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Effect of Particle Sizes on Mechanical Properties of Concrete Containing Crumb Rubber

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Abstract

This paper investigates the mechanical properties of concrete containing different particle sizes of crumb rubber. This research have been conducted on 10% replacement of fine aggregates by three different particle sizes of crumb rubber which are 1 mm crumb rubber, 0.4–1 mm fine dust crumb rubber, and 0.2–0.6 mm powder crumb rubber. Laboratory tests include slump test, compressive test, flexural test, bulk density test, water absorption test, porosity test, and ultrasonic pulse velocity (UPV) test were conducted on the concrete mixes. All concrete specimens were tested at the age of 7, 14, 28, and 56 days. The results from laboratory testing on concrete specimens were analyzed. It was found that in the inclusion of crumb rubber into concrete, it will reduce the strength of concrete. The usage of greater particle sizes of crumb rubber which is 1 mm crumb rubber gives better strength of concrete compared to the usage of smaller particle sizes of crumb rubber which is 0.2–0.6 mm powder crumb rubber. Therefore, the rubberized concrete can absorb the impact energy and suitable usage in roads and highways construction such as road divider, road pavement, and others because it can absorb impact from vehicles load, disaster and others.

Keywords: Crumb rubber, Workability, Concrete strength

1. Introduction

The utilization of recycled and hazardous waste materials in construction applications and the solution of environment problem by recycling are becoming greater concern (Bolden et al., 2013). Hazardous materials can be classified as chemical, toxic or non-decaying material accumulating with time. The accumulation of rubber can be considered non-decaying materials that disturb the surrounding environment. However, a positive method for disposing of this non-decaying material, such as reuse in concrete mixes, would have a beneficial effect. Recycling techniques are being developed around the world and many have proven to be effective in protecting our environment and conserving natural resources (Shayan and Xu, 1999; Rindl, 1998; Pierce and Blackwell, 2003; Segre and Joekes, 2000). Recycling of materials such as, rubber, glass, demolished concrete, metal, and plastic represent a clear model for the proper disposal of waste materials for a better environment (Batayneh and Marie, 2006; Shayan and Xu, 2004; Marzouk et al., 2007).

It has been reported that the United States alone has about 275 million scrap tires stockpiled across the country, with an annual increase of 290 million tires generated per year (Papakonstantinou and Tobolski, 2006). Research and development within the industrial world is continuously progressing towards finding new and innovative techniques to recycle waste materials. Worldwide, the use of recycled materials has been practiced for years in highway application and in rubberized concrete (Chanbane et al., 1999; Siddique and Naik, 2004). The latter has gained acceptance worldwide in the engineering sector, directing many researchers in recent years to focus on performing additional research on the use of waste rubber in concrete (Hernandez-Olivares et al., 2002; Siddique and Naik, 2004; Lee and Roh, 2006).

The consumption of crumb rubber in highway construction was made compulsory in projects funded by governments like the USA and France (Marzouk et al., 2007; Li et al., 2004). Savas et al. (1996), Benazzouk and Queneudec (2002), and Paine et al. (2002) investigated the effect of adding rubber to concrete mixes on freezing and thawing resistance. They concluded that there is potential for using crumb rubber as a freeze–thaw resistance agent in concrete and that the concrete with crumb rubber performed better under freeze–thaw conditions than plain concrete. It has been reported by Hernandez-Olivares and Barluenga (2004) that the addition of crumb tire rubber to structural high strength concrete slabs can improve the fire resistance and reduce the spalling damage by fire. Yang et al. (2001) concluded in their research that rubberized concrete can successfully be used in secondary structural components such as culverts, crash barriers, sidewalks, running tracks, sound absorbers, etc. However, most of the developing countries have yet to raise their awareness regarding recycling of waste materials and have not developed effective legislation with respect to the local reuse of waste materials.

Previous researches that have done to rubberized concrete found that the strength of the rubberized concrete was lower than conventional concrete (Eldin and Senouci, 1993; Khatib and Bayomy, 1999; Al-Tayeb et al., 2012; Al-Tayeb et al., 2013). Therefore, the particle size and the amount of crumb rubber in concrete mixture must be investigated to obtain relevant strength of concrete. The results of strength and durability of concrete from the previous research by using different quantities of crumb rubber in ordinary Portland cement (OPC) showed that compression strength decreased about 85% and flexible strength decreased about 50% by replacing all aggregates with crumb rubber (Eldin and Senouci, 1993). In addition, crumb rubber content must not exceed 20% of total aggregate volume to achieve relevant compressive strength (Khatib and Bayomy, 1999). More researches are required to optimize the particle size, percentage of crumb rubber, methods of pretreatment of rubber particles and other to get the solution for this problem. Al-Tayeb et al. (2012) investigated the effect of partial replacements of sand and cement by waste rubber on the fracture characteristics of concrete. They found that addition of waste tire in concrete enhanced the fracture properties, while both compressive and flexural strengths were decreased. Al-Tayeb et al. (2013) observed that the replacement of sand with the crump rubber particles in concrete cured in water for 90 days enhanced impact resistance.

The main goal of this research is to investigate the behavior of concrete using crumb rubber as aggregates replacement. The research conducted on 10% replacement of fine aggregates by three different particle sizes of crumb rubber which are 1 mm crumb rubber, 0.4–1 mm fine dust crumb rubber, and 0.2–0.6 mm powder crumb rubber.

