ECO-FRIENDLY CONSTRUCTION MATERIALS PREPARED WITH LIGHT WEIGHT AND RUBBERISED CONCRETE

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A thesis submitted in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

September 2016

CERTIFICATE OF ORIGINALITY

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___ZHANG Binyu_________ (Name of student)

Abstract of thesis entitled 'Eco-friendly construction materials prepared with lightweight and rubberised concrete'

Submitted by ZHANG Bin-Yu

for the degree of Doctor of Philosophy

at the Hong Kong Polytechnic University in 2016

ABSTRACT

In this thesis, experimental tests were focused on improving thermal insulation properties and acoustic insulation properties of lightweight aggregate concrete with recycled aggregate incorporation.

In the first part, Furnace Bottom Ash (FBA) was used to replace natural fine aggregate. The experimental results demonstrated that, the lightweight aggregate used in this study improved concrete thermal insulation properties of concrete compared to natural aggregate, and with the incorporation of FBA, the thermal conductivity of lightweight aggregate concrete was further reduced. The reduced thermal conductivity enhances the sustainability of the material.

The mechanical properties evaluation showed that the incorporation of both lightweight aggregate concrete and high volume of FBA led to strength loss and stiffness loss, the use of silica fume showed limited effect on strength loss compensation. However, with high volume of FBA incorporation, the lightweight

aggregate concrete still met the minimum strength of structural lightweight aggregate concrete. The feasibility of high volume FBA incorporation is of great importance for industrial by-product's recycling and reusing.

Lightweight aggregate and FBA incorporation resulted in poor durability properties of concrete indicated by the results of the chloride ion penetration test. High permeability of lightweight aggregate concrete is associated with high maintenance cost. In this study, silica fume was added to FBA incorporated lightweight aggregate concrete to compensate the strength loss as well as to improve the impermeability of concrete.

Furthermore, the internal curing effect has been studied. FBA and the lightweight aggregate are porous aggregates, pre-wetting was conducted before casting. The shrinkage tests showed that the incorporation of pre-wetted lightweight aggregate resulted in reduced autogenous shrinkage which was attributed to the internal curing effect of the aggregate, and the incorporation of FBA further reduced concrete's autogenous shrinkage.

In the first part, the feasibility of using high volume industrial by-product to fabricate structural lightweight aggregate concrete with improved thermal insulation properties has been proven.

In the second part, recycled rubber aggregate made from waste tires was added into concrete to partially replace FBA and to replace natural fine aggregate.

The noise attenuation test was conducted and the results showed that the incorporation of recycled rubber aggregate has a positive effect on noise reduction effect of concrete slabs. Within the frequencies range 100Hz to 3150Hz, increased rubber content led to enhanced overall noise reduction of rubberised concrete.

Segregation and poor consistency were observed when high volume of rubber aggregate was added. Various surface treatment methods had been applied to modify the rubber aggregate's surface.

Chemical modification was applied by the immersion of rubber aggregate in saturated sodium hydroxide solution and in Silane Coupling Agent (SCA) solution. However, the mechanical properties test showed that the chemical modification caused slightly strength loss, and no difference was detected at the noise attenuation test comparing the specimens containing 50% as-received rubber aggregate and 50% chemical treated rubber aggregate.

When a simple cement paste coating pre-treatment method applied to modify the rubber aggregate surface, acoustic insulation properties of rubberised concrete was further improved. Then the dynamic Young's modulus of the rubberised concrete with as-received rubber aggregate and with cement paste coated rubber aggregate has been tested. The results showed that the specimens that contained pre-treated rubber aggregate had a lower dynamic Young's modulus compared to the specimens with same amount of as-received rubber aggregate. The bonding strength test results illustrated that when the cement paste coating was applied, the bonding between rubber aggregate and the matrix became weaker.

In the second part, the use of high volume rubber aggregate to produce lightweight aggregate concrete with improved sound insulation properties has been investigated, the rubber aggregate surface modification method was found to further improved noise reduction effect of specimens. The mechanism has been proposed: cement paste coating on rubber aggregate resulted in a weaker bonding and a decreased dynamic young's modulus, thus upon vibration the specimen with pre-treated aggregate absorbs energy more quickly and easily, and consequently this pre-treatment method leads to enhanced noise attenuation capacity of rubberised concrete.

