平成 25 年度研究実施
(一財)港湾空港総合技術センター研究開発助成
助成番号　：平成 25 年 1 月 22 日付　第 12-2 号
研究開発項目：（一般）⑥建設副産物リサイクルに関するもの

ゴムチップを利用した浮体構造用
軽量コンクリートの開発

平成２６年４月３０日

九州大学大学院　工学研究院
社会基盤部門

濵田　秀則

取りまとめた論文

1. POTENTIAL IN USAGE OF USED TIRE AS SAND REPLACEMENT IN HIGH STRENGTH MORTAR

2. Strength and Surface Abrasion Resistance of Crumb Rubber Mixed Mortar

3. STRENGTH CHARACTERISTICS AND EFFECTIVE CHLORIDE DIFFUSION COEFFICIENT OF RUBBERIZED CONCRETE

POTENTIAL IN USAGE OF USED TIRE AS SAND REPLACEMENT IN HIGH STRENGTH MORTAR

Nurazuwa Md Noor*1, Daisuke YAMAMOTO*2, Hidenori HAMADA*2 and Yasutaka SAGAWA*2

*1 Graduate School of Engineering, Kyushu University（〒819-0395 Fukuoka Nishi-ku Motooka 744）
*2 Department of Civil and Structural Engineering, Kyushu University（〒819-0395 Fukuoka Nishi-ku Motooka 744）

ABSTRACT: Every year, tire generated from vehicles that is not biodegradable are increasing, and if it is not managed properly it could bring harm to the environment. Thus, this research was conducted to study the utilization potential of used tire as mortar material. Crumb rubber with size of 1 mm – 3 mm from waste tire was mixed as fine aggregate at 10% of sand volume in mortar mixture. In addition, silica fume was added as a binder at 10% and 15% of cement weight. Six series of cylindrical rubberized mortar specimen with size of 50 mm diameter and 100 mm height for compressive strength and 40 mm x 40 mm x 160 mm prism for flexural strength were prepared. Water to cement ratio was set at 0.35, 0.30 and 0.25 and all series were tested on its fresh properties, compressive strength, flexural strength, hardened density and elastic modulus. Results shows the strength of rubberized mortar without silica fume achieved more than 50% of control mixture strength and gave a good resistance against brittleness. Meanwhile, addition of 10% silica fume in the mixture helped to increase the strength. In conclusion, this study strongly suggests the potential of the crumb rubber to be used as sand replacement with or without silica fume.

KEYWORDS: Rubberized mortar, Waste utilization, Silica fume, Compressive strength, Elastic modulus, Flexural strength

1. INTRODUCTION

In Japan, 1.13 million ton of used tire is generated every year which is not biodegradable even after a long period of landfill treatment. These used tires are mostly used in fuel utilization industries, exporting industries and recycling industries.

Research on utilizing this used tire as mortar/concrete mixture component has been continued since early 90's [1]. Up-to-date, many successful achievements were reported by researchers around the world. However, in Asian cases, very rare information on the used tire as mixture component can be gathered. Thus, this research was conducted to study the potential of used tire as sand replacement in mortar mixture. All specimens were tested in the laboratory to identify the fresh properties; air content, workability, fresh density and hardened properties such as compressive strength, hardened density, modulus of elasticity and flexural strength.

2. RESEARCH SIGNIFICANCE

Utilization of used tire as crumb rubber in mortar could be a benchmark to concrete mixture. This will not only give benefits to the government in reduction of providing land for disposal, but also increase the economy growth in various sectors especially amongst construction industry.

3. EXPERIMENTAL DETAILS

3.1 Crumb Rubber as Sand Replacement

The used tire rubber in this experiment was classified as crumb rubber, (CR) [2]. This CR is a by-product produced from used tire of vehicles (car, truck, etc.). The size of the CR ranges between 1 - 3 mm with density of 1.17 g/cm^3 and was used directly as received from recycle plant without any washing procedure as shown in Fig. 1. In this study, 10% of sand volume was replaced by CR to determine its potential to be used as mixing material.

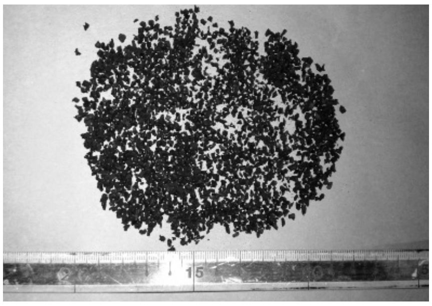


Fig. 1 Crumb rubber

3.2 Other Mortar Mix Component

Sea sand was used as fine aggregate which was in saturated dry surface and 2.77 in fineness modulus. Ordinary Portland Cement (OPC) and silica fume (SF) with density of 3.16 g/cm^3 and 2.20 g/cm^3 respectively were used as binder. In addition, silica fume was added at 10% and 15% of cement weight. The ether-based polycarboxylate superplasticizer with density of 1.07 g/cm^3 at 20^{o}C temperature was used as chemical admixture at 1.0% to 1.5% based on binder content, which is below maximum allowed dosage of 5%. Air modifying agent was also used to control the air content. Physical property of sea sand is shown in Table 1.

Table 1 Physical properties of sand

Physical property	Sea sand
Density (SSD condition) (g/cm^3)	2.58
Water adsorption (%)	1.72
Fineness modulus	2.77

3.3 Mix Proportion

Six series of rubberized mortar for water to cement ratio of 0.35, 0.30 and 0.25 were prepared as shown in Table 2. Series 1 is a control mixture which indicates the performance level of rubberized mortar. It is expected that CR will reduce the strength [3], thus the target compressive strength for series with CR was set to be at least 50% of control mixture in series 1. Table 3 shows the mix proportion used in this research.

3.4 Description of Mixing Procedure

Mortar mixing was done in a controlled room temperature at 20^{0}C. Cement and water containing chemical admixture was firstly added and mixed for 30 seconds, followed by ½ sand and ½ rubbers adding alternately until all sand and rubber completed, and was mixed for another 30 seconds. Then, the mixing machine was stopped to allow hand manual mixing. Finally, mixing was continued for an about 60 seconds that makes total mixing time, 2 minutes and 30 seconds. However, for water-to-cement ratio of 25%, total mixing time was extended to 3 – 4 minutes for better homogeneous mixture. All mixing were set at low speed rotation.

Flow test was conducted on a plate and shocked for 15 times for 15 seconds. Meanwhile, air content was measured using pressure method. Then, mortar was casted in a cylindrical steel mould with size of 50 mm diameter and 100 mm length. In addition, 40 mm x 40 mm x 160 mm prism size specimen was also prepared for flexural test. After 24 hours, specimen were de-moulded and placed in water for 7 and 28 days curing under 20^{0}C controlled temperature.

Table 2 Series of rubberized mortar mix

Series	Mixture	Description
S1	Control	Conventional mix OPC
S2	0CR-10SF	100% OPC + 10% silica fume as binder
S3	0CR-15SF	100% OPC + 15% silica fume as binder
S4	10CR-0SF	10% crumb rubber and 100% OPC as binder
S5	10CR-10SF	10% crumb rubber and 100% OPC + 10% silica fume as binder
S6	10CR-15SF	10% crumb rubber and 100% OPC + 15% silica fume as binder

4. RESULT AND DISCUSSION

4.1 Fresh Mortar Properties

Mortar flow, air content and fresh density was measured after mixing and results are shown in Fig.2, Fig.3 and Fig.4. It was observed that for overall mortar flow performance, the flow decrease with reduction of water in the mix except for series containing silica fume. From this figure, even with rubber, mortar indicates the good workability even low dosage of chemical admixture.

Fig. 3 presents the air content result of the mixture. Fedroff et al. [4] reported that higher air content should be expected when mixed with rubber as mixture component. However, in this research, it was observed that air content for series S4 (CR only) was lower compared with control mix. This result may be due to the use of air modifying agent. The largest effect can be seen in the mixes with water to cement ratio of 0.35. Air content of rubberized mortar with silica fume rapidly increased. However, this effect of air modifying agent is totally contradicted with water to cement ratio of 0.25.

In Fig. 4, it is clearly seen that the density of rubberized mortar decreased due to low density of rubber compared with control mix. Addition of silica fume in the rubber mixture gave additional density reduction. Meanwhile, due to increasing in total binder in the mixture, mixture with w/c of 0.25 show higher density value which ranges from 2.20 g/cm^3 to 2.29

Table 3 Mix proportion of mortar

Description	w/c	Water	Cement	Silica Fume	Fine Agg	Crumb Rubber
				kg/m³		
Control	0.35	217	619	0.0	1514	0.0
0CR-10SF				62	1442	0.0
0CR-15SF				93	1406	0.0
10CR-0SF				0.0	1364	69
10CR-10SF				62	1292	69
10CR-15SF				93	1255	69
Control	0.30	201	669	0.0	1514	0.0
0CR-10SF				67	1436	0.0
0CR-15SF				100	1397	0.0
10CR-0SF				0.0	1364	69
10CR-10SF				67	1286	69
10CR-15SF				100	1246	69
Control	0.25	182	728	0.0	1514	0.0
0CR-10SF				73	1429	0.0
0CR-15SF				109	1386	0.0
10CR-0SF				0.0	1364	69
10CR-10SF				73	1279	69
10CR-15SF				109	1236	69

g/cm^3, with w/c = 0.30, ranging from 2.11 g/cm^3 to 2.25 g/cm^3 and with w/c = 0.35, ranging from 2.03 g/cm^3 to 2.25 g/cm^3.