2. Materials and methods

2.1 Preliminary Investigations

For the preliminary investigations, materials used in the current study were subjected to physical and chemical analyses to determine whether they are in compliance with the standard used.

2.1.1 Cement

Ordinary Portland cement, Type I, which conforms to ASTM C150-1992, was used in this research with a specific gravity of 3.15. Initial and final setting time of the cement was 50 min and 365 min, respectively. The chemical composition of OPC is given in Table 1.

2.1.2 Water

Potable water with pH value of 7.0 was used for making concrete and curing the specimen as well. The water was free of acids, organic matter, suspended solids, alkalis and impurities which when present may have adverse effect on the strength of concrete.

2.1.3 Aggregates

Locally available natural sand with 4.75 mm maximum size was used as fine aggregate, having specific gravity and absorption of 2.67 and 5.01% respectively. Crushed stones with 20 mm maximum size were used as coarse aggregate, having specific gravity and absorption of 2.65 and 2.66% respectively. The results of the sieve analysis according to ASTM C136-06 for fine and coarse aggregates are presented in Figures 1 and 2 respectively.

Table 1. Chemical compositions of OPC

Element	Composition by weight (%)
SiO_2	19.71
Al_2O_3	5.20
Fe_2O_3	3.73
CaO	62.91
MgO	2.54
SO_3	2.72
K_2O	0.90
Na_2O_3	0.25
Loss on ignition (LOI)	0.96
SiO_2+Al_2O_3+Fe_2O_3	28.64

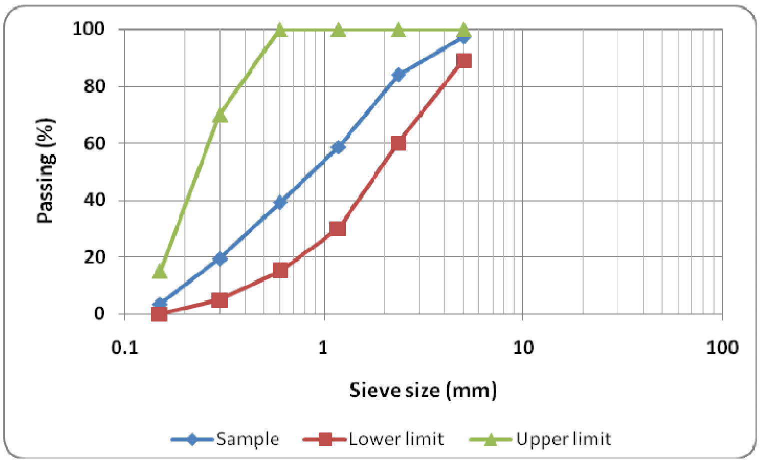

Figure 1. Sieve analysis of fine aggregate

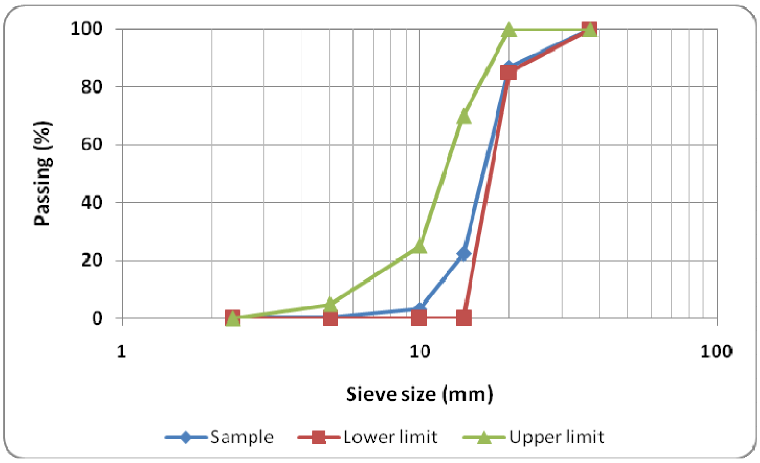

Figure 2. Sieve analysis of coarse aggregate

2.1.4 Crumb rubber

Different particle sizes of crumb rubber which are Crumb rubber (1 mm), fine dust crumb rubber (0.4–1 mm), and powder crumb rubber (0.2–0.6 mm) having relative densities of 0.66 0.64, and 0.6 respectively.

2.2 Mix Proportioning

The purpose of concrete mix design is to design the quantities of materials that have been used for concrete mixture. A trial mixes proportioning by weight was used for preparing the specimens. The mix designs were carried out for concrete grade 30 at 28 days. Concrete specimens were prepared with 10% replacement by weight of fine aggregates by different particle sizes of crumb rubber which are 0.2–0.6 mm powder, 0.4–1 mm fine dust, and 1 mm. The mix proportions were calculated for one cubic meter and presented in Table 2.