PUBLICATIONS ARISING FROM THE THESIS

The thesis is submitted for the degree of Doctor of Philosophy at the Hong Kong Polytechnic University. The work described in this thesis was carried out by the candidate during the years from 2011 to 2015 in the Department of Civil and Environmental Engineering under the supervision of Professor Poon Chi Sun, the chief supervisor.

Five papers were written by the candidate based on the work presented in this thesis.

Academic Journal Papers:

1. **Zhang Binyu**, Poon ChiSun* (2015). Use of Furnace Bottom Ash for producing lightweight aggregate concrete with thermal insulation properties. *Journal of Cleaner Production*, 99, 94-100.

2. **Zhang Binyu**, Poon ChiSun* (2017). Internal Curing Effect of High Volume Furnace Bottom Ash (FBA) Incorporation on Lightweight Aggregate Concrete. *Journal of Sustainable Cement-Based Materials*. 1-18.

3. **Zhang Binyu**, Poon ChiSun* (Submitted in 2017). Sound Insulation Properties of Rubberized Lightweight Aggregate Concrete. *Journal of Cleaner Production.*

Conference Papers:

4. **B. Zhan**, C.S. Poon, (2014), A study on the sound and thermal insulation properties of light weight aggregates concrete with pre-treated recycled rubber particles incorporation. *Proceedings of International Symposium on Environmentally Friendly Concrete-ECO-Crete*, August 13-15, 2014, Reykjavik, Iceland.

5. **B. Zhan** and C. S. Poon* (2015), “Improved sound insulation properties of light weight rubberised concrete due to pretreatment of rubber aggregate (Abstract only)”. *2nd International Conference on Sustainable Urbanization* (ICSU 2015). Hong Kong, China, 7-9 January 2015.

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Lastly, I would like to thank my parents for their unconditional support.

ABBREVIATIONS

FBA	Furnace Bottom Ash
SF	Silica Fume
NAC	Normal Aggregate Concrete
LWC	Lightweight Aggregate Concrete
LWA	Lightweight Aggregate
SSD	Surface Saturated Dried
OD	Oven-dried
SCA	Silane Coupling Agent

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Chapter 1. – INTRODUCTION

This chapter will give a brief introduction to the thermal insulation properties and acoustic insulation properties of building materials. Then the research objectives will be listed. The layout of the thesis will be outlined by the end of this chapter.

1.1 Thermal Insulation

1.1.1 Energy efficiency in buildings

Energy saving is an important issue in sustainability. Statistics published by the Hong Kong Electrical and Mechanical Services Department (ESMD) during the year 2009 to 2013 showed that air conditioning contributes to 21% to 23% of total energy consumption in local residential buildings and 24% to 26% in local commercial buildings, respectively.

