | 2362 | 6.6 |
| With steel fiber | 8.2 | 2410 | 7.0 |

#### 4.3.2.2 Compressive strength

The compressive strength of the samples cast with field concrete were tested in the lab and the results are shown in Table 14. As presented in Table 15 Compressive strength test results, the compressive strength of filed concrete samples all passed than 4000 psi at the age of 28 days, which fulfill the requirement of rigid pavement construction (4000 psi). In addition, the failure mode, shown in Figure 27 Failure mold of the specimens, indicated that the mixture has decreased brittleness compared with normal concrete since the failure of the field concrete samples showed gradually-developed damage rather than the sudden failure.

Figure 27 Failure mold of the specimens

Table 15 Compressive strength test results

| Compressive Strength (psi) | Age(days) | Test results |
|---|---|---|
| Normal batch | 3 | 2833.3 |
| | 14 | 3657.67 |
| | 28 | 4398.00 |
| With meshed fiber | 3 | 2523.3 |
| | 14 | 3024.5 |
| | 28 | 4150.3 |
| With steel fiber | 3 | 2733.3 |
| | 14 | 3425.0 |
| | 28 | 4228.6 |

## 4.4 Conclusion

The rubber-modified concrete was used in the secondary structure construction in this project, 9,000 lbs waste tire rubber has been used for paving a 0.75 miles sidewalk. It is imaginable that a considerable volume of rubber particles will be suitably recycled by adding to ordinary Portland cement concrete for civil construction. Comparing to traditional concrete, the rubber-modified concrete material will have a lower elastic modulus after hardening, which is more comfortable for driver. In addition, the rubber-modified concrete has a good durability performance and corrosive resistance. The pavement established by rubber-modified concrete will have a good in-service behavior. Meanwhile, the cost of the construction can be significantly reduced. Therefore, this kind of environmental-friendly material can be widely used in civil construction.

# 5. Conclusion and Future Work

## 5.1 Conclusion

In this study, the waste tire rubber had been introduced to the plain concrete. The fine aggregate in the plain concrete was partially replaced by the recycled waste tire rubbers. The different performances in mechanical behavior and durability were investigated in this study. In the mechanical test of PVA-fiber reinforced rubber concrete, the compressive results shown that the addition of PVA-fiber could lead to a minor reduction on the strength. The PVA-fiber could reduce the workability of the mixtures, thus decrease the compressive strength. With the increasing rubber content, the compressive strength of the specimens were reduced as well. Nevertheless, the compressive strength can still reach about 6,000 psi after introduction of PVA-fiber and 15% rubber aggregate. In addition, the flexural behavior in the three points test shown that the specimens with PVA-fiber and rubber could achieve a higher fracture energy and a larger displacement in the notched crack opening mouth. The specimens with PVA-fiber reinforcement and 25% rubber aggregate could achieve a high fracture energy, which was five times higher than the control samples that without any fiber and rubber. At the same time, with the addition of PVA-fiber and replacement of fine aggregate by recycled rubber particles, the durability performance were improved, the modified specimens represented a good behavior in the ASR expansion and the drying shrinkage tests. The rubber particles and the PVA-fiber could resist the expansion that caused by the alkali-silica reaction. In the drying shrinkage test, the PVA-fiber can prevent the shrinkage and finally offset the more shrinkage change that caused by rubber particles.

In the investigation of rubberized self-compacting concrete, the fine aggregate were partially replaced by waste tire rubber. The fresh-stage properties were not affected by the addition of tire rubber, the workability could still maintain in a good level. The rubber aggregate could lead to a reduction in compressive strength. However, after introduction the NaOH surface treatment method for the rubber aggregate, the compressive strength was increased. The process also improved the indirect tensile strength. In addition, the durability performance shown that the treatment method also improved ASR expansion and drying shrinkage behavior of the rubberized self-compacting concrete (RSCC).

Overall, the introduction of PVA-fiber could increase the fracture energy and the post-crack behavior of plain concrete together with recycled rubber. NaOH surface treatment method for rubber aggregate could also improve the mechanical and durability performance of the mixtures. Thus, using rubber aggregate as a partially replacement of fine aggregate in concrete is an environmental-friendly way to recycle waste tires and also improve the properties of ordinary Portland cement concrete.

## 5.2 Future works

1. The bonding condition between the PVA-fiber and the concrete cement paste still need to be studied, the failure specimens in the compressive test and the three points bending test shown that the PVA-fiber were almost pull-out. However, the strain-hardening

behavior was not shown in normal concrete, which was different from the engineering cementitious composite (ECC). The performance without oil treating could be discovered in normal concrete.

2. The length of the fiber could be an effective factor in the performance of the fiber-reinforced concrete, the fiber, which was used in this investigation, is only 8mm, the longer fiber may have a better contribution to the results or make a huge differences. Thus, the fibers with different length could be added into the mixtures, and also be evaluated.

3. The flexural behavior the PVA fiber-reinforced rubber concrete beams can be evaluated by finite-element analysis. The beam model can be established to study the different behavior between the experimental results and the computational results. The fracture energy can be calculated by the model, and also compared with the experimental data.

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