4.2 Compressive Strength and Elastic Modulus

Results are presented in Fig. 5 and Fig. 6. A systematic reduction can be seen in the mixture with CR with and without silica fume in 7 days and 28 days. At 7 days, the minimum strength is more than 30 N/mm^2 which means that all mixture gave acceptable strength value at early stage and it kept increasing until 28 days. In Fig. 6, control mixture (series S1) achieved almost 80 N/mm^2 strength meanwhile the strength for series S4 (CR only) achieved more than 45 N/mm^2 for water to cement ratio of 0.35 and the strength increased for lower water to cement ratio. This shows that, mixture with CR alone gave strength more than 50% of control mixture strength. Mixture with silica fume gave improvement in strength value, and when 10% of silica fume was added in CR mixture, it helps to increase the strength slightly. The small increment in strength by silica fume may be due to higher air content in the silica fume mixture. It is necessary to control the air content between 4%-5% to give good comparison between non-silica fume mixtures.

Meanwhile, addition of 15% SF (series S6) gave slightly higher strength compared to 10% silica fume addition (series S5). Thus, considering high price of silica fume, and small effect of 15% silica fume addition, it is recommended the use of silica fume to 10% as adequate replacement ratio due to the economical reason.

Relationship between compressive strength and hardened density is presented in Fig.7. Linear relationship is shown for each series mixture and in mixtures with CR, the density and compressive strength is lower compared to those of the control mixture with and without silica fume. However, the density was more than 90% of that of control mixture. Thus, in case of producing lightweight mixture, it is necessary to increase the percentage of CR up to the accepted level.

The results of modulus of elasticity test are given in Fig. 8 to Fig. 10. As expected, replacing the sand with CR reduced the elastic modulus. Basically, aggregates with higher elastic modulus gave higher elastic modulus [5]. Thus, the present of CR in the mixture gave lower elastic modulus compared to

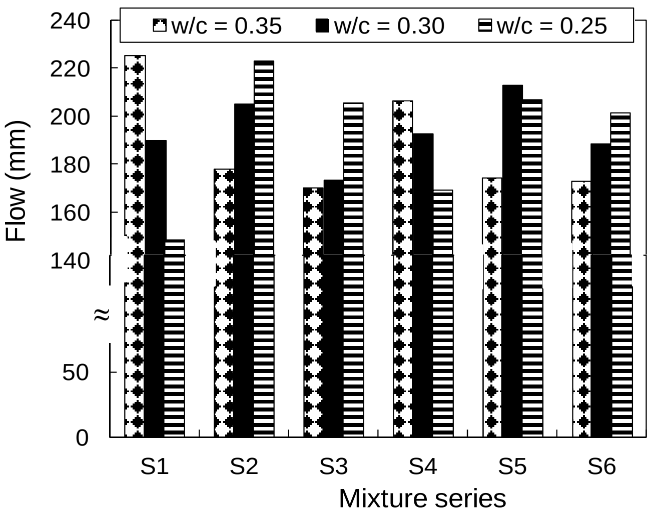


Fig.2 Mortar flow

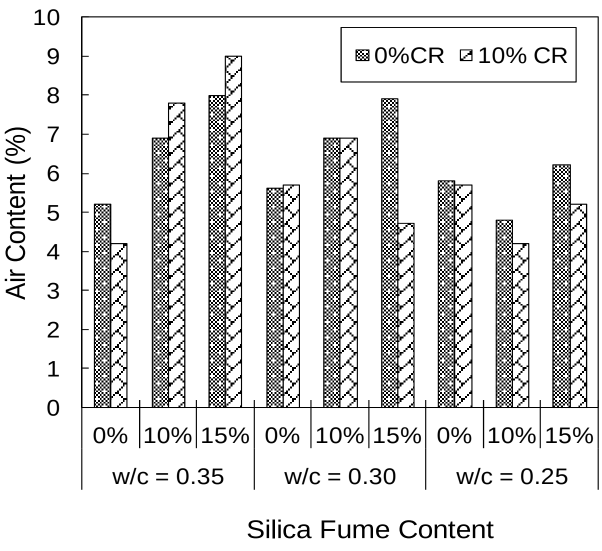


Fig. 3 Air content of the rubberized mortar using pressure method

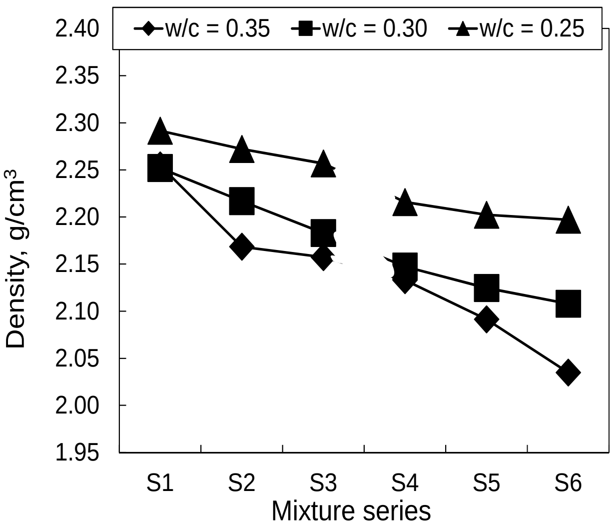


Fig.4 Density of rubberized mortar in fresh state

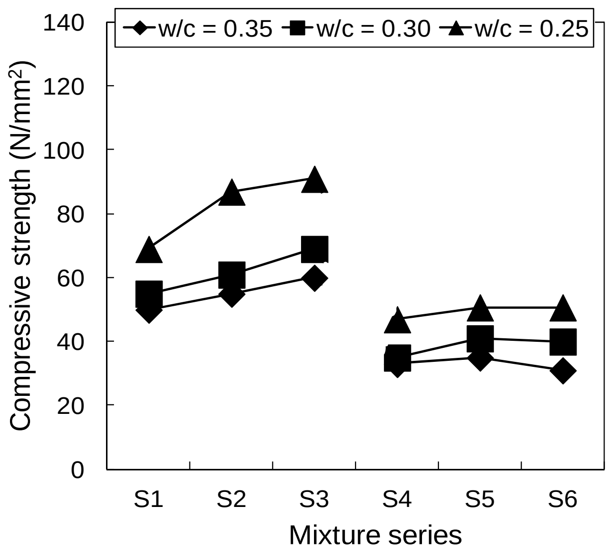


Fig.5 Strength development of rubberized mortar at 7 days

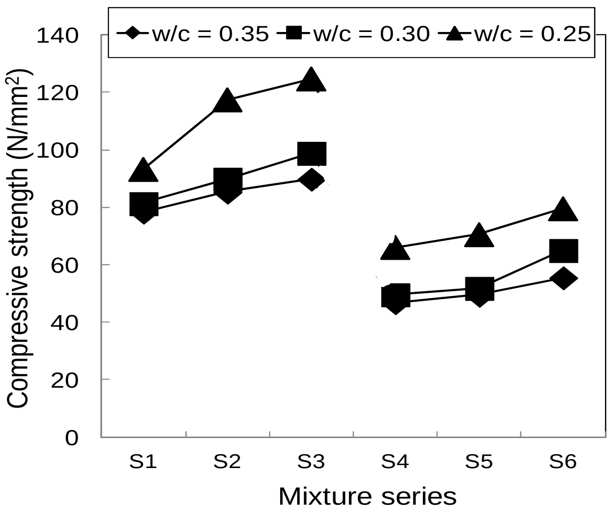


Fig.6 Strength development of rubberized mortar at 28 day strength

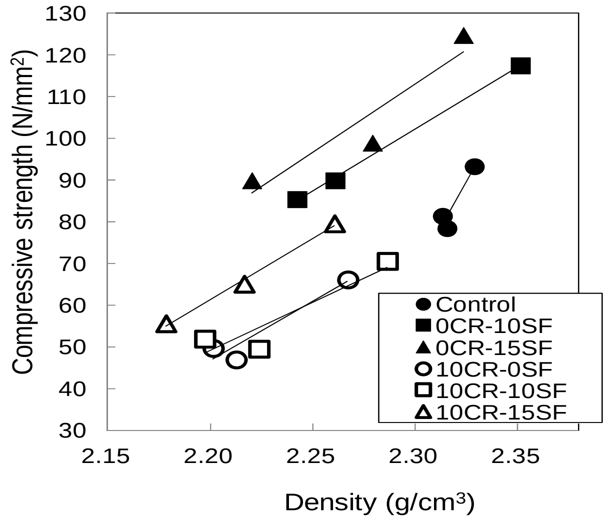


Fig.7 Relationship between compressive and hardened density at 28 days

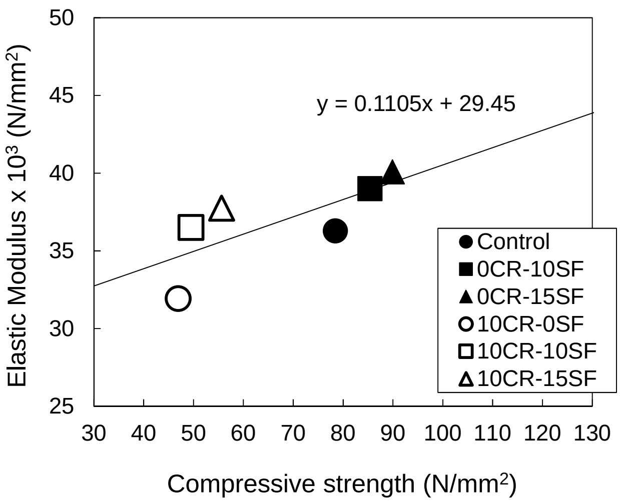


Fig.8 Relationship between compressive strength and elastic modulus for w/c = 0.35 at 28 days

