MECHANICAL, DURABILITY AND DAMPING PROPERTIES FOR OPTIMUM RUBBERISED CONCRETE PERFORMANCE

MOHAMAD SYAMIR BIN SENIN
B. E.

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy

Faculty of Civil Engineering and Build Environment
University Tun Hussein Onn Malaysia

FEBRUARY 2022

For my beloved mother, father, wife, daughter and family.

ACKNOWLEDGEMENTS

All praises be to Allah S.W.T for giving me the strength, health, knowledge and patience to complete this 6-year PhD journey. I would like to acknowledge the financial support provided by the Ministry of Higher Education Malaysia (Mybrain15), Perbadanan Tabung Pendidikan Tinggi National (PTPTN), Yayasan Pelajaran Johor (YPJ) and Geran Penyelidikan Pasca Siswazah (GPPS) Vot U572 for my PhD research.

My deepest appreciation goes to my supervisor, Prof. Madya Ir. Ts. Dr. Shahiron Bin Shahidan who guided me with his dedication, attention, expertise and advice throughout the process of this research work. I would also like to thank my co-supervisors, Dr. Siti Radziah Binti Abdullah and Dr. Nor Hayati Binti Abd Ghafar for giving me full support during my PhD research.

Special thanks to my late father, Senin Bin Ahmad and my mother Foiziah Binti A. Wahab who always pray to God and support me with love and patience. I would also like to thank my brother, Mohamad Syafiq Bin Senin and my sister Nurul Syahirah Binti Senin who have always supported me. To my beloved wife, Maszrilemyliya Binti Misbae and my princess, Qaisara Batrisya Binti Mohamad Syamir, thank you for your understanding and moral support when I needed it most.

I would like to extend my heartfelt gratitude to all the technicians (Mr. Suhaimi, Mr. Amran and Mr Afandi) from the Heavy Structure Lab, Jamilus Research Centre, University Tun Hussein Onn Malaysia for their assistance while I was conducting tests in the lab.

Last but not least, to all my friends (Dr. Alif Syazani, Dr. Nurul Izzati Raihan and especially Ir. Ts. Dr. Mohd Fairuz Ab Rahman) thank you for lending me your hands, eyes and ears, and keep telling me not to give up for my PhD. Thank you very much. May Allah bless all of you always.

ABSTRACT

Waste tyres pose significant health and environmental concerns if there are not recycled or appropriately discarded. Partial replacement of natural aggregate with waste tyres in the concrete mixture has been proven to be more economical and sustainable. Many researchers have study on mechanical and durability properties of rubberised concrete. However, there are lack of study on damping properties of rubberised concrete. Previous study has shown that incorporating rubber in concrete mix caused significant reduction on mechanical and durability properties of rubberised concrete and thus discourage its commercialisation. Large rubber particle and high percentage of rubber replacement causes substantial reduction on mechanical and durability properties of rubberised concrete. The goal of this research is to investigate the mechanical, durability and damping properties by using small rubber particles, namely rubber ash and rubber crumb, to partially replace sand in concrete at low percentage namely 3%, 5%, 7% and 9%. The material properties of sand, rubber ash and rubber crumb, namely: (1) bulk density; (2) specific gravity; (3) particle size distribution; (4) morphology; and (5) chemical composition, are determined by using five different tests. Further eight tests were conducted to determine the engineering properties of the concrete mix with rubber ash or rubber crumb, namely: (1) workability; (2) bulk density; (3) compressive strength; (4) flexural strength; (5) splitting tensile strength; (6) modulus of elasticity; (7) water absorption; and (8) water permeability. Damping properties of the concrete mix with rubber ash or rubber crumb, namely: (1) frequency; (2) mode shape; and (3) damping ratios, are determined by using impact hammer test. The mechanical, durability and damping properties of rubber ash concrete and rubber crumb concrete are compared with the control concrete. The results show that the rubber ash and rubber crumb are suitable to partially replace sand in the concrete mix. Both the mechanical, durability and damping properties have improved by up to 15%. This study found that the optimum content for rubber ash to replace sand in concrete mix is found to be at 5%, whilst the rubber crumb is at 3% for

achieving improved engineering properties. The optimised rubber ash or rubber crumb to replace sand in concrete mix are 3% and 9%, respectively, for achieving improved damping properties. The experimental results of damping properties for rubber ash concrete and rubber crumb concrete are validated by computational modelling, and thus the damping properties of any rubberised concrete structure within the range of this study can be determine by computational modelling. The results of this study indicate the huge potential of the waste rubber to be recycled and used to partially replace sand in concrete mix, and hence reduce dumped tyre waste as well as reduce the use of natural resources (sand).