Table 2. Mix proportion for concrete grades 30 (for one cubic meter volume)

Mix	Cement content (kg)	Water content (kg)	Fine aggregate (kg)	Coarse aggregate (Kg)	Crumb Rubber (kg)
Control	335	190	660	1220	0
Powder crumb rubber	335	190	594	1220	66
Fine dust crumb rubber	335	190	594	1220	66
One mm crumb rubber	335	190	594	1220	66

2.3 Preparation of Specimens

A cube of size 100 x 100 x 100 mm and prism of size 100 x 100 x 500 mm for the control and fine aggregates replacements were produced. All specimens were tested on 7, 14, 28, and 56 days respectively. All concrete mixes in the study were prepared following the procedure prescribed in ASTM C192 / C192M-05. All the concrete specimens were cast under laboratory conditions, demoulded at 24 h after casting, and then fully submerged in water at (25 ± 2)°C until further testing.

2.4 Testing of Specimens

Laboratory tests include slump test, compressive test, flexural test, bulk density test, water absorption test, porosity test, and ultrasonic pulse velocity (UPV) test were carried out on the concrete mixes at the specified ages.

3. Results and discussion

The results of all tests that have been performed on the trial mixes are shown below.

3.1 Workability

The workability property of concrete mixes was measured by conducting slump cone test according to ASTM C143 / C143M-05. The slump test results of concrete mixes of the C30 grade concrete are presented in Figure 3.

As shown in Figure 3, the slump of rubberized concrete is lower than normal concrete. All specimens had high moisture content in its interior due to water absorbed during curing process. The water was kept inside the voids in the interior of specimens with rubber content. The formation of voids can be explained due to the low slump that concrete containing crumb. Hence, adhesion between cement paste and rubber was not enough to cover all rubber particles, resulting in voids between cement and rubber. The formation of voids derived into concrete specimens with a very porous surface.

The angular particles and percentage of voids in a loose condition between aggregate will caused the requirement of water content to achieve acceptable slump value. The crumb rubber contributes to decrease slump value due to its fineness and surface area of crumb rubber particles. From the result of slump test, addition of crumb rubber in concrete will reduced the value of slump test compared to normal concrete. In general, the rubberized concrete specimens have acceptable workability in terms of ease of handling, placement, and finishing.

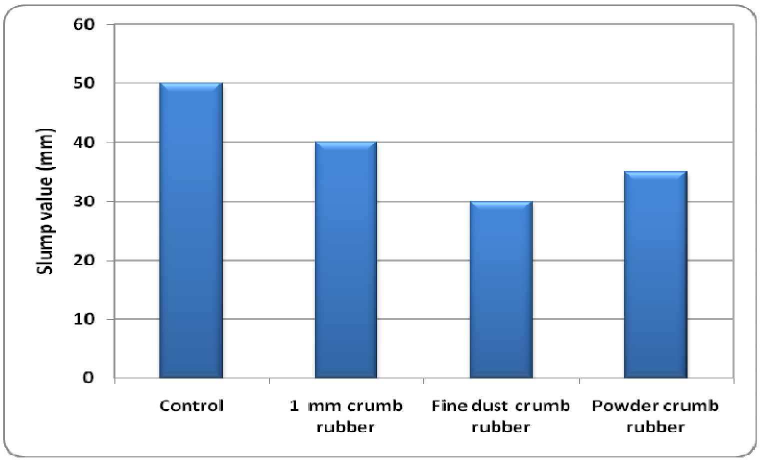

Figure 3. Slump of concrete mixes

3.2 Bulk density

The bulk density of concrete mixes was conducted according to ASTM C138 / C138M-07 by measuring the dimensions and weights of the cubes before crushing at ages 7, 14, 28 and 56 days. The bulk density of cured specimens results of the C30 grade concrete at 7, 14, 28 and 56 days age are presented in Figure 4.

As shown in Figure 4, the larger particle sizes of crumb rubber in concrete give higher value of density compared to small particle sizes of crumb rubber in concrete. However, the normal concrete still had a higher value than rubberized concrete. At 56 days, the density of normal concrete is 2371.23 kg/m^3. The maximum value of rubberized concrete is 2263.47 kg/m^3 for the 1 mm crumb rubber and the minimum value is 2172.79 kg/m^3 for powder crumb rubber concrete.

This behavior is due to the physical properties of rubber, since it has lower density than sand, which reduces the mass per unit volume. The effect for smaller rubber particles due to the greater porosity of the composite obtained. It shows that the greater quantity of spaces filled with water within the interface rubberized concrete. The decrease on aggregates density generates an increase in composites volume obtaining greater performance, even when aggregates weight remains constant.

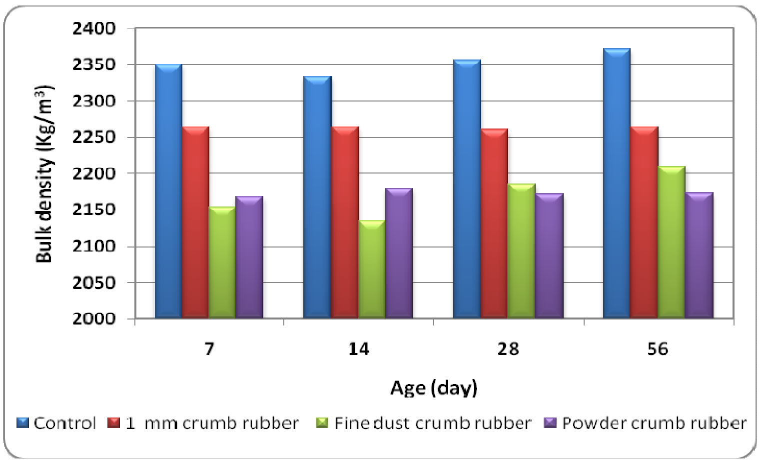

Figure 4. Bulk density of concrete mixes

3.3 Compressive strength

The compressive strength test was conducted in compliance with BS EN 12390-3: 2009 on 100 mm concrete cubes under uniaxial compression testing machine with maximum capacity of 3000 kN to obtain compressive strength of C30 grade of concrete. The compressive strength results of the C30 grade concrete at 7, 14, 28 and 56 days age are presented in Figure 5.