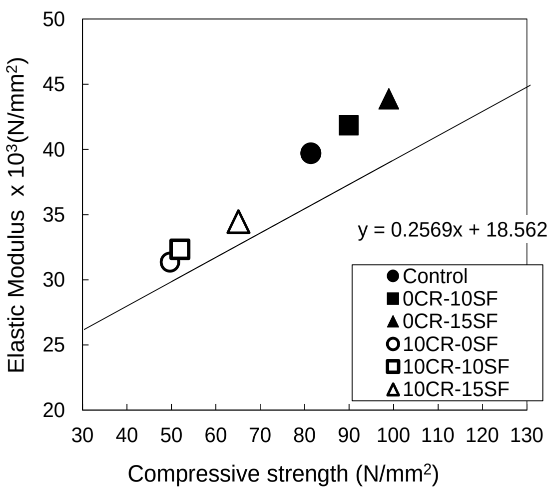


Fig.9 Relationship between compressive strength and elastic modulus for w/c = 0.30 at 28 days

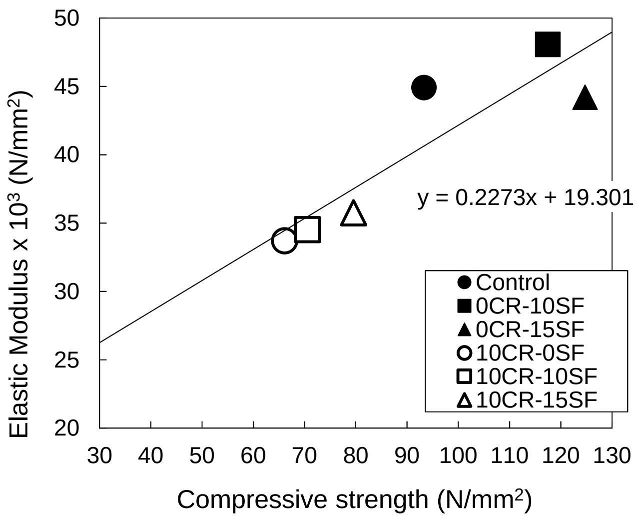


Fig.10 Relationship between compressive strength and elastic modulus for w/c = 0.25 at 28 days

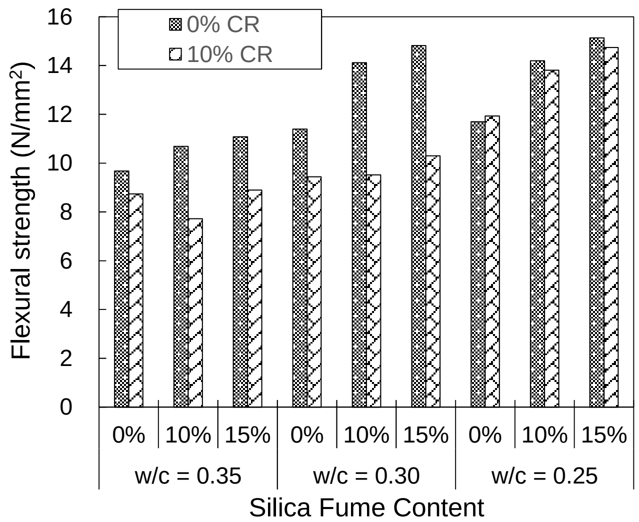


Fig.11 Flexural strength at 28 days

control mixture.

4.3 Flexural Strength

Fig. 11 show results of flexural strength at 28 days. A clear behavior can be seen from this figure, that is, flexural strength of CR mixture is low. Referring to series 4, a reduction of 10% with respect to the control specimen was observed in the mixture with water to cement ratio of 0.35, and almost 15% reduction in water to cement ratio of 0.30. However, inverse behavior was observed in water to cement ratio of 0.25 where no reduction was occurred. Addition of silica fume in series 4 mixture increased the behavior of flexural strength of rubberized mortar.

Table 4 shows the ratio of flexural strength to compressive strength, showing a good ratio ranging from 1/5 to 1/7. From this table, mixture with CR only gave ratio 18.6%, 19% and 18% for water to cement ratio 0.35, 0.30 and 0.25 respectively. This indicates that mixture with crumb rubber both with and without silica fume gave good resistance to brittleness

Table 4 Ratio of flexural strength to compressive strength (%)

Description	w/c		
	0.35	0.3	0.25
Control	12.3	14.0	12.5
0CR-10SF	12.5	15.7	12.1
0CR-15SF	12.3	15.0	12.1
10CR-0SF	18.6	19.0	18.0
10CR-10SF	15.6	18.3	19.6
10CR-15SF	16.0	15.8	18.5

5. CONCLUSION

From this research, several conclusions can be drawn as follows,

(1) All mixture series gave a good workability with respect to containing crumb rubber with and without silica fume, even low chemical admixture dosage were used.

(2) Air content decreased up to 20% reduction ratio for rubberized mortar compared to control mixture in series S4 for w/c = 0.35.

(3) Due to low density of rubber, density of series S4 mix (10% crumb rubber, 100% OPC as binder, 0% SF) decreased compared to the control mix.

(4) As expected, using crumb rubber as mixture component decreased the strength, however, in this research, the strength of rubberized mortar achieved more than 50% of control mixture strength. Meanwhile, elastic modulus also decreased due to low elastic modulus of rubber.

(5) 10% addition of silica fume in rubber mixture gave slightly strength increment in rubberized mortar, and the effect of 15% silica fume replacement was also same. Thus, it is suggested that the silica fume to 10% addition is adequate level.

(6) In flexural strength test, crumb rubber gave a good resistance against brittleness and this advantage may be due to the rubberized.

Overall, it is recommended that usage of 10% crumb rubber as sand replacement has a good potential to be further study in future especially in concrete mixture with water to cement ratio of 0.35. The use of silica fume can be 10% addition, since 15% silica fume addition gave almost the same performance with

10% addition.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Hikari World Company Limited for their support in supplying the crumb rubber. Authors' appreciation also goes to all lab members for their support and advice.

REFERENCE:

1) Filipe, V.,Miguel, B. and Jorge, B.: "Concrete With Used Tire Rubber Aggregates: Mechanical Performance," ACI Material Journal, Vol. 109, May-June pp. 283-292 (2012)
2) Rafat, S. and Tarun, R.K.: "Properties of Concrete Containing Scrap-Tire Rubber- An Overview," Waste Management Journal, Vol. 24, pp. 563-569 (2004)
3) Kumaran, G.S., Nurdin, M. and Lakshmipathy, M.: "A Riveiw on Construction Technologies That Enables environmental Protection: Rubberized Concrete, "AJEAS1, Vol. 1, pp. 41-45 (2008)
4) Fedroff, D., Ahmad, S. and Savas, B.Z.: "Mechanical Properties of Concrete with Ground Waste Tire Rubber," Transportation Research Board, Report No. 1532, pp 66-72 (1996)
5) Eshmaiel, G., Morteza, K. and Ali, A.M.: "Scrap-Tire-Rubber Replacement for Aggregate and Filler in Concrete," Construction and Building Material Journal, Vol. 23, pp 1828-1836 (2009)

【土木構造・材料論文集 第 29 号 2013 年 12 月】

Strength and Surface Abrasion Resistance of Crumb Rubber Mixed Mortar

Nurazuwa Md Noor*, Daisuke Yamamoto**, Hiroki Goda***, Hidenori Hamada**, Yasutaka Sagawa**

*Graduate School of Engineering, Kyushu University, Fukuoka, Japan, 819-0395
** Department of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan, 819-0395
*** Department of Civil and Architectural Engineering, Kyushu Institute of Technology, Kitakyushu, Japan, 804-8550

This study is focusing on physical properties, such as strength and abrasion resistance, of crumb rubber mixed mortar. Also, effectiveness of crumb rubber on in-plane displacement under compression was studied by using two-dimensional digital image correlation method. Deformation of mortar surface containing 10% crumb rubber and 10% silica fume before and after compression loading was digitally recorded and measured. Meanwhile, abrasion test was carried out to achieve better understanding on the crumb rubber effect against surface abrasion wearing. Experimental results show that axial strain under compression was larger in mortar with crumb rubber followed by the strength reduction. As for abrasion test, crumb rubber could give significant improving effect on wear resistance in the mixture with the water to cement ratio (w/c) of 0.35 and 0.30, however, this effect cannot be found in w/c = 0.25.