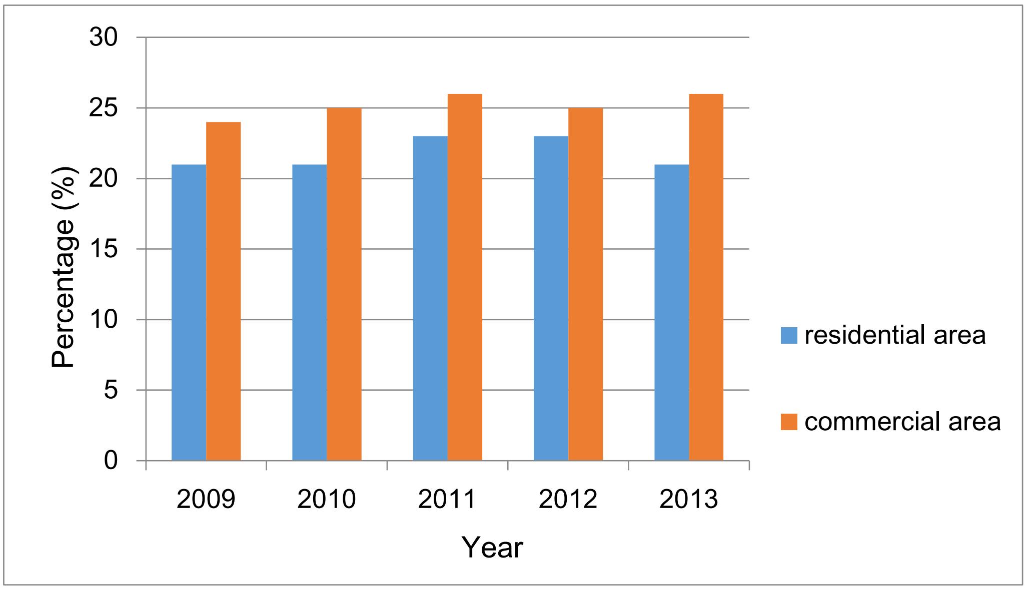
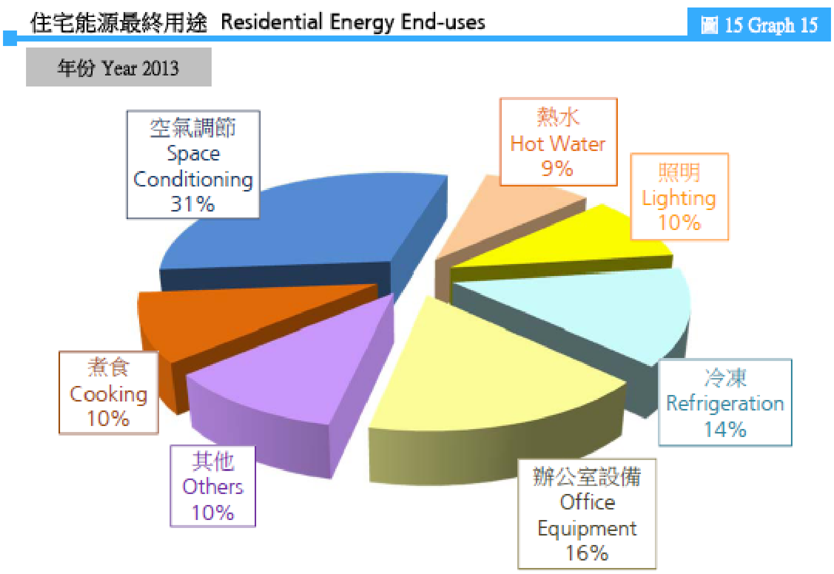


Figure 1-1 Percentage of total energy consumption in residential and commercial area by air conditioning(Electrical and Mechanical Services Department 2016)

In terms of the electricity consumption in the year 2013, as demonstrated by the charts below, air conditioning contributed to 31% of the electricity consumption in residential areas and 30% in commercial areas, respectively.



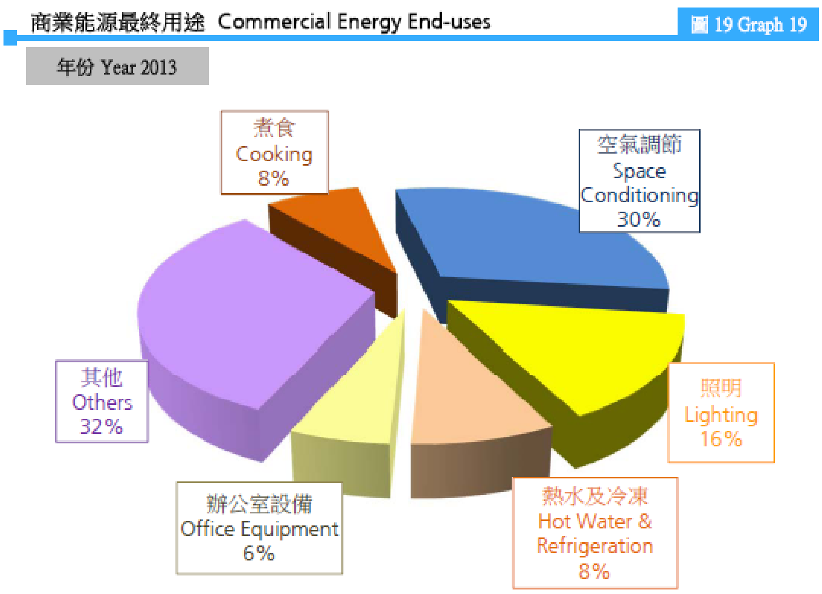


Figure 1-2 Electricity consumption breakdown in residential areas and commercial areas of Hong Kong in 2013(Electrical and Mechanical Services Department 2016)