As shown in Figure 5, the strength of the normal concrete is higher than rubberized concrete. The specified compressive strength for this study is 30 N/mm^2 at 28 days. The actual 28 days strength for the normal concrete is 33.5 N/mm^2 which is greater than specified strength. The strength value for rubberized concrete with larger particle sizes is greater than concrete containing smaller particle sizes. At the 28 days of compression test, the strength of concrete containing 1 mm crumb rubber is 19.4 N/mm^2 and the strength of concrete containing powder crumb rubber is 14.1 N/mm^2. The lower strength is 13.4 N/mm^2 for concrete containing fine dust crumb rubber.

The reason for the strength reduction could be attributed both to a reduction of quantity of the solid load carrying material and lack of adhesion at the boundaries of the rubber aggregate, soft rubber particles may behave as voids in the concrete matrix. The addition of 1 mm crumb rubber gives higher compressive strength than addition of powder crumb rubber. The small rubber particles originate greater interstitial voids that filled with water, so a low interaction between aggregate and concrete is achieved, with subsequent loss in compressive strength. The result suggests by using larger size of crumb rubber will gives better compressive strength value.

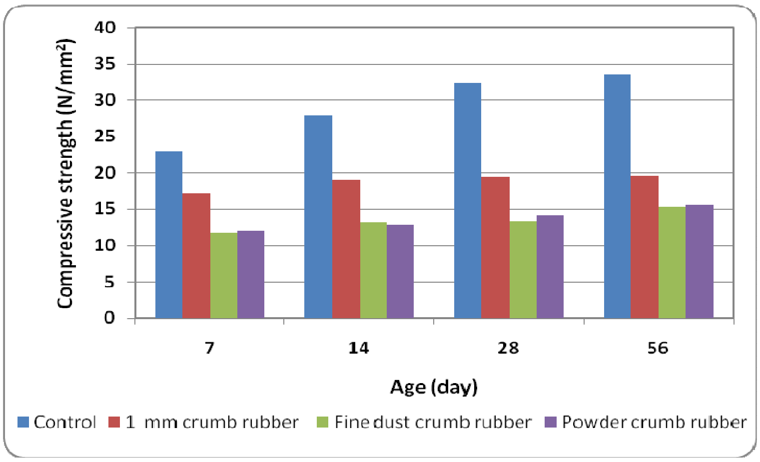

Figure 5. Compressive strength of concrete mixes

3.4 Flexural strength

Flexural strength test was conducted to measure the ability of a concrete beam to resist bending. This test involves with fabrication of the prism specimens with dimensions of 100 × 100 × 500 mm and the test procedure were performed in accordance to ASTM C78 / C78M-10e1. The flexural strength results of the C30 grade concrete at 7, 14, 28 and 56 days age are presented in Figure 6.

As shown in Figure 6, the flexural strength of rubberized concrete is lower than the normal concrete. The flexural strength for normal concrete at 56 days is 3.717 N/mm^2. The maximum flexural strength for rubberized concrete is 2.938 N/mm^2 for 1 mm crumb rubber while the minimum strength is 2.380 N/mm^2 for fine dust crumb rubber concrete.

The rubberized concrete is softer than normal concrete. Concrete specimens show early failure because of its weakness against tension. Crumb rubber behaving like springs delay the widening of the existing cracks. Continuous application of compressive load generates more cracks. When the bond between cement paste and rubber is overcome, fracture occurs. Due to a low modulus of elasticity with respect to mineral aggregates, rubber aggregates act as large pores and do not contribute to the resistance to externally applied loads.

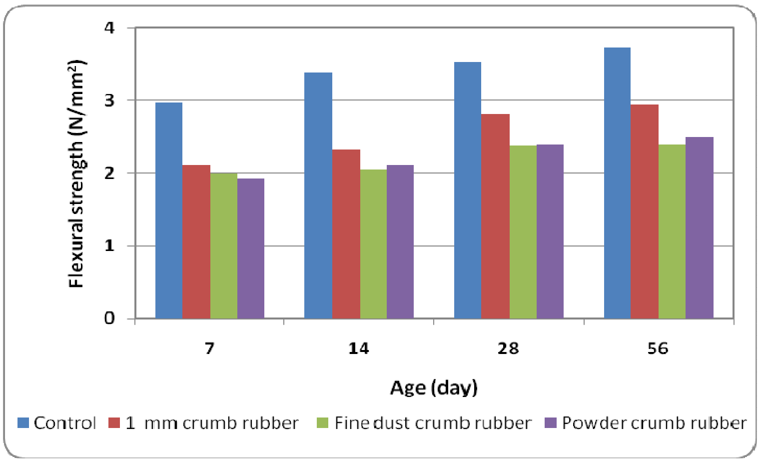

Figure 6. Flexural strength of concrete mixes

3.5 Water absorption

The water absorption test was determined using a method based on that described in ASTM C1585-04 with using cylinder samples of 50 mm diameter and 40 mm length. The water absorption results of the C30 grade concrete at 7, 14, 28 and 56 days age are presented in Figure 7.