1. Introduction

Research on utilizing the used tire rubber from vehicles as concrete material started in 1994 by Eldin and Ahmad Senouci which focusing on strength characteristics[1]. High reduction in compressive strength due to the rubber leads to development of various methods to achieve the accepted structural strength level. In this study, effect of crumb rubber on the distribution of the surface strain under compression stress is measured using digital image correlation method (DICM). In order to determine strain, DIC method can be classified as non-destructive test, with extra benefits; low-cost and time-saving, compared to the method using strain gage[2].

The effectiveness of crumb rubber to improve wear resistance tested by using surface abrasion test was also discussed in this paper. Research done by Filipe Valadares et al.[3] on various rubber replacement ratio and size shows significant benefit in enhancing the abrasion resistance. Thus, an experimental study was conducted to see the behavior of crumb rubber with silica fume on abrasion wear resistance under different water to cement ratio.

2. Experimental Program

2.1 Materials, mix proportion and specimen preparation

Crumb rubber (CR) with density of 1.17g/cm^3 and size between 1mm-3mm was added in the mortar at 10% of sand volume replacement. Other materials were ordinary portland cement, sea sand and silica fume (10% of cement weight addition). The ether-based polycarboxylate superplasticizer with density of 1.07 g/cm^3 at 20ºC temperature was used as chemical admixture at 1.0% to 1.5% based on binder content, below maximum allowed dosage of 5%. Air modifying agent was also used to control the air content. Physical property of the materials is shown in Table 1.

Table 1 Physical properties of materials

Component	Physical properties	
Ordinary Portland Cement	Density, g/cm^3	3.16
Silica fume	Density, g/cm^3	2.20
Sea Sand	Density, g/cm^3 (SSD condition)	2.58
	Water absorption (%)	1.72
	Fineness modulus	2.77
Ether-based polycarboxylate superplasticizer	Density, g/cm^3	1.07
Air modifier agent	Density, g/cm^3	1.00

Table 2 Mixture of rubberized mortar

Series	SF/C (%)	CR/(S+CR) (Vol. %)	w/c	Water W (kg/m^3)	Cement C (kg/m^3)	Silica Fume SF (kg/m^3)	Sand S (kg/m^3)	Crumb Rubber CR (kg/m^3)
S35-1	0	0	0.35	217	619	0.0	1514	0.0
S35-2	0	10				0.0	1364	69
S35-3	10	10				62	1292	69
S30-1	0	0	0.30	201	669	0.0	1514	0.0
S30-2	0	10				0.0	1364	69
S30-3	10	10				67	1286	69
S25-3	0	0	0.25	182	728	0.0	1514	0.0
S25-2	0	10				0.0	1364	69
S25-3	10	10				73	1279	69

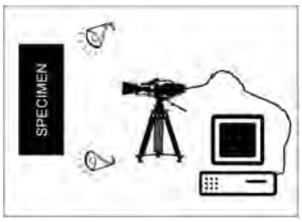
Several series of mixture were prepared as shown in Table 2. S35-1 and S35-2 (w/c = 0.25) were tested in DICM at 14 days, meanwhile all other series with w/c of 0.35, 0.30 and 0.25 were tested for abrasion at 28 curing days. Specimens were prepared in two shape; 100 x 100 x 100mm of cube size for DCIM test and 50 x 100mm cylinder size for abrasion test.

2.2 Digital image correlation method

The objective of this test was to study the strain distribution of rubberized mortar surface under compression loading. Two dimensional image correlations were taken by using a digital device that connected to the computer to measure the surface deformation before and after compression loading test as shown in Fig. 1. In order to capture the displacement image, specimen surface should be flat, and must have random speckle pattern either naturally existed or artificially made by spraying the black or white paints on the surface[4]. Strain distribution is calculated by comparing the two images under different loading using a motion movement of square reference subset. Reference subsets are used for tracking the motion of its center point as shown in Fig. 2. The displacement vector is calculated to determine the ε_x, ε_y and ε_{xy}. In this study, two series of specimen were tested, which were S35-1 as control specimen and S35-2 with 10% CR replacement without silica fume. Images were taken at every 50kN compression load increment until failure. In addition, strain gages were attached on both side of specimen in x and y direction to measured stress-strain distribution.

2.3 Abrasion test

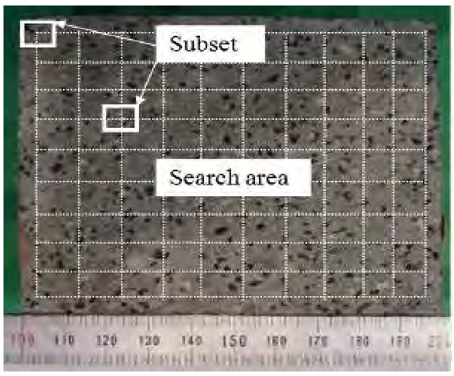
This test was carried out to measure the CR effectiveness on surface wearing resistance using abrasion machine shown in Fig. 3. Three series of specimen were prepared at each w/c shown in Table 2. Cylinder specimen was cut into three small parts and both surface of each part should be flat and 90^0. Data



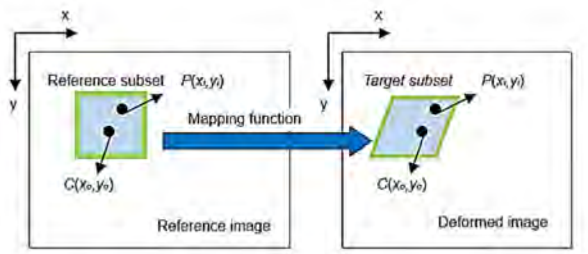
(a) Schematic diagram

(b) Experimental setup

Fig. 1 DCIM measurement device



(a) Searching area on the specimen surface; the small thick white square is the reference subset



(b) Reference square subset before and after the deformation

Fig. 2 Mechanism of capture image

Fig. 3 Abrasion test machine

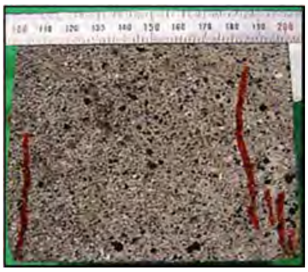
such as weight and depth were recorded at every 500 abrasion rotation to maximum rotation of 4000. Silica sand was used as contact material in order to give friction on mortar surface.

3. Result and Discussion

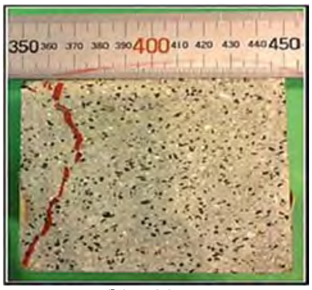
3.1 Physical properties of rubberized mortar

Fresh and hardened properties of rubberized mortar are shown in Table 3. Mixtures with crumb rubber were lower in flow and this action can be seen clearly when w/c is decreasing. Meanwhile, addition of silica fume in binder reduces the mortar flow but increased air content. Dosage of chemical admixture was increased to avoid dry mixtures due to low w/c and silica fume.

The presence of crumb rubber in the mixture reduces the hardened strength of the rubberized mortar but 10% silica fume addition helps to increase slightly the strength. Due to low elastic modulus of crumb rubber itself, the elastic modulus of hardened mixture is also decreased.