The development of novel building materials with improved thermal insulation properties compared to conventional construction materials has a promising future in the urban sustainable development.

1.1.2 Concrete with improved thermal insulation properties

Various materials, e.g. wood, insulation mortar layer, etc., have been employed to add extra thermal insulation to construction materials. However, the disadvantages of composite materials, such as the inconvenience of construction works and the maintenance problems resulted from poor durability properties, are difficult to be avoided and limit the application of these insulation materials in buildings.

Concrete is the most commonly used construction material in buildings. Improving the thermal insulation properties of concrete is a better way to reduce the building energy consumption.

Lightweight aggregate concrete has been proved to possess significantly enhanced thermal insulation properties than conventional concrete in previous research works, mainly attributed to the higher porosity of aggregate. However, lightweight aggregate generally has lower strength than normal aggregate used in conventional concrete. Consequently, strength loss occurs when lightweight aggregate was used to replace natural aggregate.

In this study, a type of lightweight aggregate (LECA) was used to produce low strength lightweight aggregate concrete with lower thermal conductivity than normal concrete, then silica fume was added to compensate the strength loss and to enhance the impermeability of the mixture. A type of by-product material generated from power plant has also been incorporated in the lightweight aggregate concrete to further improve the thermal insulation properties.

1.2 Acoustic insulation

1.2.1 Noise pollution and regulations

Building occupants are mostly affected by two types of noise sources: airborne noise and impact noise. Airborne noise generators include road traffic, air traffic, factories, etc., while impact sound can be produced by tapping machine, walking on the upper floor, suddenly dropped metal balls, etc.

Noise pollution is an ongoing issue for inhabitants of urban and industrial areas but insufficient attention has been paid to establish proper Regulations or Planning Authorities.

It has been pointed out by Holmes (Holmes et al. 2014) that in areas with high building density, the use of materials like concrete as building envelope materials has limited effect on noise attenuation, as illustrated by figure 1-3, sound waves are reflected away but not reduced in magnitude and become problematic in enclosed space.

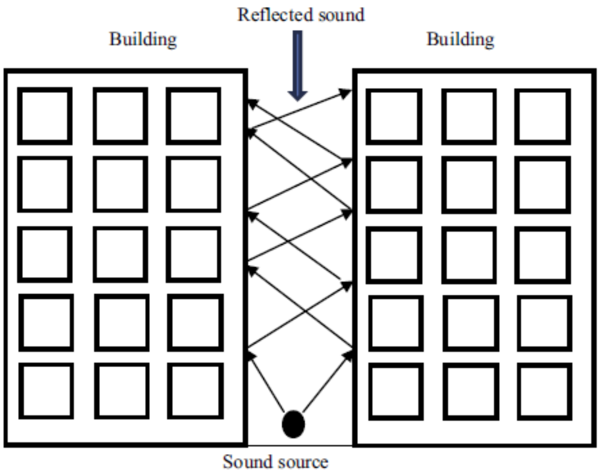


Figure 1-3 Reflections of sound waves in an enclosed narrow street (Holmes et al. 2014)

1.2.2 Improved acoustic insulation in buildings

Acoustic insulation construction materials are materials that provide effective and efficient barriers for both airborne sound and impact sound. Sound insulation is important for building occupants, and building materials with adequate acoustic insulation properties helps providing residents from being annoyed by noises created by neighborhoods or from other outdoor noise sources as well as protecting residents' privacy and avoiding impact noise transmission that may affect their neighbors.