ABSTRAK

Sisa buangan tayar menimbulkan kebimbangan kesihatan dan persekitaran yang signifikan jika tidak dikitar semula atau dibuang dengan sewajarnya. Penggantian sebahagian batu baur semula jadi dengan sisa buangan tayar dalam campuran konkrit telah terbukti lebih ekonomi dan lestari. Ramai penyelidik membuat kajian terhadap sifat mekanikal dan ketahanan konkrit getah. Namun kurang kajian mengenai sifat redaman konkrit getah. Kajian terdahulu menunjukkan bahawa memasukkan getah dalam campuran konkrit menyebabkan pengurangan yang ketara pada sifat mekanikal dan ketahanan konkrit getah dan dengan itu tidak menggalakkan pengkomersialannya. Partikel getah yang besar dan peratusan penambahan getah yang tinggi menyebabkan penurunan ketara pada sifat mekanikal dan ketahanan konkrit getah. Tujuan penyelidikan ini adalah untuk mengkaji sifat mekanikal, ketahanan dan redaman dengan menggunakan partikel getah kecil, iaitu abu getah dan remah getah, untuk menggantikan sebahagian pasir dalam konkrit dengan peratusan rendah iaitu 3%, 5%, 7% dan 9%. Sifat bahan pasir, abu getah dan serbuk getah, iaitu: (1) ketumpatan pukal; (2) graviti tentu; (3) taburan saiz zarah; (4) morfologi; dan (5) komposisi kimia, ditentukan dengan menggunakan lima ujian yang berbeza. Selanjutnya lapan ujian telah dijalankan untuk menentukan sifat kejuruteraan campuran konkrit dengan abu getah atau rumah getah, iaitu: (1) kebolehkerjaan; (2) ketumpatan pukal; (3) kekuatan mampatan; (4) kekuatan lenturan; (5) kekuatan tegangan membelah; (6) modulus keanjalan; (7) penyerapan air; dan (8) kebolehtelapan air. Sifat redaman bagi campuran konkrit dengan abu getah atau remah getah, iaitu: (1) frekuensi natural; (2) bentuk mod; dan (3) nisbah redaman ditentukan melalui ujian tukul impak. Sifat mekanikal, ketahanan dan redaman konkrit abu getah dan konkrit remah getah dibandingkan dengan konkrit kawalan. Dapatan ujian menunjukkan bahawa abu getah dan remah getah adalah sesuai untuk menggantikan sebahagian pasir dalam campuran konkrit. Sifat mekanikal, ketahanan dan redaman telah bertambahbaik sehingga 15%. Kajian ini mendapati kandungan optimum untuk abu getah untuk menggantikan pasir dalam

campuran konkrit didapati pada 5%, manakala serbuk getah adalah pada 3% untuk mencapai penambahbaikan sifat mekanikal dan ketahanan. Kandungan optimum abu getah atau remah getah untuk menggantikan pasir dalam campuran konkrit adalah masing-masing pada 3% dan 9% untuk mendapatkan sifat redaman yang terbaik. Hasil eksperimen sifat redaman untuk konkrit abu getah dan konkrit remah getah disahkan oleh pemodelan komputasi, dan oleh itu sifat redaman apa-apa struktur konkrit getah dalam julat kajian ini dapat ditentukan dengan pemodelan komputasi. Dapatan kajian ini menunjukkan sisa tayar mempunyai potensi yang besar untuk dikitar semula dan digunakan untuk menggantikan sebahagian pasir dalam campuran konkrit, dan sekali gus mengurangkan lambakan tayar buangan selain mengurangkan penggunaan sumber semula jadi (pasir).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

%	-	Percentage
<	-	Small/ Less Than
>	-	Larger/ More Than
-	-	Negative
C	-	Degree Celsius
H	-	Hour
mm	-	Millimetre
Hz	-	Hertz
AS	-	Australian Standards
ACI	-	American Concrete Institute
ASTM	-	American Society for Testing and Materials
Ctrl	-	Control
BS	-	British Standards
BS EN	-	British Adoption of European Standards
MK	-	Metakaolin
MS EN	-	Malaysian Standards
OPC	-	Ordinary Portland Cement
RAC	-	Rubber Ash Concrete
RCC	-	Rubber Crumb Concrete

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nowadays, road authorities struggle to maintain a substantial number of ageing bridges, which do not comply with the current standard. This can be due to: (1) deterioration and structural deficiencies developed over time; or (2) the escalating demands imposed by increased traffic intensity and higher axle loads (Mara *et al.*, 2014). As a result, the maintenance of bridges is costly and has turned into a very challenging task for the road authorities. Bridge maintenance is even more expensive and complicated in urban areas compared to rural areas, with the additional indirect costs due to traffic disruption. New maintenance methods that minimize the traffic disruption and disturbance in highly populated areas are therefore beneficial for road authorities or owners. One aspect that can be further improved is the use of durable material for concrete deck on bridge structure.

Portland cement concrete is one of the most versatile materials commonly used in construction industry. The widespread use of this type of cement had facilitated industrial growth in the last century and also contributed to environmental issues (Petersen *et al.*, 2015). Gupta *et al.* (2014) argued that concrete industry is one of the most environmentally demanding industries as its production processes involved mining of natural aggregates, use of increasingly scarce freshwater resources, and development of new chemical admixtures. Most of the research today and the current state-of-practices related to resource productivity in structural concrete are limited to cement conservation through the partial replacement of cement with industrial by-product, for example, fly ash, ground granulated blast furnace slag, and silica fume

(González-López *et al.*, 2015). Unfortunately, there has been a slight overlook on the development of suitable substitution materials to the concrete mixture, such as industrial and agricultural wastes, that resulted in concrete mixture with superior mechanical properties.

The National Solid Waste Management Department, Ministry of Housing and Local Government of Malaysia reported that approximately 300,000 tonnes of scrap tyres are generated annually (Chemisian Konsultant Sdn. Bhd., 2011). This value is estimated to increase at about 5% every year, in line with the percentage increment of vehicle usage. Through this study, it can be estimated that by 2021, the volume of scrap tyres generated is expected to be approximately 471,221 tonnes. This problem, however, is not localised as other countries such as the United States of America generates approximately 300,000,000 scrap tyres annually, about 40% of which are used as fuel for generating energy, 26% ground into crumb rubber, 13% discarded in landfills, and only about 5.5% used in civil engineering applications (Shu & Huang, 2014). In the meantime, Xiong *et al.* (2021) reported that approximately 1 billion tyres end their service life every year around the world and more than 50% are discarded without any treatment.