As shown in Figure 7, the value of water absorption of rubberized concrete is lower than normal concrete. At the age of 56 days, the water absorption for normal concrete is 6.11% while the water absorption for concrete containing 1 mm crumb rubber is 5.47%. The water absorption for concrete containing powder crumb rubber and fine dust crumb rubber are 6.70% and 5.80% respectively.

The crumb rubber has low specific gravity. The larger particle sizes of crumb rubber tend to increase the level of water entrainment. Increasing of this level may be due to the ability of crumb rubber to repel water by the closed empty pores between crumb rubber particles and concrete matrix. The low value of water absorption also caused by the matrix interfacial zone of rubberized concrete due to the bonds between concrete matrix and crumb rubber particles.

Due to the non-polar nature of rubber particles and their tendency to entrap air in their rough surfaces, tire–rubber concrete specimens contain higher air content. Due to their tendency to repel water, the tire particles attract air. Air can then adhere to the tire particles; hence the tire content results in a higher air content in rubberized concrete mixtures that gives strength reduction in concrete specimens.

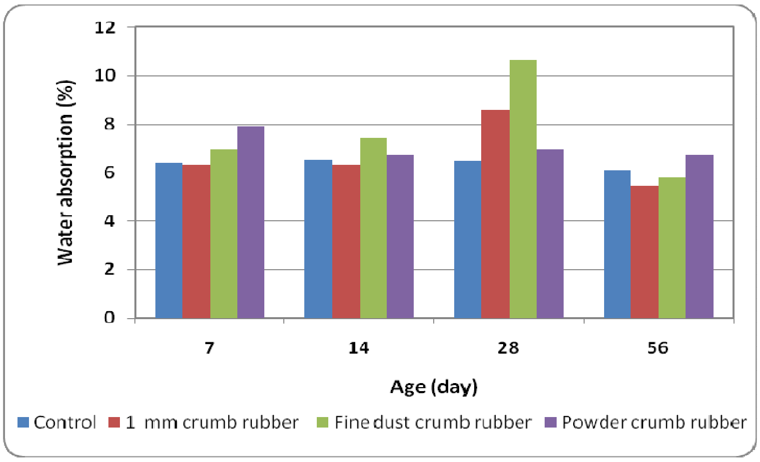

Figure 7. Water absorption of concrete mixes

3.6 Porosity

The porosity of concrete was determined using the vacuum saturation method developed by RILEM (1984). The porosity results of the C30 grade concrete at 7, 14, 28 and 56 days age are presented in Figure 8.

As shown in Figure 8, porosity of specimens decreases with the increasing of specimen age. The values of porosity for normal concrete are 14.09%, 14.21%, 14.23% and 14.05% at the 7 days, 14 days, 28 days and 56 days respectively. The lower value is 11.98% at 56 days for concrete containing 1 mm crumb rubber. The porosity influences adhesion between aggregates and cement paste and plays an important role on concrete strength.

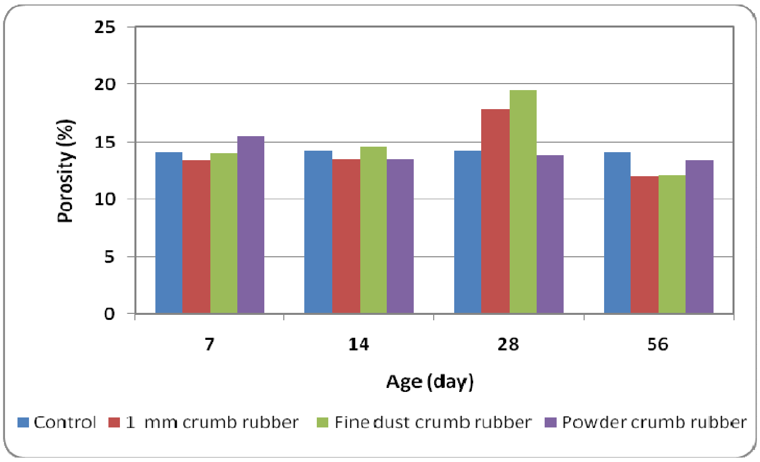

Figure 8. Porosity of concrete mixes

3.7 Ultrasonic pulse velocity (UPV)

Ultrasonic pulse velocity (UPV) test is a non-destructive method to measure the speed of ultrasonic pulse passing through the materials. This test is applicable for predicting the concrete strength or distinguishing the presence of internal flaws, such as voids and cracks. The UPV test in this study was conducted in accordance with ASTM C597-09 on concrete specimens. Direct transmission and semidirect transmission methods were used to determine the quality of 100 x 100 x 100 mm of rubberized and normal concrete cubes. Direct transmission, semidirect transmission and indirect transmission methods were used to determine the quality of 100 x 100 x 500 mm of rubberized and normal concrete beams. The results of ultrasonic pulse velocity for normal concrete and rubberized concrete are shown in Figures 9 to 13.