It is well recognized that the used of soft materials or porous fabrics are effective in noise absorption and these materials are commonly used in cinemas or recording studios to reduce the reverberation time in the room. However, for building envelope materials, a more reliable way to deal with noise pollution is to use supplementary materials in concrete to improve the acoustic insulation properties.

As illustrated by the figure 1-4, different construction materials possess noise attenuation effect for the noise source with a certain range of frequencies.

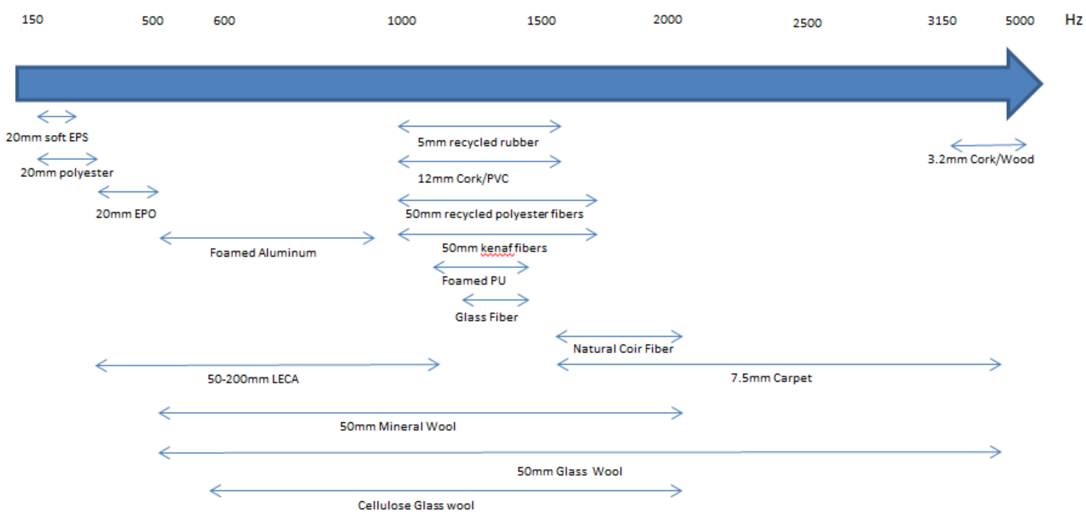


Figure 1-4 Illustration of noise attenuation materials and corresponding spectrum between 150Hz to 5000Hz (Simančík et al. 1995; Kim et al. 2009; Asdrubali 2006; Asdrubali et al. 2012)

Intensive research works have shown that recycled rubber aggregate is effective in improving concrete acoustic insulation properties as well as dealing with solid waste problem.

In this study, high volume fraction (up to 100%) of recycled rubber aggregate has been incorporated into concrete as fine aggregate and the noise attenuation test results showed that the use of recycled rubber aggregate had significant noise reduction effect in the range from 100Hz to 3150Hz.

1.3 Research objectives

This study aimed at performance improvement thermal insulation and improved acoustic insulation of concrete blocks prepared with lightweight aggregate and recycled aggregates.

The main objectives of the research study are:

- To explore the feasibility of using Furnace Bottom Ash (FBA) in both lightweight aggregate concrete and normal aggregate concrete;
- To investigate the effects of internal curing of FBA in lightweight aggregate concrete and normal aggregate concrete;
- To investigate the effects of acoustic insulation properties of lightweight aggregate concrete with high volume rubber incorporation;
- To reveal the mechanism of noise reduction capability enhancement via rubber aggregate surface modification.

1.4 Thesis outline

The thesis structure is briefly presented below:

Chapter 1 provides an introduction of the proposed research in terms of background and objectives.

Chapter 2 reviews the literatures through the following two perspectives: lightweight aggregate, recycled rubber aggregate, furnace bottom ash, and the use of such aggregate in concrete and related effects. All these topics are related to the study.

Chapter 3 gives an overall introduction to the common properties of the materials used, experimental methodologies including mix design, sample preparation, and testing methods.

Chapter 4 gives the experimental results and discussion based on the analyses of results.

Chapter 5 summarizes the general conclusions and also proposed recommendations for future research works.