The significant increase in the number of vehicles worldwide and the lack of both technical and economical mechanisms resulting in waste tyres are considered serious pollution problems in terms of waste disposal. The best way to dispose of waste tyres is to reuse them (Lv *et al.*, 2015). The interest in recycling tyre is due to its availability and the high generation volume. The rate of scrap tyre generation is expected to continue growing as the world population and vehicle usage increase (Onuaguluchi & Panesar, 2014). Throughout the United States, there were still 128,000,000 tyres remain stockpiled (Xue & Shinozuka, 2013). Waste tyre management and disposal are major environmental concerns in many countries. Stockpiling is dangerous, not only due to potential adverse environmental impacts, but also because it poses a fire hazard and provides breeding for vector such as rats, mice, vermin, and mosquitoes (Elchalakani, 2015). Also, when such tyres dumbs catch fire it is notoriously difficult and costly to extinguish (Youssf *et al.*, 2014).

Rubber is also one of the industrial wastes that attracts the interest of many researchers. For example, Pelisser *et al.* (2011) mixed rubber into concrete mixture to produce a concrete product with low density and increased thermal insulation and soundproofing. The increase in the waste tyre content in the concrete mixture was found to lower the density of concrete to as low as 75% of the normal concrete weight (Abd. Aziz *et al.*, 2014). Nadal Gisbert *et al.* (2014) found that the addition of rubber particles produces lighter concrete, which can be used for specific applications and have the characteristic of occluding a large amount of air inside that further improves its workability. Furthermore, the increased capacity to dissipate and absorb energy favours its usage in many applications, including the production of sound barriers (Nadal Gisbert *et al.*, 2014). Rubber has a high resistance to cracking in which it does not only improves the resistance of the cementitious to cracking from impact load but also enhances the overall impact strength (Dehdezi *et al.*, 2015).

Construction materials used for engineering applications including the airport runway, road pavement, bridge deck and other structural systems are expected to be concrete structure of high impact resistance. These applications are often exposed to dynamic impact loading thus making its energy-absorbing ability or durability very important. It is established that incorporating rubber to a concrete mixture contributes to a significant improvement in its durability, and hence resistant to impact (Liu *et al.*, 2012). However, the main disadvantages of adding waste tyre rubber in concrete are reduction of the compressive strength and elastic modulus (Hilal, 2017; Khorami & Ganjian, 2011; Thomas & Gupta, 2016; Youssf *et al.*, 2016). Eldin and Senouci (1993) were the first to study concrete consisting tyre aggregate of 38, 25 and 19 mm, in 1993 they found that concrete exhibits lower compressive strength and splitting tensile strength. A notable result was that the failure mode of the concrete was ductile rather than brittle. Thomas *et al.* (1994) further investigated the effects of adding rubber into a concrete mixture by replacing fine (1 mm) and coarse (6 mm, 19 mm, 25 mm and 38 mm) aggregate. Their results supported the findings of the previous study, in that the concrete tyre aggregate had lower compressive and tensile strength. Several studies (Thomas *et al.*, 1994; Bravo & de Brito, 2012) have shown that the increase in the size of the tyre aggregate will result in decreasing compressive strength. They also observed that the loss of compressive strength increased with the size of the tyre aggregate (Bravo & de Brito, 2012). The greater the size of rubber particles added to the concrete, the lower the strength of the concrete, and vice versa (Li *et al.*, 2014; Liu *et al.*, 2012).

The increasing amount of waste tyres worldwide makes the disposal of tyres a crucial problem to be solved. One of the most critical environmental issues all around the world is the disposal of waste materials. Accumulations of discarded waste tyres have been a major concern because waste rubber is not easily biodegradable even after a long period of landfill treatment. However, there are material and energy that can be extracted from waste rubber. Other researchers propose to use it as fuel material or as raw materials of rubber goods (Sukontasukkul & Tiamlom, 2012). Recycled used rubber conserves valuable natural resources and reduces the amount of rubber entering landfill (Youssf *et al.*, 2015).

The use of recycled rubber particles as alternative aggregates in concrete has received significant attention over the last two decades. This is due to the massive quantities of scrap vehicle tyres that have already accumulated and the increased annual production estimated to be one billion tyres produced worldwide in 2011 (Hall & Najim, 2014). Utilization of rubber wastes in the construction industry is now well developed for sustainability in two ways. First, reuse the materials which otherwise would become a burden to the environment and occupy scarce land resource. Second, it minimizes the degradation of land and the environment because of comparatively less digging. Recycling is an all-prevailing practice now as it conserves the planet resources (Gesoğlu & Güneyisi, 2011). Rubberised concrete has become an emerging research topic in recent years. To date, most research is focused on the evaluation of mechanical properties of the rubberised concrete mixture (Xue & Shinozuka, 2013).

The replacement of fine aggregate with waste tyre rubber, at a volume of 5%, causes the strength to increase up to 10% (da Silva *et al.*, 2015). The addition of shredded scrap tyres to concrete provides some favourable characteristics for concrete and alters some of the concrete properties. The ordinary cement-based concrete is generally brittle, however, the addition of rubber in the concrete material increases its ductility and impact resistance (Moustafa & ElGawady, 2015; Pham *et al.*, 2020). The rubberize concrete is recommended to be used in circumstances where vibration damping is required, such as for bridge construction as a shock-wave absorber (Chou *et al.*, 2010; Li *et al.*, 2020). Experimental studies on rubberised concrete materials have shown that using rubber in concrete as partial replacement of mineral aggregates enhances its ductility, toughness, impact resistance, energy dissipation, and damping ratio (Youssf *et al.*, 2015). A recent study by Moustafa & ElGawady (2015) investigated the methods for increasing the damping capacity of concrete by replacing up to 20% of the fine aggregate with shredded rubber. Generally, the study reported an increase in damping and a decrease in compressive strength (Moustafa &

REFERENCES

Abd. Aziz, F. N. A., Bida, S. M., Nasir, N. A. M., & Jaafar, M. S. (2014). Mechanical properties of lightweight mortar modified with oil palm fruit fibre and tire crumb. *Construction and Building Materials*, *73*, 544–550.