(a) S35-1



(b) S35-2

Fig. 4 Crack pattern on mortar surface

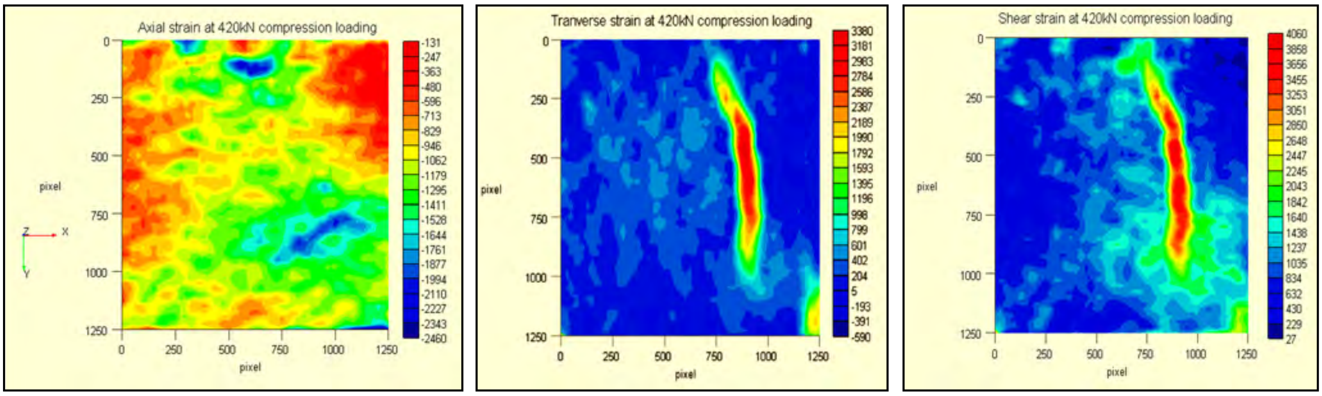
3.2 Strain due to in-plane displacement of specimen surface

(1) Strain by digital image correlation method

Result of strain distribution due to compression loading in y-direction is presented in Figs. 5-6. The full displacement field was determined by comparing the corresponding coordinate of the subset before and after the compression test. Then the axial, transverse and shear strain was calculated using strain relationship equation. Compressive strength for control specimen (S35-1) was 74.3N/mm^2, meanwhile specimen with crumb rubber (S35-2) reached ultimate cube compressive strength of 54.2N/mm^2. It was observed that larger axial strain was observed from edge side surface towards center of

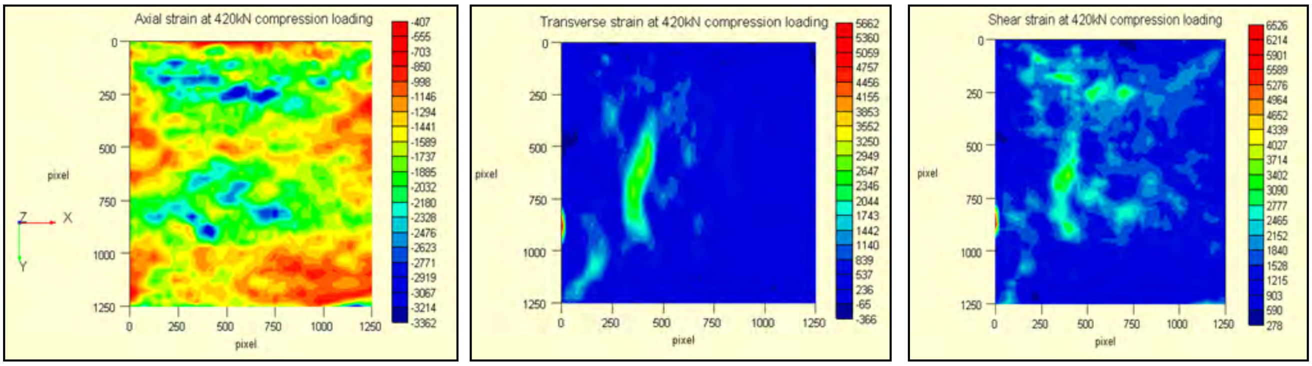
Table 3 Fresh and hardened properties of rubberized mortar

Properties	S35-1	S35-2	S35-3	S30-1	S30-2	S30-3	S25-1	S25-2	S25-3
Flow (mm)	226	207	175	190	193	213	149	170	207
Air content (%)	5.2	4.2	7.8	5.6	4.7	6.9	5.8	5.7	4.2
Cube compressive strength at 14 days (N/mm^2)	74.1	54.3	-	-	-	-	-	-	-
Cylinder compressive strength at 28 days (N/mm^2)	78.4	47.0	49.5	81.4	49.7	51.9	93.3	66.1	70.6
Flexural strength (N/mm^2)	9.7	8.7	7.7	11.4	9.4	9.5	11.7	11.9	13.8
Elastic modulus at 28 days (kN/mm^2)	36.3	31.9	36.5	39.7	31.4	32.3	44.9	33.7	34.5



(a) Axial strain (b) Transverse (c) Shear strain

Fig. 5 Strain on S35-1 due to 420kN compression load



(a) Axial strain (b) Transverse strain (c) Shear strain

Fig.6 Strain on S35-2 due to 420kN compression load

specimen surface as load increased. Observing the axial strain distribution for both S35-1 and S35-2, the strain was -2.46×10^{-3} and -3.36×10^{-3} respectively. The S35-2 sustains larger displacement compared to S35-1 and it failed at 520kN as ultimate load. Meanwhile, S35-1 has small displacement and this displacement kept increasing until failure load of 720kN. This proved the mechanism of compressive strength reduction due to the crumb rubber in the mixture.

Meanwhile in transverse strain, local strain was initiated at 330kN load and 360kN for S35-1 and S35-2 respectively. In S35-1, the local strain kept increasing until the elastic limit at about 630kN and surface crack was occurred as the load increased as shown in Fig. 4. As for S35-2, cement matrix reached elastic limit around 500kN and the local strain started to reduce the ultimate load.

(2) Stress-strain relationship

Figure 7 shows relationship between stress and strain for S35-1 and S35-2 resulted from DIC method and strain gage method. Control mixture shows maximum stress around 70N/mm^2, meanwhile 10%CR mixture shows more than 50N/mm^2 cube strength. Due to the crumb rubber in the mixture, compressive strength decreased about 30%. As proved in previous discussion, this mixture (S35-2) sustains larger displacement compared to control mixture that leads to strength reduction. As for S35-2, the difference between DICM and strain gage method was observed. This can be due to the random distribution of the crumb rubber, that is, the surface under strain gage and the surface measured by DCIM image was different.

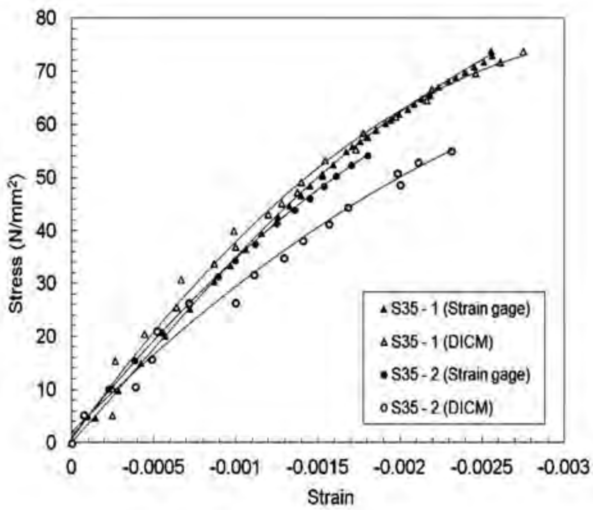
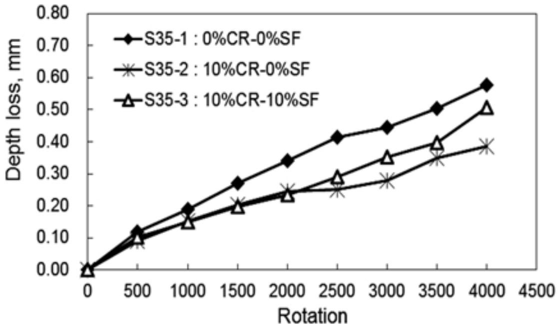
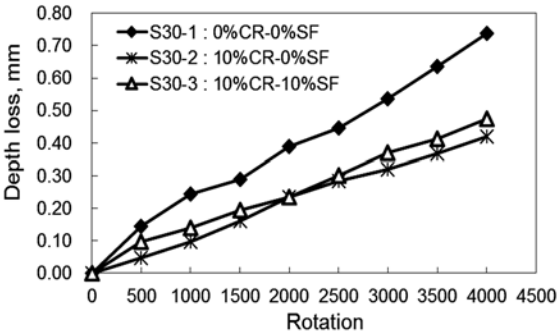


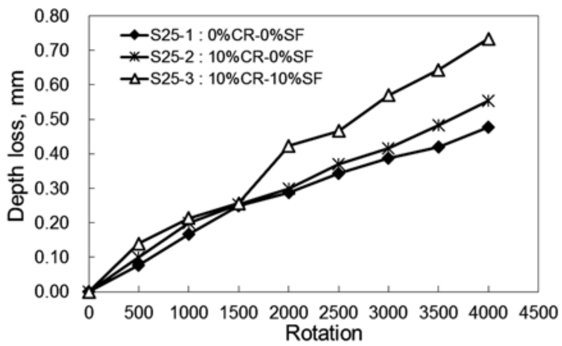
Fig. 7 Stress-strain relationship of cube rubberized mortar at 14 days curing age.