As shown in all figures, ultrasonic pulse velocity of the rubberized concrete is lower than normal concrete. The comparison between particle sizes of crumb rubber shows that 1 mm crumb rubber concrete have higher value than fine dust crumb rubber concrete. From the behavior showed by the ultrasonic pulse velocity with time, the ultrasonic pulse velocity was relatively dependent of particle size and coupling agent employed. This was due to the greater volume that rubber occupies.

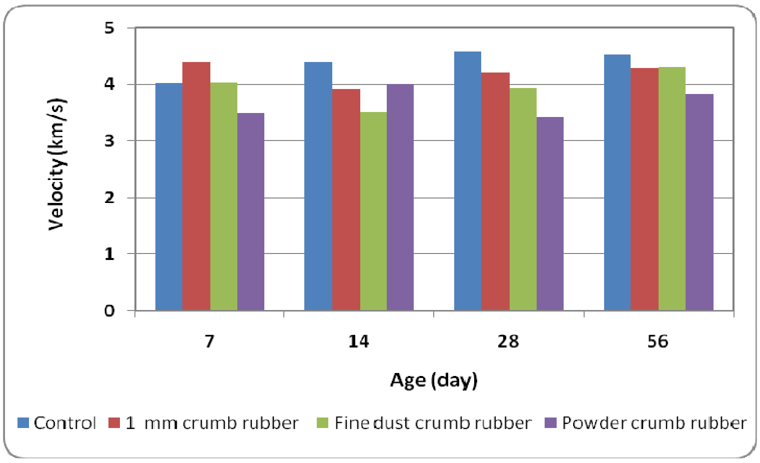

Figure 9. Ultrasonic pulse velocity of concrete for direct transmission of cube specimens

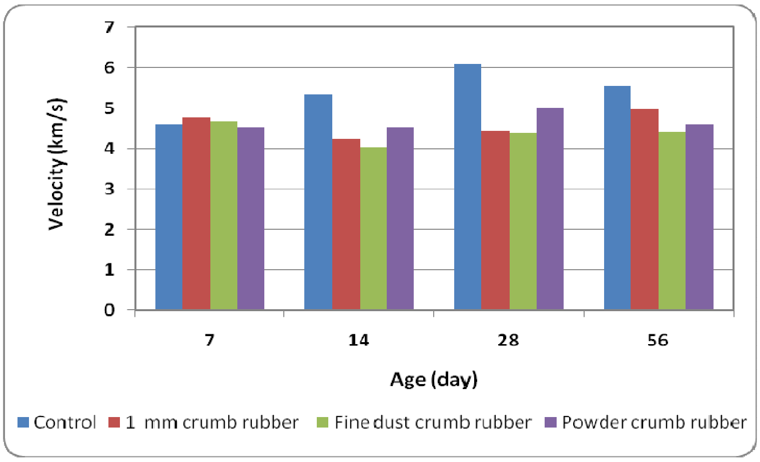

Figure 10. Ultrasonic pulse velocity of concrete for semidirect transmission of cube specimens

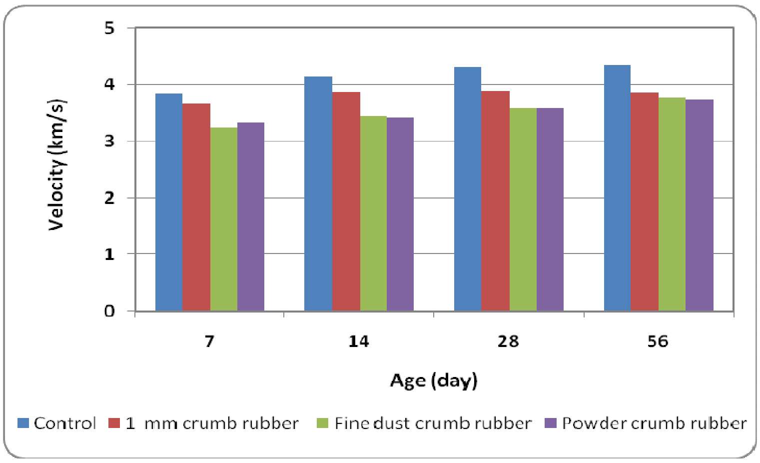

Figure 11. Ultrasonic pulse velocity of concrete for direct transmission of beam specimens

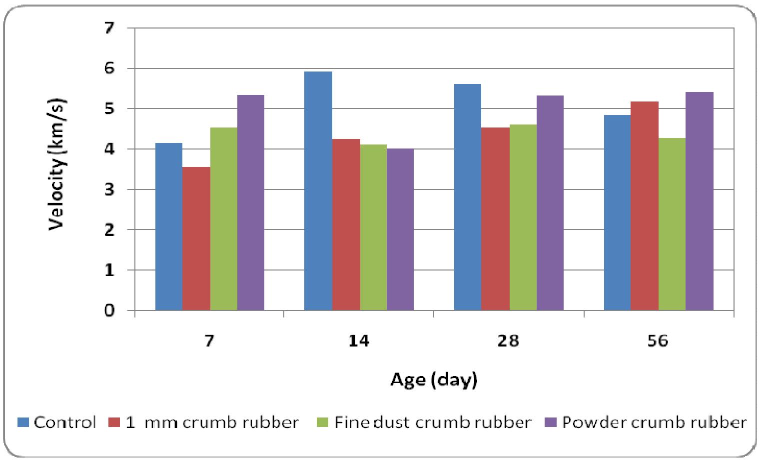

Figure 12. Ultrasonic pulse velocity of concrete for semidirect transmission of beam specimens