ACI318-11. (2011). *ACI 318-11 Building Code Requirements for Structural Concrete (ACI 318-11) Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary*.

ACI363R-92. (1992). State-of-the-Art Report on High-Strength Concrete. *East African Medical Journal*, *49*(6), 440–447.

Aiello, M. A., & Leuzzi, F. (2010). Waste tyre rubberized concrete: properties at fresh and hardened state. *Waste Management (New York, N.Y.)*, *30*(8–9), 1696–1704.

Aïtcin, P.-C. (1998). *High-Performance Concrete*. E & FN SPON.

Al-Akhras, N. M., & Smadi, M. M. (2004). Properties of tire rubber ash mortar. *Cement and Concrete Composites*, *26*(7), 821–826.

Al-Tayeb, M. M., Abu Bakar, B. H., Ismail, H., & Akil, H. M. (2013). Effect of partial replacement of sand by recycled fine crumb rubber on the performance of hybrid rubberized-normal concrete under impact load: experiment and simulation. *Journal of Cleaner Production*, *59*, 284–289.

Anda, K. C. P., Arhi, P. S. P., & Ena, T. J. (2012). *Scrap-Tyre-Rubber Replacement for Aggregate in Cement Concrete : Experimental Study*. *05*(06).

Angelin, A. F., Miranda, E. J. P., Santos, J. M. C. D., Lintz, R. C. C., & Gachet-Barbosa, L. A. (2019). Rubberized mortar: The influence of aggregate granulometry in mechanical resistances and acoustic behavior. *Construction and Building Materials*, *200*, 248–254.

AS3600. (2009). *Concrete structures, Design Properties of materials, Standards Australia International Ltd*. *2009*.

Assaggaf, R. A., Ali, M. R., Al-Dulaijan, S. U., & Maslehuddin, M. (2021). Properties of concrete with untreated and treated crumb rubber – A review. *Journal of*

Materials Research and Technology, *11*, 1753–1798.

Astm:C33-02. (2010). Standard Specification for Concrete Aggregates. *ASTM International*, *i*(C), 1–11.

Astm. (2010). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use. *Annual Book of ASTM Standards*, 3–6.

ASTM C496. (2011). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. *American Society for Testing and Materials*, 1–5.

Atahan, A. O., & Yücel, A. Ö. (2012). Crumb rubber in concrete: Static and dynamic evaluation. *Construction and Building Materials*, *36*, 617–622.

Bahoria, B., Parbat, D. K., Nagarnaik, P. B., & Waghe, U. P. (2013). Effect of replacement of natural sand by quarry dust and waste plastic on compressive & split tensile strength of M20 concrete. *Procedia Engineering*, *March*, 9.

Bayraktar, A., Türker, T., & Altunişik, A. C. (2015). Experimental frequencies and damping ratios for historical masonry arch bridges. *Construction and Building Materials*, *75*, 234–241.

Benazzouk, A., Douzane, O., Langlet, T., Mezreb, K., Roucoult, J. M., & Quéneudec, M. (2007). Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes. *Cement and Concrete Composites*, *29*(10), 732–740.

Benazzouk, A., Mezreb, K., Doyen, G., Goullieux, A., & Quéneudec, M. (2003). Effect of rubber aggregates on the physico-mechanical behaviour of cement-rubber composites-influence of the alveolar texture of rubber aggregates. *Cement and Concrete Composites*, *25*(7), 711–720.

Bisht, K., & Ramana, P. V. (2017). Evaluation of mechanical and durability properties of crumb rubber concrete. *Construction and Building Materials*, *155*, 811–817.

Bravo, M., & de Brito, J. (2012). Concrete made with used tyre aggregate: durability-related performance. *Journal of Cleaner Production*, *25*, 42–50.

BS 1881-125. (2013). *Testing concrete — Part 125: Methods for mixing and sampling fresh concrete in the laboratory*. 1–8.

BS EN 1097-3. (1998). Tests for mechanical and physical properties of aggregates - Part 3: Determination of loose bulk. *British Standard Institutions (BSI)*.

BS EN 12350-6. (2009). Testing fresh concrete - Part 6: Density. *BSI - British Standards Institution*.

BS EN 12390-02. (2009). *Testing hardened concrete - Part 2: Making and curing specimens for strength tests*. *3*(1), 420–457.

BS EN 12390-1. (2012). Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds. *BSI - British Standards Institution*.

BS EN 12390-2. (2009). *Testing hardened concrete*. *3*(1), 420–457.

BS EN 12390-3. (2009). Testing hardened concrete - Part 3: Compressive strength of test speciemens. *BSI - British Standards Institution*.

BS EN 12390-6. (2009). Testing hardened concrete - Part 6: Tensile splitting strength of test specimens. *BSI - British Standards Institution*, *3*(1), 420–457.

BS EN 12390-7. (2009). Testing hardened concrete Part 7: Density of hardened concrete. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699.

BS EN 12390-8. (2009). *Testing hardened concrete Part 8: Depth of penetration of water under pressure*. *3*(1), 420–457.

BS EN 12620. (2008). Aggregates for concrete. *British Standard Institutions (BSI)*, *3*(May 2004), 33–64.

BS EN 15326. (2009). Bitumen and bituminous binders — Measurement of density and specific gravity — Capillary-stoppered pyknometer method. *British Standard Institutions (BSI)*, *3*.