(a) w/c = 0.35

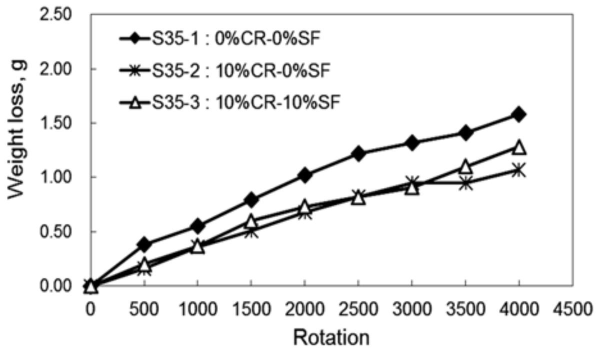


(b) w/c = 0.30

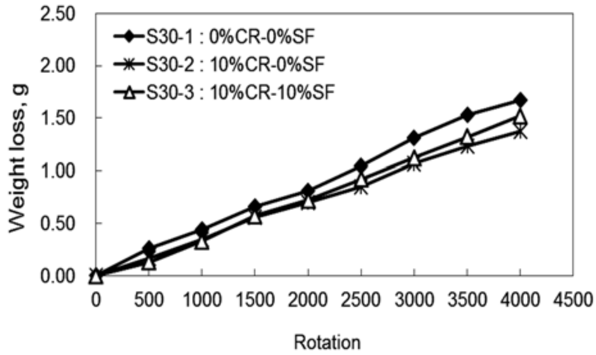


(c) w/c = 0.25

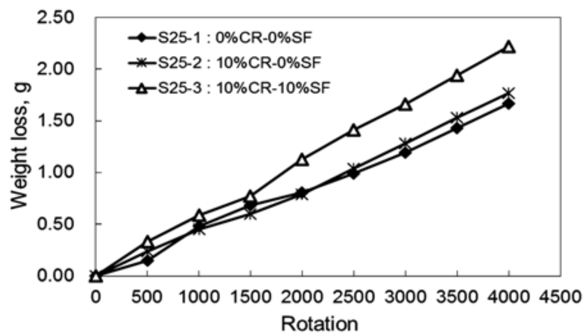
Fig. 8 Depth loss versus abrasion rotation of rubberized mortar at 28 days



(a) w/c = 0.35



(b) w/c = 0.30



(c) w/c = 0.25

Fig. 9 Weight loss versus abrasion rotation of rubberized mortar at 28 days

3.3 Surface resistance against abrasion

(1) Depth loss and weight loss

Figures 8 and 9 show the depth and weight loss of mortar after abrasion tests. In all samples, it was observed that the abrasion increased with the increase of abrasion rotation.

As explained by Filipe Valadares et al.[3] in their research, rubber can resist against wear better than cement matrix, thus during the test, the rubber particles jut out from the surface and prevent the cement matrix from the wearing action. However, in this study, crumb rubber did not have any effect in improving the wearing resistance in mixture with w/c = 0.25. This may be due to the low elastic modulus of crumb rubber that is not able to accommodate with the increasing of hardened matrix strength. It leads to a weak bonding which caused bond cleavage between crumb rubber and cement matrix when subjected to rotation load.

(2) Relationship with compressive strength

Fig. 10 shows relationship between depth loss and 28 days compressive strength at 4000 abrasion rotation. According to G. Singh, in his study on waste foundry sand[5], mixture with higher strength could lead to an increase in abrasion resistance improvement. However, from this figure, inverse behavior is observed in mixture of w/c = 0.25 where the depth loss increased up to 0.6mm and 0.7mm compared to mixture with w/c = 0.35 when crumb rubber is added. From these results, it was observed that compressive strength is an important factor affecting the abrasion resistance.

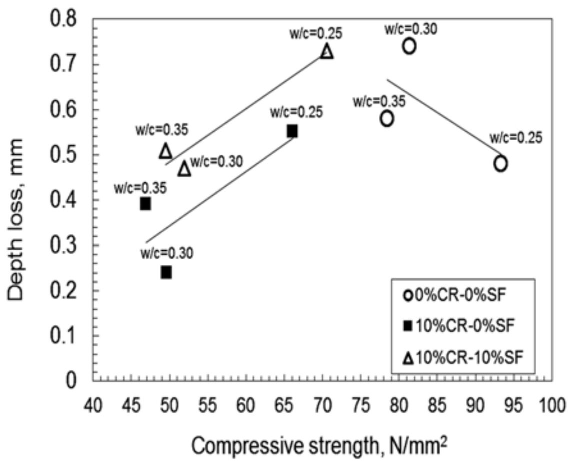


Fig. 10 Relationship between depth loss and compressive strength at 4000 abrasion rotation

4. Conclusions

From this study, several conclusions can be drawn as follows,

1. In fresh properties, crumb rubber as sand replacement material reduces the workability of the mixture and increase the air content.
2. For hardened properties, compressive strength was decreased with the addition of crumb rubber.
3. Axial strain was larger in the mixture with crumb rubber compared to the mixture without crumb rubber at same stress level.
4. Local strain was progressively developed in both mixture with and without crumb rubber, until their elastic limits at 500kN and 600kN, respectively.
5. In abrasion test, crumb rubber shows good potential in providing high abrasion resistance to cement matrix.

Acknowledgement

The authors would like to express their gratitude to Hikari World Company Limited for their continuous support in supplying the crumb rubber. Authors' appreciation also goes to all laboratory members for their help during specimen preparation and testing.

References

1) Rafat Siddique and Tarun R. Naik:Properties of concrete containing scrap-tire rubber – an overview, Waste Management Journal, Vol. 24, pp. 563-569, 2004
2) Shih-Heng Tung, Jui Chao Kuo and Ming Hsiang Shih: Strain distribution analysis using digital image correlation method, The Eigthteenth KKCNN Symposium on Civil Engineering, 2005.12
3) Filipe Valadares, Miguel Bravo and Jorge de Broti: Concrete with used tire rubber aggregates: mechanical performance, ACI Materials Journal, Vol. 109. Pp. 283-292, 2012
4) Bing Pan et al: Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review, Journal of Measurement and Technology, Vol. 20, 2009
5) Gurpreet Sing and Rafat Siddique: Abrasion resistance and strength properties of concrete containing waste foundry sand (WFS), Construction and Building Materials, Vol. 28, pp.421-426, 2012

(2013.6.30 受付)

-Technical Paper-

STRENGTH CHARACTERISTICS AND EFFECTIVE CHLORIDE DIFFUSION COEFFICIENT OF RUBBERIZED CONCRETE

Nurazuwa MD NOOR[*1], Hidenori HAMADA[*2], Yasutaka SAGAWA[*3] and Daisuke YAMAMOTO[*4]

ABSTRACT

In this study, crumb rubber was used as fine aggregate at 10%, 15% and 20% sand volume replacement to produce rubberized concrete with satisfied compressive strength. Rubberized concrete was tested on its fresh properties, mechanical strength and effective diffusion coefficient of chloride ion. In addition, silica fume as 10% of cement was added to investigate the effect on the strength and resistance against chloride penetration. Results shows mechanical strength reached to the acceptable value for satisfied strength as structural concrete and chloride ion resistance was improved with silica fume.

Keywords: Rubberized concrete, strength, air content, chloride ion diffusion coefficient

1. INTRODUCTION

The worldwide increase in used tyre which is biodegradable industrial waste is expected with increasing population of man and traffic which developed environmental problems. According to the European Association of Tyres and Rubber Producer, 3.2 millions of used tyre in 2009 were retreated and reused, recycled and used for energy production [1].

In concrete performance, utilization of used tyre as concrete components has been studied since 1990`s in terms of strength characteristics and durability. The utilization of this material is important to decrease the negative impact to the environment. On the other hand, the use of de-icing salt in cold country, could lead to penetration of chloride ion into the concrete pores which can cause a problem if it reached steel reinforcement. Corrosion of steel reinforcement makes the structure distress and high cost of maintenance and repair are required to overcome this problem. In the worst case, it could lead to the structural collapse.

Thus, this research was conducted to produce concrete with satisfied strength using simple way of materials preparation and mixing procedure. In addition, this concrete, named as rubberized concrete could give good resistance against chloride ion penetration into the concrete. This will give benefits to structure in aggressive environment such as marine environment and structure exposed to high chloride ion.

2. SPECIMEN PREPARATION AND TESTING

2.1 Crumb rubber as fine aggregates

Crumb rubber (CR) is by-product produced from used tyre of vehicles. The size of CR ranges between 1-3mm with density of 1.17g/cm^3 as shown in Fig.1. The presence of rubber in the mix cause almost 85% of strength reduction which lead to various ways to increase the strength by either washing the rubber or pre-coating the rubber [2]. Thus, in this research, the CR was used directly as received from recycled plant without any washing procedure in producing rubberized concrete.

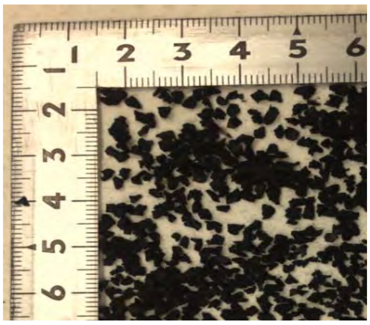


Fig. 1 Crumb rubber

2.2 Other concrete mix components

Ordinary Portland cement (OPC) was used as the main binder and silica fume (SF) was added at 10% weight of OPC in several mixes to investigate the effect on strength development. Sea sand passing 5mm sieve with density of 2.58 g/cm^3 and water absorption of 1.72 % which was less than 3.5% as stated in JIS standard was used as fine aggregate. Meanwhile, crushed stone with 20mm maximum size was used as coarse aggregate. All aggregate were prepared under surface saturated dry condition. As for workability, ether-based polycarboxylate superplasticizer was added at 0.5%-0.7% of 5% maximum allowable dosage. Air content was controlled by using air-entrained agent (to increase air content) for mixing without SF and air-modifying agent (to reduce air content) for mixing

*1 Student, Graduate School of Engineering, Kyushu University, M. Sci., JCI Member
*2 Professor, Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*3 Associate Prof., Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*4 Technical Officer, Dept. of Civil and Structural Engineering, Kyushu University, M. Sci., JCI Member

with SF. Table 1 shows details of physical properties of concrete mix components.