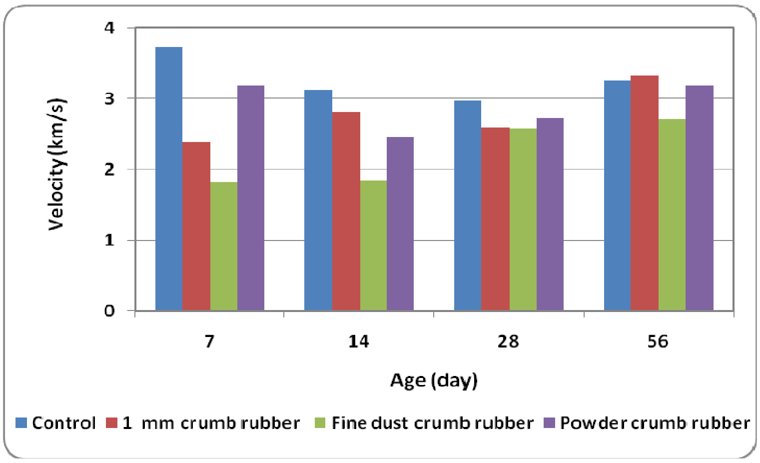

Figure 13. Ultrasonic pulse velocity of concrete for indirect transmission of beam specimens

It is also shown that the particle sizes influence the ultrasonic velocity. When a particle size is bigger, the ultrasonic velocity is greater which means the attenuation by dispersion is not much. Due to the significant reduction in the ultrasonic modulus, a porous composition is expected for rubberized concrete. The rubberized concrete is a suitable material for the dampening of sound and other shaking energies and can be used in noisy sites to serve as sound insulation.

4. Conclusions

The main outcome for this study was to investigate the effect of concrete containing different particle sizes of crumb rubber on mechanical properties of concrete. Based on the results presented above, the following conclusions can be drawn:

- Addition of crumb rubber into concrete caused the slump value of concrete decreased. The slump value was decreased from 50 mm for the normal concrete to 40 mm for 1 mm crumb rubber concrete and 30 mm for fine dust crumb rubber concrete. The reduction was about 20% for the highest slump value for rubberized concrete compared to normal concrete. The comparison between different particles sizes of crumb rubber showed that the bigger sizes of crumb rubber gives better slump value than smaller sizes of crumb rubber. Although the slump value of rubberized concrete was decreased, these values were still acceptable to specified slump value which is 30 – 60 mm.
- Compressive strength of rubberized concrete was lower than normal concrete. The compressive strength for normal concrete is 33.5 N/mm^2 that was greater than specified strength about 11.67%. The

compressive strength for crumb rubber with greater particle sizes was better than smaller particle sizes. Similarly to the compressive strength, flexural strength also reduced for rubberized concrete. This is due to the reduction of quantity of the solid load carrying material and lack of adhesion at the boundaries of the rubber aggregate.

- Density of concrete also showed the same trends with compressive strength and flexural strength. At 56 days, the density of normal concrete is 2371.23 kg/m^3. It seems very different value of density for normal concrete and rubberized concrete which is more than 100 kg/m^3. Besides that, the different between the higher value and lower value of rubberized concrete is about 100 kg/m^3. The reduction of concrete density was due to density of crumb rubber which is lower than sand and it occupied greater volume.
- The water absorption and porosity were related to each others. All these values showed the same scale of reduction between normal concrete and rubberized concrete. It also showed the similar reduction between larger particle sizes and smaller particle sizes of crumb rubber which is the value of water absorption and porosity of 1 mm rubberized concrete lower than powder rubberized concrete. The low value for the water absorption and porosity were caused by the matrix interfacial zone of rubberized concrete due to the weak bonds.
- Ultrasonic pulse velocity (UPV) was relatively due to the particle sizes. The results of UPV test for all cubes by the direct and semidirect transmission and for all beams by direct, semidirect and indirect transmission showed there is not much different UPV value among them. 1 mm crumb rubber concrete had a greater value which means the attenuation by dispersion is not much. This indicated that the quality of concrete reduced when the big sizes of crumb rubber was used.

A characteristic function that quantifies the reduction in strength for rubberized concrete mixes was developed that could be useful for mix design purposes. Rubberized concrete mixes may be suitable for nonstructural purposes such as lightweight concrete walls, building facades, and architectural units. They could also be used as cement aggregate bases under flexible pavements. Fire hazards are of major concern and need to be thoroughly investigated before recommendations for practical implementation are drawn.

References

ASTM C 150-92. (1992). Standard specification for Portland cement. Annual Book of ASTM Standard. Vol. 04.02. Philadelphia.

ASTM C 143/C 143M-05. (2005). Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM International, West Conshohocken, PA.

ASTM C138 / C138M-07. (2007). Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, ASTM International, West Conshohocken, PA.

ASTM C192 / C192M-05. (2005). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA.