BS EN 1992-1-1. (2014). Eurocode 2 : Design of concrete structures — Part 1-1: General rules and rules for buildings. *BSI - British Standards Institution*, *3*(January).

BS EN 933-1. (2012). Tests for geometrical properties of aggregates Part 1: Determination of particle size distribution — Sieving method. *British Standard Institutions (BSI)*.

BS1881-122. (2011). *BSI Standards Publication Testing concrete Part 122 : Method for determination of water absorption*. 1–8.

Carro-López, D., González-Fonteboa, B., de Brito, J., Martínez-Abella, F., González-Taboada, I., & Silva, P. (2015). Study of the rheology of self-compacting concrete with fine recycled concrete aggregates. *Construction and Building Materials*, *96*, 491–501.

Chemisian Konsultant Sdn. Bhd. (2011). A Study on Scrap Tyres Management For Peninsular Malaysia. In *National Solid Waste Management Department, Ministry of Housing and Local Government*. http://jpspn.kpkt.gov.my/resources/index/user_1/Sumber_Rujukan/kajian/Tyre Study_Final Report_Eng Version.pdf

Chou, L.-H., Yang, C.-K., Lee, M.-T., & Shu, C.-C. (2010). Effects of partial oxidation of crumb rubber on properties of rubberized mortar. *Composites Part B: Engineering*, *41*(8), 613–616.

da Silva, F. M., Gachet Barbosa, L. A., Lintz, R. C. C., & Jacintho, A. E. P. G. A. (2015). Investigation on the properties of concrete tactile paving blocks made with recycled tire rubber. *Construction and Building Materials*, *91*, 71–79.

Dehdezi, P. K., Erdem, S., & Blankson, M. A. (2015). Physico-mechanical, microstructural and dynamic properties of newly developed artificial fly ash based lightweight aggregate – Rubber concrete composite. *Composites Part B: Engineering*, *79*, 451–455.

Elchalakani, M. (2015). High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers. *Structures*, *1*, 20–38.

Eldin, N. N., & Senouci, A. B. (1993). Rubber-Tire Particles as Concrete Aggregate. *Journal of Materials in Civil Engineering*, *5*(4), 478–496.

Farhan, A. H., Dawson, A. R., & Thom, N. H. (2016). Characterization of rubberized cement bound aggregate mixtures using indirect tensile testing and fractal analysis. *Construction and Building Materials*, *105*, 94–102.

Fattuhi, N. I., & Clark, L. A. (1996). Cement-based materials containing shredded scrap truck tyre rubber. *Construction and Building Materials*, *10*(4), 229–236.

Feng, W., Liu, F., Yang, F., Li, L., & Jing, L. (2018). Experimental study on dynamic split tensile properties of rubber concrete. *Construction and Building Materials*, *165*, 675–687.

fib. (2010). fib Model Code for Concrete Structures 2010 VOLUME 1. In *International Federation for Structural Concrete (fib)* (Vol. 39, Issue 5). Ganjian,

E., Khorami, M., & Maghsoudi, A. A. (2009). Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials*, *23*(5), 1828–1836.

Gerges, N. N., Issa, C. A., & Fawaz, S. A. (2018). Rubber concrete: Mechanical and dynamical properties. *Case Studies in Construction Materials*, *9*.

Gesoğlu, M., & Güneyisi, E. (2011). Permeability properties of self-compacting rubberized concretes. *Construction and Building Materials*, *25*(8), 3319–3326.

Gesoğlu, M., Güneyisi, E., Khoshnaw, G., & İpek, S. (2014a). Investigating properties of pervious concretes containing waste tire rubbers. *Construction and Building Materials*, *63*, 206–213.

Gesoğlu, M., Güneyisi, E., Khoshnaw, G., & İpek, S. (2014b). Abrasion and freezing–thawing resistance of pervious concretes containing waste rubbers. *Construction and Building Materials*, *73*, 19–24.

González-López, J. R., Ramos-Lara, J. F., Zaldivar-Cadena, A., Chávez-Guerrero, L., Magallanes-Rivera, R. X., & Burciaga-Díaz, O. (2015). Small addition effect of agave biomass ashes in cement mortars. *Fuel Processing Technology*, *133*, 35–42.

Gupta, T., Chaudhary, S., & Sharma, R. K. (2014). Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. *Construction and Building Materials*, *73*, 562–574.

Gupta, T., Chaudhary, S., & Sharma, R. K. (2015). Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. *Journal of Cleaner Production*, *112*, 702–711.

Gupta, T., Sharma, R. K., & Chaudhary, S. (2015). Impact resistance of concrete containing waste rubber fiber and silica fume. *International Journal of Impact Engineering*, *83*, 76–87.

Gupta, T., Siddique, S., Sharma, R. K., & Chaudhary, S. (2018). Lateral force microscopic examination of calcium silicate hydrate in rubber ash concrete. *Construction and Building Materials*, *179*, 461–467.

Gupta, T., Siddique, S., Sharma, R. K., & Chaudhary, S. (2019). Behaviour of waste rubber powder and hybrid rubber concrete in aggressive environment. *Construction and Building Materials*, *217*, 283–291.

Hafiz, A., & Schumacher, T. (2019). Effects of elastic supports and flexural cracking on low and high order modal properties of a reinforced concrete girder. *Engineering Structures*, *178*(March 2018), 573–585.

Hall, M. R., & Najim, K. B. (2014). Structural behaviour and durability of steel-reinforced structural Plain/Self-Compacting Rubberised Concrete (PRC/SCRC). *Construction and Building Materials*, *73*, 490–497.