2.3 Selection of water to cement ratio

Mortar mixing was firstly conducted in order to determine suitable water to cement ratio for rubberized concrete mix. Four group of w/c of 0.25, 0.30, 0.35 and 0.40 were conducted. From mortar mixing, it was found that w/c of 0.40 achieved low compressive strength thus in further study, other w/c (0.25, 0.30, 0.35) with addition of silica fume were mixed [3].

From this initial study, w/c of 0.35 was chosen for concrete mixture in terms of fresh properties control, satisfied compressive strength and flexural strength. In addition, testing on resistance against abrasion of the mortar showed good correlation between the abrasion resistance and compressive strength for w/c = 0.35.

Table 1 Physical properties of materials

Component	Physical properties	
Ordinary Portland Cement	Density, g/cm^3	3.16
Silica fume	Density, g/cm^3	2.20
Crumb Rubber	Density, g/cm^3	1.17
Fine Aggregate	Density, g/cm^3 (SSD condition)	2.58
	Water absorption (%)	1.72
	Fineness modulus	2.77
Coarse Aggregate	Density, g/cm^3	2.91
Ether-based polycarboxylate superplasticizer	Density, g/cm^3 at 20^{o}C	1.07
Air entrained agent	Density, g/cm^3	1.04
Air-modifying agent	Density, g/cm^3	1.00

2.4 Mix design and specimen preparation

Four series of rubberized concrete without SF and three series of rubberized concrete with SF was prepared as shown in Table 2. From previous research, 50% strength reduction was the maximum strength target, thus, in this research; a simple way of mixing procedure was introduced with the target compressive strength for mixes with CR was set to be 50% with respect to the control mix in order to achieve strength under excepted structural strength.

All concrete mixing was done in 20^{o}C controlled room. Coarse aggregate was firstly added in the mixing drum, followed by OPC and sand. As for series with SF, SF and OPC were pre-mixed in the plastic bag before added in the mixing drum. Meanwhile, CR and sand were mixed sufficiently until all sand and CR completely added. All these materials were dry mixed and after 30 seconds, water was added and continued for additional 90 seconds mixing. Then, the mixing drum was stopped for the hand mixing. When all materials were ensured as well mixed, mixing drum was finally continued for 60 seconds, and then total mixing time became 3 minutes.

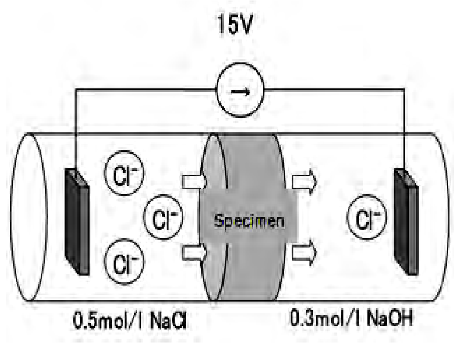
Table 2 Mix proportion of rubberized concrete

Series	CR/(S+CR)	SF/C	w/c	Water	Cement	Silica Fume	Fine Aggregate	Crumb Rubber	Coarse Aggregate		Chemical Admixture		
				W	C	SF	S	CR	G1	G2	Ether-based polycarboxylate superplasticizers	Air-entrained agent	Air modifying agent
	(Vol.%)	(%)		kg/m^3							%	%	%
Control	0	0	0.35	160	457	0	741	0	608	405	0.5	0.8	
10CR-0SF	10						667	34			0.5	0.8	
15CR-0SF	15						629	50			0.7	0.8	
20CR-0SF	20						594	67			0.7	0.7	
10CR-10SF	10	10	0.35	160	457	46	613	34	608	405	0.7		1.5
15CR-10SF	15						575	50			0.7		2.2
20CR-10SF	20						540	67			0.7		2.8

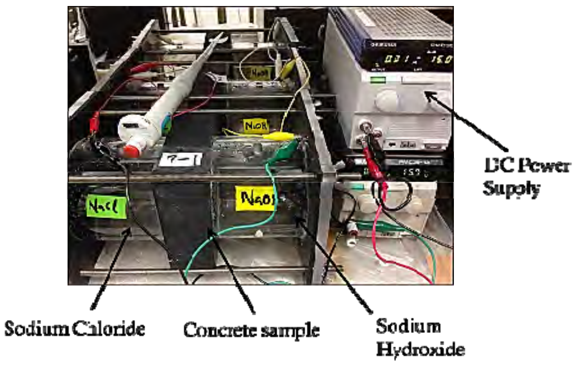
2.5 Testing procedure

In this research, air content was set as ranging from 4% to 5%. Fresh rubberized concrete were casted in cylindrical casting-metal mold with size of 100mm diameter and 200mm length, followed by water curing for 7, 28, 56 and 91 days, then compressive strength test was done. At 28 days, splitting tensile test and chloride ion migration test was prepared. Meanwhile, for flexural test, specimen was prepared in 10cm x 10cm x 40cm size prism specimen, and water cured until 28 days.

For chloride ion migration test, cylindrical sample were cut into 100mm diameter x 50 mm thickness. Test was carried out according to JSCE-G571-2003 to measure chloride ion migration from cathode towards the anode through the pore solution of rubberized concrete under the influence of 15V constant voltage as shown in Fig. 2. When the increment rate of chloride ion in the anode side becomes constant, it is assumed as steady state



(a) Schematic diagram



(b) Experimental setup

Fig. 2 Migration cell

condition and effective diffusion coefficient, D_e was calculated by using Nernst-Planck Equation [4],

$$D_e = \frac{J_{Cl} R T L}{|z_{Cl}| F C_{Cl} (\Delta E - \Delta E_c)} \cdot 100 \quad (1)$$

where, D_e is effective diffusion coefficient in cm^2/year, R is gas constant = 8.31 J/mol K, T is absolute temperature in K units, Z_{Cl} is charge of chloride ion = -1, F is Faraday constant = 96,500 C/mol, C_{Cl} is measured chloride ion concentration in cathode side in mol/l units, ΔE-ΔEc is electrical potential difference between specimen surfaces in V units and L is length of specimen in mm.

3. RESULT AND DISCUSSION

3.1 Fresh properties

Air content and concrete slump result are presented in Table 3. As mentioned above, the only controlled parameter in this research was the air content ranging from 4%-5%. Air content could be controlled as 4 -5%, by using air-entraining agent for mix without SF, and air-modifying agent for mix with SF.

Meanwhile, it was difficult to control the slump value in CR mixed concrete both for non SF mix and SF mix. From the previous research [5], it was predicted that the slump is decreased when CR is added, thus dosage of chemical admixture was increased up to 0.7%. The same behavior was observed in this experiment. The control of slump is still problem when mixing crumb rubber concrete.

Segregation was controlled by reducing the amount of water and increasing the cementitious materials and aggregate for w/c = 0.35. Meanwhile, the use of superplasticizer which was specially designed for the low w/c, helps to prevent segregation or drying of the mixture.

Table 3 Fresh properties of rubberized concrete

Mixture series	Air content (%)	Slump (cm)
Control	4.7	7.0
10CR-0SF	5.1	6.0
15CR-0SF	4.5	19.5
20CR-0SF	4.0	19.5
10CR-10SF	4.2	10.0
15CR-10SF	4.1	9.0
20CR-10SF	4.2	15.5

3.2 Hardened properties

Compressive strength for 7, 28, 56 and 91 days for both mixed with and without SF is presented in Fig. 3 and Fig.4. A systematic strength increment can be seen in all mixes. At 28 days, strength for 20% CR addition without SF was more than $40N/mm^2$, on the other hand, control mix was almost $70N/mm^2$ where reduction of strength by crumb rubber was about 43%. This strength reduction became lesser when 10% and 15% of CR replacement. The mechanism of strength reduction was discussed by Moncef Nehdi [6] where three possible reasons were discussed; firstly the rubber is much softer than the cement paste, secondly rubber may be viewed as voids in concrete mix thus it gave weak bonding between the rubber particles and cement paste and thirdly due to the density, size and hardness of the aggregates. From result of the compressive strength test, the method of mixing used in this experiment was categorized as simple way in producing rubberized concrete with satisfied strength.

Meanwhile, addition of 10% SF in all rubberized concrete slightly increased the mechanical strength and improved the strength reduction for about 10-15%. And, strength was still increased until 91 days.