ASTM C78 / C78M-10e1. (2010). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, West Conshohocken, PA.

ASTM C1585-04. (2004). Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, ASTM International, West Conshohocken, PA.

ASTM C597-09. (2009). Standard Test Method for Pulse Velocity Through Concrete, ASTM International, West Conshohocken, PA.

ASTM C136-06. (2006). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA.

Al-Tayeb, M.M., Abu Bakar, B.H., Akil, H.M., and Ismail, H. (2012). Effect of partial replacements of sand and cement by waste rubber on the fracture characteristics of concrete. Polymer-Plastics Technology and Engineering 51 (6), 583-589.

Al-Tayeb, M.M., Abu Bakar, B.H., Ismail, H., and Akil, H.M. (2013). Effect of partial replacement of sand by fine crumb rubber on impact load behavior of concrete beam: experiment and nonlinear dynamic analysis. Materials and Structures 46 (8). 1299-1307.

Batayneh, M., Marie, I., Asi, I. (2006). Use of selected waste materials in concrete mixes. Waste Management Journal 27 (12), 1870–1876.

Benazzouk, A., Queneudec, M. (2002). Durability of cement–rubber composites under freeze thaw cycles. In: Dhir, R.K. et al. (Eds.), Proceedings of the International Conference on Sustainable Concrete Construction. University of Dundee, Scotland, UK, pp. 356–362.
Bolden, J., Abu-Lebdeh, T. and Fini E. (2013). Utilization of recycled and waste materials in various construction applications. Am. J. Environ. Sci., 9: 14-24. DOI: 10.3844/ajessp.2013.14.24.
BS EN 12390-3. (2009). Testing hardened concrete. Compressive strength of test specimens. British Standards Institution, London.
Chanbane, B., Sholar, G.A., Musselman, J.A., Page, G.C. (1999). Ten-year performance evaluation of asphalt-rubber surface mixes. Transportation Research Record No. 1681, Transportation Research, Washington, DC, pp. 10–18.
Eldin, N.N. and Senouci, A.B. (1993). Rubber-Tire Particles as Concrete Aggregates. Journal of Materials in Civil Engineering, ASCE 5(4), 478–496.
Hernandez-Olivares, F., Barluenga, G. (2004). Fire performance of recycled rubber-filled high-strength concrete. Elsevier Cent and Concrete Research 34 (1), 109–117.
Hernandez-Olivares, F., Barluenga, G., Bollati, M., Witozek, B. (2002). Static and dynamic behaviour of recycled tyre rubber-filled concrete. Cement Concrete Research 32, 1587–1596.
Khatib, Z.R., Bayomy, F.M. (1999). Rubberized portland cement concrete. ASCE Journal of Materials in Civil Engineering 11 (3), 206–213.
Lee, H.J., Roh, H.S. (2006). The use of recycled tire chips to minimize dynamic earth pressure during compaction of backfill. Construction Building Materials Journal. doi:10.1016/j.conbuildmat.2006.02.003.
Li, G., Stubblefield, M.A., Garrick, G., Eggers, J., Abadie, C., Huang, B. (2004). Development of waste tire modified concrete. Cement Concrete Research 34, 2283–2289.
Marzouk, O.Y., Dheilly, R.M., Queneudec, M. (2007). Valorization of post-consumer waste plastic in cementitious concrete composites. Waste Management 27, 310–318.
Paine, K.A., Dhir, R.K., Moroney, R., Kopasakis, K. (2002). Use of crumb rubber to achieve freeze thaw resisting concrete. In: Dhir, R.K. et al. (Eds.), Proceedings of the International Conference on Concrete for Extreme Conditions. University of Dundee, Scotland, UK, pp. 486–498.
Papakonstantinou, C.G., Tobolski, M.J. (2006). Use of waste tire steel beads in Portland cement concrete. Cement Concrete Research 36, 1686–1691.
Pierce, C.E., Blackwell, M.C. (2003). Potential of scrap tire rubber as lightweight aggregate in flowable fill. Waste Management 23, 197–208.
RILEM recommendations. (1984). Absorption of water by immersion under vacuum. Material Structure, RILEM CPC 11.3, vol. 101, pp. 393–394.
Rindl, J. (1998). Recycling Manager, report by Recycling Manager, Dane County, Department of Public Works, Madison, USA.
Savas, B.Z., Ahmad, S., Fedroff, D. (1996). Freeze–thaw durability of concrete with ground waste tire rubber. Transportation Research Record No. 1574, Transportation Research Board, Washington, DC, pp. 80–88.
Segre, N., Joekes, I. (2000). Use of tire rubber particles as addition to cement paste. Cement Concrete Research 30, 1421–1425.
Shayan, A, Xu, A. (1999). Utilization of glass as a pozzolonic material in concrete ARRB TR Internal Report RC91132.
Shayan, A., Xu, A. (2004). Value-added utilization of waste glass in concrete. Cement Concrete Research 34 (1), 81–89.
Siddique, R., Naik, T.R. (2004). Properties of concrete containing scraptire rubber – an overview. Waste Management 24, 563–569.
Yang, S., Kjartanson, B., Lohnes, R. (2001). Structural performance of scrap tire culverts. Canadian Journal of Civil Engineering 28 (2), 179–189.