Chapter 2. – LITERATURE REVIEW

2.1 Aggregates

2.1.1 Lightweight aggregate

Both natural lightweight aggregate and artificial lightweight aggregate have been used in the production of lightweight aggregate concrete. The density and water absorption of different lightweight aggregates are listed in the table 2-1.

Table 2-1 Density and water absorption of different lightweight aggregates

Lightweight aggregate	Density (Kg/m^3)	24h Water absorption (%)	Reference
Oil palm kernel shell	1140-1620	11-33	(Alengaram et al. 2013)
Spherical expanded clay a	593	11.0/1h	(Cui et al. 2012)
Spherical expanded clay b	1172	8.1/1h	
Elongated clay	1067	9.2/1h	
Expanded shale	1544	4.8/1h	
Shale & Pulverized fuel ash aggregate	1620	8.5/1h	
Lytag	1390	2.5/1h	(Zhang 2011)
Ceramsite	1478	4.06	(Ji et al. 2015)

Low strength LWC has wide applications as insulation material.

To contribute to sustainable development by reducing natural resource consumption and to mitigate the solid waste problem, in recent years, attention has been paid to develop procedures to produce lightweight aggregate from recycled industrial or agricultural waste materials.

In early 2000s, production of lightweight aggregate from incinerator bottom ash via rapid sintering has been proposed (Cheeseman et al. 2005), and it was pointed out that this type of lightweight aggregate can be used for improving thermal insulation & acoustic insulation purposes.

A comprehensive scheme to produce pellet lightweight aggregate, as shown by figure 2-1, via carbonation process of quarry fines and a range of combustion residues have been reported (Gunning et al. 2009), the successful pilot test showed that the aggregate produced had a bulk density less than 1000Kg/m^3 and possessed a crushing strength stronger than commonly used expanded clay aggregate in UK, and this type of lightweight aggregate has been successfully used in concrete blocks and in green roof systems.

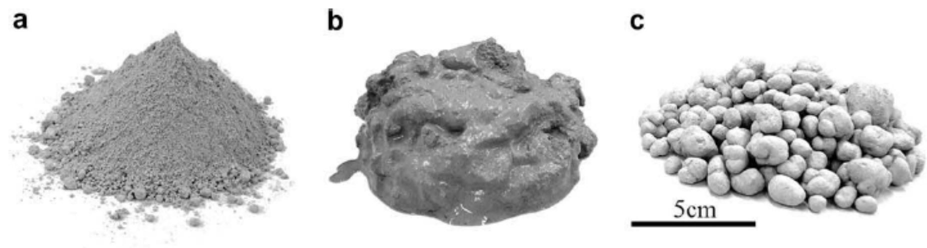


Figure 2-1 The production of lightweight aggregate (a) raw material; (b) quarry fines and (c) pelletized product (Gunning et al. 2009)

2.1.2 Furnace bottom ash (FBA)

Furnace Bottom Ash (FBA) is a by-product of the coal fired power generation process. The FBA used in this study was collected from the local power generation plant Castle Peak Power Station (see figure 2-2). The plant was built in 1980 to meet the increasing demanding of electricity for the city development. The primary fuel used in this power plant is coal and the backup fuels include natural gas and ultra-low-sulphur diesel.

Figure 2-2 Castle Peak Power Station located at Tuen Mun, Hong Kong (CLP Hong Kong 2016)