Hassanli, R., Youssf, O., & Mills, J. E. (2017a). Experimental investigations of reinforced rubberized concrete structural members. *Journal of Building Engineering*, *10*, 149–165.

Hassanli, R., Youssf, O., & Mills, J. E. (2017b). Seismic Performance of Precast Posttensioned Segmental FRP-Confined and Unconfined Crumb Rubber Concrete Columns. *Journal of Composites for Construction*, *21*(4), 04017006.

He, L., Ma, Y., Liu, Q., & Mu, Y. (2016). Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete. *Construction and Building Materials*, *120*, 403–407.

Hernández-Olivares, F., & Barluenga, G. (2004). Fire performance of recycled rubber-filled high-strength concrete. *Cement and Concrete Research*, *34*(1), 109–117.

Hilal, N. N. (2017). Hardened properties of self-compacting concrete with different crumb rubber size and content. *International Journal of Sustainable Built Environment*, *6*(1), 191–206.

Ho, A. C., Turatsinze, A., Hameed, R., & Vu, D. C. (2012). Effects of rubber aggregates from grinded used tyres on the concrete resistance to cracking. *Journal of Cleaner Production*, *23*, 209–215.

Huber, G. A., Kennedy, T. W., & Anderson, M. (1994). *The Superpave Mix Design Manual for New Construction and Overlays*.

Ismail, M. K., & Hassan, A. A. A. (2016). Use of metakaolin on enhancing the mechanical properties of self-consolidating concrete containing high percentages of crumb rubber. *Journal of Cleaner Production*, *125*, 282–295.

Jokar, F., Khorram, M., Karimi, G., & Hataf, N. (2019). Experimental investigation of mechanical properties of crumbed rubber concrete containing natural zeolite. *Construction and Building Materials*, *208*, 651–658.

Kardos, A. J., & Durham, S. A. (2015). Strength, durability, and environmental properties of concrete utilizing recycled tire particles for pavement applications. *Construction and Building Materials*, *98*, 832–845.

Kashani, A., Ngo, T. D., Mendis, P., Black, J. R., & Hajimohammadi, A. (2017). *A sustainable application of recycled tyre crumbs as insulator in lightweight cellular concrete*.

Khalil, E., Abd-Elmohsen, M., & Anwar, A. M. (2015). Impact Resistance of Rubberized Self-Compacting Concrete. *Water Science*, *29*, 45–53.

Khaloo, A. R., Dehestani, M., & Rahmatabadi, P. (2008). Mechanical properties of concrete containing a high volume of tire-rubber particles. *Waste Management*, *28*(12), 2472–2482.

Khatib, Z. K., & Bayomy, F. M. (1999). *Rubberized Portland Cement Concrete*. *August*, 206–213.

Khorami, M., & Ganjian, E. (2011). Comparing flexural behaviour of fibre–cement composites reinforced bagasse: Wheat and eucalyptus. *Construction and Building*

Materials, *25*(9), 3661–3667.

Khouadjia, M. L. K., Mezghiche, B., & Drissi, M. (2015). Experimental evaluation of workability and compressive strength of concrete with several local sand and mineral additions. *Construction and Building Materials*, *98*, 194–203.

Kouroussis, G., Ben Fekih, L., & Descamps, T. (2017). Assessment of timber element mechanical properties using experimental modal analysis. *Construction and Building Materials*, *134*, 254–261.

Li, L., Ruan, S., & Zeng, L. (2014). Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles. *Construction and Building Materials*, *70*, 291–308.

Li, X., Ling, T. C., & Hung Mo, K. (2020). Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – A review. *Construction and Building Materials*, *240*, 117869.

Liang, C., Liu, T., Xiao, J., Zou, D., & Yang, Q. (2015). Effect of stress amplitude on the damping of recycled aggregate concrete. *Materials*, *8*(8), 5298–5312.

Liu, F., Chen, G., Li, L., & Guo, Y. (2012). Study of impact performance of rubber reinforced concrete. *Construction and Building Materials*, *36*, 604–616.

Lopez, G., Alvarez, J., Amutio, M., Mkhize, N. M., Danon, B., Van Der Gryp, P., Görgens, J. F., Bilbao, J., & Olazar, M. (2017). *Waste truck-tyre processing by flash pyrolysis in a conical spouted bed reactor*.

Lv, J., Zhou, T., Du, Q., & Wu, H. (2015). Effects of rubber particles on mechanical properties of lightweight aggregate concrete. *Construction and Building Materials*, *91*, 145–149.

Mara, V., Haghani, R., & Harryson, P. (2014). Bridge decks of fibre reinforced polymer (FRP): A sustainable solution. *Construction and Building Materials*, *50*, 190–199.

Martínez, J. D., Puy, N., Murillo, R., García, T., Navarro, M. V., & Mastral, A. M. (2013). Waste tyre pyrolysis - A review. In *Renewable and Sustainable Energy Reviews* (Vol. 23, pp. 179–213).

Mashaan, N. S., & Karim, M. R. (2012). Investigating the rheological properties of crumb rubber modified bitumen and its correlation with temperature susceptibility. *Materials Research*, *16*(1), 116–127.

Md Noor, N. (2014). *Physical performance and durability evaluation of rubberized concrete. PhD thesis, Kyushu University.*

Mendis, A. S. M., Al-Deen, S., & Ashraf, M. (2017). *Behaviour of similar strength crumbed rubber concrete (CRC) mixes with different mix proportions*.

Mendis, A. S. M., Al-Deen, S., & Ashraf, M. (2018). Flexural shear behaviour of reinforced Crumbed Rubber Concrete beam. *Construction and Building Materials*, *166*, 779–791.