Fig 5 and Fig 6 shows the 28 days of flexural and splitting tensile strength for all mixes. The presence of CR in the mixture reduced both flexural and tensile strength slightly as with CR addition for each mixes with and without SF. It was clearly seen that the strength reduction was less than 10% compared to control mix and it was implied that this reduction was much smaller than that in compressive strength; where the reduction was more than 10%. However, substitution of 10% SF in the mixed helped to improve

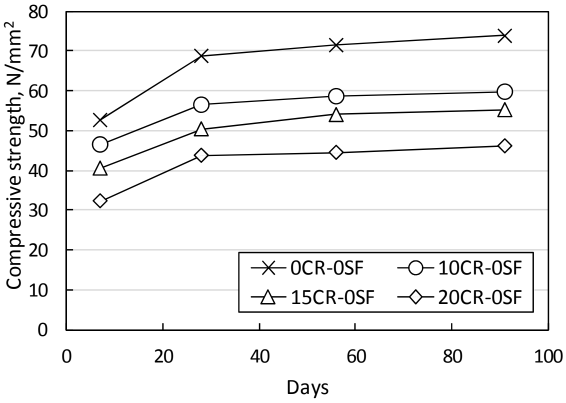


Fig. 3 Strength development of rubberized concrete without silica fume

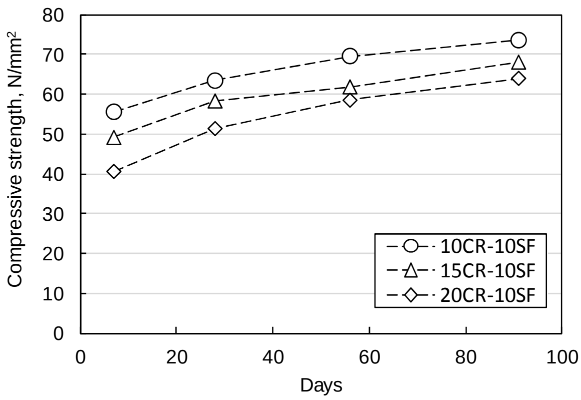


Fig. 4 Strength development of rubberized concrete with 10% silica fume

the bonding between cement paste and CR, where flexural and splitting tensile strength showed higher strength compared with control mix.

3.3 Effective chloride ion diffusion coefficient, D_e

Fig. 7 and Fig 8 shows the relationship between D_e and 28 days compressive strength of rubberized concrete for all mixes. From this figure, it was found that CR could gave benefits in providing resistance on chloride ion migration through the concrete. The same pattern can be observed when SF was added in the mixture.

The highest resistance in chloride ion migration through concrete was clearly seen when SF was used as additional binder for about 60-65% reduction compared to control mix. This may be due to the ultrafine particle of SF which allowed it to fill the voids between cement particles and aggregate particles [7]. Good filling of concrete paste lead to the reduction of porosity and provide dense concrete.

Referring to the literature, both strength and chloride transport characteristics are linked to the pore structure of the rubberized concrete [8]. Thus, this relationship shows that even though the strength was reduced, the positive improvement in chloride ion migration resistance indicates that the pore structure of the rubberized concrete was still under accepted level. This behavior was clearly seen when 10% SF was added in the rubberized mixed.

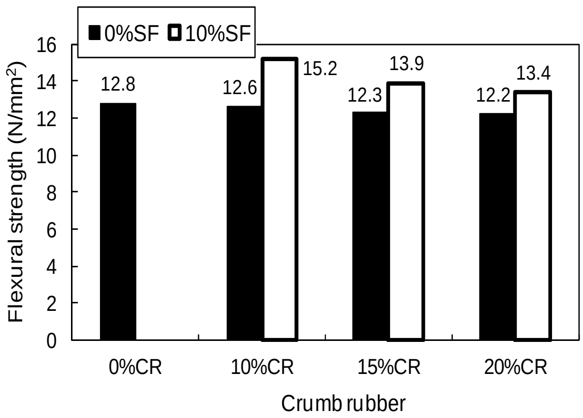


Fig. 5 Flexural strength of rubberized concrete at 28 days

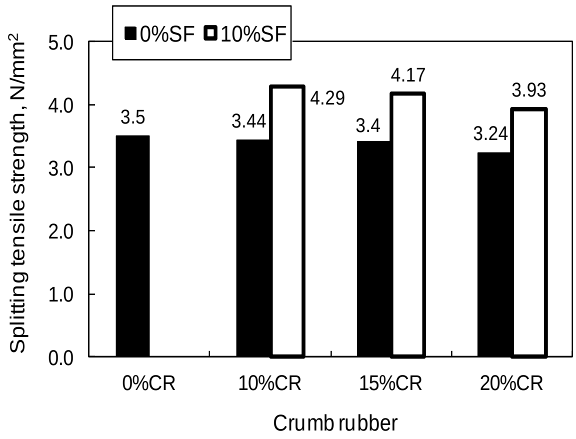


Fig. 6 Splitting tensile strength of rubberized concrete at 28 days

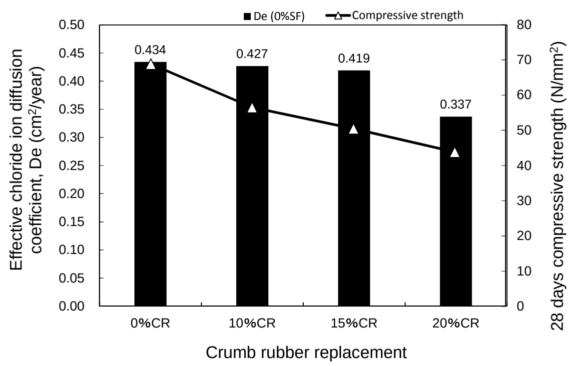


Fig. 7 Relationship between effective chloride ion diffusion coefficients and compressive strength at 28 days of rubberized concrete without silica fume

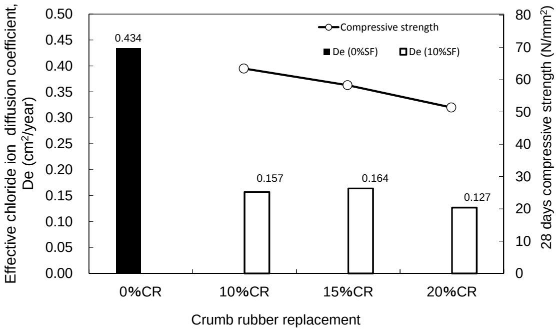


Fig. 8 Relationship between effective chloride ion diffusion coefficients and compressive strength at 28 days of rubberized concrete with silica fume

4. CONCLUSION

From this research, several conclusions can be drawn as follows,

1. Addition of CR and silica fume in the mixture makes air content control in concrete very difficult. Thus, selection and usage of air-modifying agent was important to make air content in concrete as 4-5%.
2. Increment of crumb rubber in the mixture decrease the workability behavior for both rubberized concrete with and without silica fume.
3. Due to the low density of crumb rubber, compressive strength reduction of 43% was observed in 20% crumb rubber mixed without silica fume and this reduction was improved when silica fume was added.
4. Addition of 10% SF improved the resistance of rubberized concrete against chloride ion. And also CR addition reduced chloride ion migration coefficient of concrete.
5. Chloride transport characteristics were improved by increasing the amount of CR due to the fact that CR has the ability to repel water.

ACKNOWLEDGEMENT

Grateful acknowledgement to Hikari World Company Limited for his support in supplying the crumb rubber. Special thanks were also dedicated to Malaysia Ministry of Higher Education in providing financial study to the first author. Authors` appreciation was also goes to all laboratory members for their kind support and help in preparing the specimen.

REFERENCE

[1] Miguel Bravo, Jorge de Brito, “Concrete Made with Used Tyre Aggregate:Durability-related Performance”, Journal of Cleaner Production, Vol. 25, 2012, pp. 42-50

[2] Kumaran, G.S., Nurdin, M. and Lakshmipathy, M., “A Review on Construction Technologies That Enables Environmental Protection: Rubberized Concrete,” AJEAS1, Vol. 1, pp. 41-45, 2008

[3] Nurazuwa M.N., H. Hamada, Y. Sagawa and D. Yamamoto, “Strength Characteristics of Mortar Mixed with Tire Crumb Rubber as Fine Aggregate”, Proceeding of 67th Conference of Cement Technology, 2013

[4] JSCE-G571-2003, “Test Method for Effective Diffusion Coeficient of Chloride Ion in Concrete by Migration”, JSCE Guidelines for Concrete No.2, 2004

[5] Erhan Gűneyisi, Mehmet Gesoğlu and Turan Ozturan, “Properties of Rubberized Concretes Containing Silica Fume”, Cement and Concrete Research, Vol. 34, 2004, pp. 2309-2317

[6] Nehdi, M. and Khan, A., “ Cementitiuos Composites Containing Recycled Tire Rubber: An Overview of Engineering Properties and Potential Applications”, Cement, Concrete, and Aggregates, CCAGDP, Vol. 23, No.1, June 2001, pp.3-10

[7] Mehmet Gesoğlu and Erhan Gűneyisi, “ Strength Development and Chloride Penetration in rubberized Concretes with and without Silica Fume”, Materials and Structures, Vol. 40, 2007, pp. 953-964

[8] “Chloride Resistance of Concrete”, Report of Cement Concrete & Aggregates Australia, June 2009