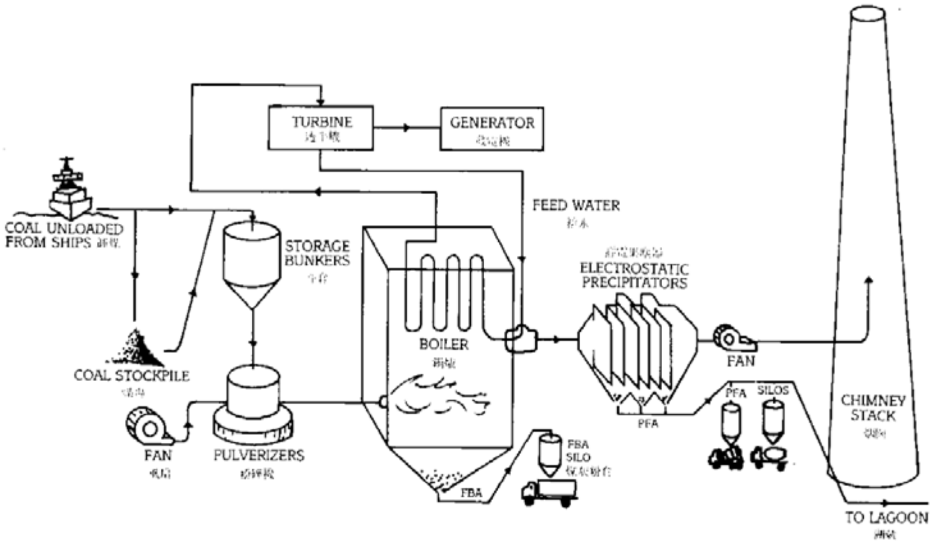


Figure 2-3 Scheme of FBA generation (CLP Hong Kong 2016)

The generation of FBA is illustrated by the figure 2-3. A huge amount of coal is being burnt every day and a huge quantity of furnace bottom ash is being generated. The annual output of FBA in the Castle Peak Power Station was estimated to reach 33,000 tons, which as a solid waste material, created high pressure to the already congested landfills in Hong Kong.

The recycle and reuse of FBA in concrete is an alternative way of contributing to sustainable development.

2.1.3 Recycled rubber aggregate

Figure 2-4 shows a typical waste tires disposal site. Waste tires have been an environmental issue for decades. Not only do they take up a large physical volume of landfill, but waste tires are also associated with other problems. For example, the liner of landfills can be affected by the product from the chemical reaction between waste tires and methane gases, which may lead to contaminants leakage from landfills (Youssf & ElGawady 2014). Other issues caused by waste tires disposal include bearing mosquitos, potential fire hazard, etc. Pacheco-Torgal pointed out that the disposal of waste tires has negative impact on the biodiversity due to the toxic and soluble components; besides, toxic gases can be generated upon the ignition of waste tires (Pacheco-Torgal et al. 2012).

Figure 2-4 Waste tires & shredded waste tires (Wikipedia 2015)

The recycling and reusing of waste tires not only helps release pressure on landfills and mitigate other environmental problems associated with waste tires disposal, but also contributes to saving natural resources.

It is commonly recognized that the incorporation of rubber aggregate into concrete has positive impact on improving concrete ductility, damping, and insulation properties.

2.2 Lightweight aggregate concrete (LWC)

The first known use of lightweight concrete dates back over 2000 years (Ries et al. 2010). Lightweight aggregate (LWA) has been used in construction materials due to its lower density compared to traditional aggregate, reduced self-load of concrete helps improving the strength efficiency as well as improving building insulation properties.

2.2.1 Fresh properties of LWC

A sophisticated review (Hassanpour et al. 2012) has been conducted on the use of fiber in lightweight aggregate concrete as reinforcement and it was pointed out that for lightweight aggregate concrete, lower density is associated with a lower slump, which can be attributed to the influence of gravity.

Another review (Alengaram et al. 2013) on the utilization of oil palm kernel shell as lightweight aggregate in concrete considering research works from 1984 to 2011 has reported that with the incorporation of oil palm kernel shell aggregate in concrete, slump value ranges from 0 to 260mm can be obtained, and the use of proper amount of superplasticizer helps adjusting the slump value of fresh mixed lightweight aggregate concrete.

Despite using lightweight aggregate, air entrance can also be applied in preparing light weight aggregate with lower density than normal concrete. Kim et al. (Kim et al. 2012) have cast lightweight concrete with air entrance of 0.5%, 1.0% and 1.5% of cement by weight, the slump flow test result showed that with no 0.5%

entrained air, the slump flow value of light weight concrete can be improved from 200mm to near 500mm. When the entrained air volume increased to 1.0% of cement content by weight, the slump flow was further increased to higher than 550 mm, which indicated that introducing air volume has significant effect on improving light weight concrete workability.