Mo, J., Zeng, L., Guo, F., Liu, Y., Ma, L., Chen, B., & Liu, X. (2020). Experimental study on damping properties of rubber powder modified styrene-acrylic emulsion concrete beam. *Journal of Building Engineering*, *32*(July), 101728.

Mo, J., Zeng, L., Liu, Y., Ma, L., Liu, C., Xiang, S., & Cheng, G. (2020). Mechanical properties and damping capacity of polypropylene fiber reinforced concrete modified by rubber powder. *Construction and Building Materials*, *242*, 118111.

Moustafa, A., & ElGawady, M. A. (2015). Mechanical properties of high strength concrete with scrap tire rubber. *Construction and Building Materials*, *93*, 249–256.

Nadal Gisbert, A., Gadea Borrell, J. M., Parres García, F., Juliá Sanchis, E., Crespo Amorós, J. E., Segura Alcaraz, J., & Salas Vicente, F. (2014). Analysis behaviour of static and dynamic properties of Ethylene-Propylene-Diene-Methylene crumb rubber mortar. *Construction and Building Materials*, *50*, 671–682.

Neville, A. M., & Brooks, J. J. (2010). *Concrete Technology, 2nd edition* (p. 460). Pearson Education Limited.

Noaman, A. T., Abu Bakar, B. H., Akil, H. M., & Alani, A. H. (2017). Fracture characteristics of plain and steel fibre reinforced rubberized concrete. *Construction and Building Materials*, *152*, 414–423.

Nochaiya, T., Sekine, Y., Choopun, S., & Chaipanich, A. (2015). Microstructure, characterizations, functionality and compressive strength of cement-based materials using zinc oxide nanoparticles as an additive. *Journal of Alloys and Compounds*, *630*, 1–10.

O'Neil, L. P., Catling, D. C., & Elam, W. T. (2018). Optimized Compton fitting and modeling for light element determination in micro-X-ray fluorescence map datasets. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 436*(July 2018), 173–178.

Onuaguluchi, O., & Panesar, D. K. (2014). Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. *Journal of Cleaner Production*, *82*, 125–131.

Pacheco-Torgal, F., Ding, Y., & Jalali, S. (2012). Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. *Construction and Building Materials*, *30*, 714–724.

Pelisser, F., Zavarise, N., Longo, T. A., & Bernardin, A. M. (2011). Concrete made with recycled tire rubber: Effect of alkaline activation and silica fume addition. *Journal of Cleaner Production*, *19*(6–7), 757–763.

Pereira-de-Oliveira, L. A., Castro-Gomes, J. P., & Nepomuceno, M. C. S. (2012). Effect of acrylic fibres geometry on physical, mechanical and durability properties of cement mortars. *Construction and Building Materials*, *27*(1), 189–196.

Petersen, A. M., Melamu, R., Knoetze, J. H., & Görgens, J. F. (2015). Comparison of second-generation processes for the conversion of sugarcane bagasse to liquid biofuels in terms of energy efficiency, pinch point analysis and Life Cycle Analysis. *Energy Conversion and Management*, *91*, 292–301.

Pham, T. M., Chen, W., Khan, A. M., Hao, H., Elchalakani, M., & Tran, T. M. (2020). Dynamic compressive properties of lightweight rubberized concrete. *Construction and Building Materials*, *238*, 117705.

Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M., & Flores Medina, N. (2016). *Optimisation of rubberised concrete with high rubber content: An experimental investigation*.

Ramarad, S., Khalid, M., Ratnam, C. T., Luqman Chuah, A., & Rashmi, W. (2015). Waste tire rubber in polymer blends: A review on the evolution, properties and future. *Progress in Materials Science*, *72*, 100–140.

Ramdani, S., Guettala, A., Benmalek, M. L., & Aguiar, J. B. (2019). Physical and mechanical performance of concrete made with waste rubber aggregate, glass powder and silica sand powder. *Journal of Building Engineering*, *21*, 302–311.

Rezaifar, O., Hasanzadeh, M., & Gholhaki, M. (2016). Concrete made with hybrid blends of crumb rubber and metakaolin: Optimization using Response Surface Method. *Construction and Building Materials*, *123*, 59–68.

Richardson, A., Coventry, K., Edmondson, V., & Dias, E. (2015). Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size). *Journal of Cleaner Production*.

Sandeep, M. S., Nagarajan, P., & Shashikala, A. P. (2018). Behaviour of Steel Fibre Reinforced Rubberized Continuous Deep Beams. *IOP Conference Series:*

Materials Science and Engineering, *330*(1).

Sgobba, S., Borsa, M., Molfetta, M., & Marano, G. C. (2015). Mechanical performance and medium-term degradation of rubberised concrete. *Construction and Building Materials*, *98*, 820–831.

Shahjalal, M., Islam, K., Rahman, J., Ahmed, K. S., Karim, M. R., & Billah, A. M. (2021). Flexural response of fiber reinforced concrete beams with waste tires rubber and recycled aggregate. *Journal of Cleaner Production*, *278*, 123842.

Shu, X., & Huang, B. (2014). Recycling of waste tire rubber in asphalt and portland cement concrete: An overview. *Construction and Building Materials*, *67*, 217–224.

Siddique, R., & Naik, T. R. (2004). Properties of concrete containing scrap-tire rubber--an overview. *Waste Management (New York, N.Y.)*, *24*(6), 563–569.

Son, K. S., Hajirasouliha, I., & Pilakoutas, K. (2011). Strength and deformability of waste tyre rubber-filled reinforced concrete columns. *Construction and Building Materials*, *25*, 218–226.

Sugapriya, P., & Ramkrishnan, R. (2018). Crumb Rubber Recycling in Enhancing Damping Properties of Concrete. *IOP Conference Series: Materials Science and Engineering*, *310*(1).

Sugapriya, P., Ramkrishnan, R., Keerthana, G., & Saravanamurugan, S. (2018). Experimental Investigation on Damping Property of Coarse Aggregate Replaced Rubber Concrete. *IOP Conference Series: Materials Science and Engineering*, *310*(1).

Sukontasukkul, P., & Tiamlom, K. (2012). Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size. *Construction and Building Materials*, *29*, 520–526.

Sung, C.-H., Huang, R., Wu, Y.-H., Tsai, C.-J., & Lai, H.-W. (2016). Influence of sulfur trioxide on volume change and compressive strength of eco-mortar. *Construction and Building Materials*, *114*, 464–469.

Taha, M. M. R., Asce, M., & El-wahab, M. A. A. (2009). *Mechanical , Fracture , and Microstructural Investigations*. *20*(10), 640–649.

Thomas, B. S., & Chandra Gupta, R. (2016). Properties of high strength concrete containing scrap tire rubber. *Journal of Cleaner Production*, *113*, 86–92.

Thomas, B. S., Gupta, R. C., Mehra, P., & Kumar, S. (2015). Performance of high strength rubberized concrete in aggressive environment. *Construction and*

Building Materials, *83*, 320–326.

Thomas, B. S., Gupta, R. C., & Panicker, V. J. (2016). Recycling of waste tire rubber as aggregate in concrete: durability-related performance. *Journal of Cleaner Production*, *112*, 504–513.

Topçu, I. B., & Avcular, N. (1997). Collision behaviours of rubberized concrete. *Cement and Concrete Research*, *27*(12), 1893–1898.

Xiong, C., Li, Q., Lan, T., Li, H., Long, W., & Xing, F. (2021). Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: mechanical properties and ecological evaluation. *Journal of Cleaner Production*, *279*, 123624.

Xue, J., & Shinozuka, M. (2013). Rubberized concrete: A green structural material with enhanced energy-dissipation capability. *Construction and Building Materials*, *42*, 196–204.

Yang, F., Feng, W., Liu, F., Jing, L., Yuan, B., & Chen, D. (2019). Experimental and numerical study of rubber concrete slabs with steel reinforcement under close-in blast loading. *Construction and Building Materials*, *198*, 423–436.

Youssf, O., ElGawady, M. A., & Mills, J. E. (2015). Experimental Investigation of Crumb Rubber Concrete Columns under Seismic Loading. *Structures*, *3*, 13–27.

Youssf, O., ElGawady, M. A., Mills, J. E., & Ma, X. (2014). An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes. *Construction and Building Materials*, *53*, 522–532.

Youssf, O., Mills, J. E., & Hassanli, R. (2016). Assessment of the mechanical performance of crumb rubber concrete. *Construction and Building Materials*, *125*, 175–183.

Zain, M. F. M., Safiuddin, M., & Yusof, K. M. (2000). Influence of different curing conditions on strength and durability of high-performance concrete. *American Concrete Institute, ACI Special Publication*, *SP-193*(September 2016), 275–292.

Zheng, L., Sharon Huo, X., & Yuan, Y. (2008). Experimental investigation on dynamic properties of rubberized concrete. *Construction and Building Materials*, *22*, 939–947.

List of Publications

1. **Characterization of tyre rubber ash and crumb as fine aggregate resource**
   Shahidan, S., Mangi, S.A., Senin, M.S., Mohd Zuki, S.S., Ibrahim, M.H.W.
   Journal of Engineering Science and Technology, 2021, 16(1), pp. 510–526
2. **Properties of Concrete Containing Rubber Ash and Rubber Crumb as Partial Replacement of Sand**
   Shahidan, S., Mangi, S.A., Senin, M.S., Mohd Zuki, S.S., Ibrahim, M.H.W.
   International Journal of Advanced Science and Technology, 2020, 29(9), pp. 2053–2059
3. **The effect of using different substitutes of rubber ash on compressive strength of cement mortar**
   Senin, M.S., Shahidan, S., Ghafar, N.H.A., ...Ibrahim, M.H.W., Nazri, F.M.
   Malaysian Construction Research Journal, 2018, 4(2 Special Issue), pp. 72–83
4. **A review on the suitability of rubberized concrete for concrete bridge decks**
   Senin, M.S., Shahidan, S., Abdullah, S.R., Guntor, N.A., Leman, A.S.
   IOP Conference Series: Materials Science and Engineering, 2017, 271(1), 012074
5. **The durability of concrete containing recycled tyres as a partial replacement of fine aggregate**
   Senin, M.S., Shahidan, S., Leman, A.S., ...Ibrahim, M.H.W., Mohd Zuki, S.S.
   IOP Conference Series: Materials Science and Engineering, 2017, 271(1), 012075
6. **The optimum content of rubber ash in concrete: Flexural strength**
   Senin, M.S., Shahidan, S., Shamsuddin, S.M., ...Khalid, F.S., Nazri, F.M.
   IOP Conference Series: Materials Science and Engineering, 2017, 271(1), 012009
7. **Analysis of Physical Properties and Mineralogical of Pyrolysis Tires Rubber Ash Compared Natural Sand in Concrete material**
   Mohamad Syamir Senin, Shahiron Shahidan, Alif Syazani Leman and Nurul Izzati Raihan Ramzi Hannan
   IOP Conference Series: Materials Science and Engineering, 2016, 160(1), 012053
8. **Properties of Cement Mortar Containing Rubber Ash as Sand Replacement** Mohamad Syamir Senin, Shahiron Shahidan, Alif Syazani Leman and Nurul Izzati Raihan Ramzi Hannan
   IOP Conference Series: Materials Science and Engineering, 2016, 160(1), 012055