2.2.2 Mechanical properties of LWC

The incorporation of lightweight aggregates may cause negative impact on concrete strength development and results in lower strength compared to normal aggregate concrete. To mitigate the strength loss, additives like silica fume can be used in concrete, it has also been reported that fiber reinforcement (most commonly used steel fiber) in lightweight aggregate concrete significantly improves compressive ductility, toughness and energy absorption at early age (Hassanpour et al. 2012).

An indicator f_c/D can be used to evaluate the strength effectiveness of concrete, where f_c is the compressive strength of concrete in MPa and D is the surface saturated density of concrete in g/cm^3.

Most previously developed lightweight aggregate concrete possessed low strength effectiveness,

It has been reported (Akçaözoğlu et al. 2013) that when using up to 60% WPLA as aggregate, even at cement content $500Kg/m^3$, the compressive strength of the concrete was only 9.5 MPa after 28 d curing and 11.1 MPa after 90 d curing. The strength effectiveness of LWC was only 6.0-7.0.

Fraj prepared lightweight aggregate concrete with a polyurethane foam waste (density 21 kg/m^3, water absorption 13.9% by volume) as coarse aggregate in LWC, the results showed that at a w/c ratio of 0.55, after 28 days curing, the lightweight aggregate concrete only gained 16.5 MPa and the f_c/D ratio was only 10.7 (Ben Fraj et al. 2010).

However, high strength effectiveness LWC was also developed.

By using a vacuum saturated pumice (Green et al. 2011) to serve as both the fine and coarse aggregates, with the w/c controlled between 0.21 to 0.25, the LWC achieved a 28 d compressive strength between 36.5 MPa and 40.5 MPa, the f_c/D ratio tested at 28 d curing age ranged from 18.1 to 19.6.

LWC prepared with expanded clay at different w/c ratios (Chia & Zhang 2002), the compressive test results showed that at w/c ratio of 0.35, LWC obtained f_c/D ratio of 27.4 after 28 days curing, the incorporation of silica fume improved the f_c/D ratio up to 30.4.

Attempts have been made to reduce the density of lightweight aggregate concrete without causing further strength loss.

It has been reported by Hassanpour (Hassanpour et al. 2012) that the use of fiber in lightweight aggregate concrete has a positive effect on improving concrete compressive strength despite of the lightweight aggregate content. It has been reported in the review that with 1.5% steel fiber incorporation into LWC with lightweight aggregate content ranges from 210Kg/m^3 to 790Kg/m^3, increase in compressive strength from 10.4% to 21.1% can be expected while the density of concrete would not be affected significantly

Stiffness, indicated by the modulus of elasticity, is another important indicator to evaluate concrete mechanical properties. Generally, LWAC possesses a modulus of elasticity 20% to 25% lower than NWC with equivalent compressive strength, and a reduction of stiffness occurs with the increase of LWA content (Hassanpour et al. 2012).

Kurugol (Kurugöl et al. 2008) reported that when 0.75% steel fiber was added into normal weight concrete, an increase of up to 36% in concrete stiffness can be expected. Though, Hassanpour (Hassanpour et al. 2012) have concluded that fibers has limited effect on improving lightweight aggregate concrete stiffness determined by modulus of elasticity.

2.2.3 Durability properties of LWC

Lightweight aggregate has higher porosity than normal aggregate, which usually leads to higher permeability and poorer durability properties.

The accelerated chloride ion penetration test has been commonly conducted as an indicator to evaluate the durability properties of lightweight aggregate concrete. Chia and Zhang prepared lightweight aggregate concrete with a type of expanded clay with 9% water absorption (Chia & Zhang 2002) and the chloride ion penetration test showed that at w/c ratio of 0.55, both Normal Weight Concrete (NWC) and Light Weight Concrete (LWC) showed high total charge passed volume, while the NWC sample possessed slightly higher charge passed volume (5445 coulombs) than LWC sample (5095 coulombs), the chloride ion penetration test results also indicated that either applying a lower w/c ratio or using silica fume in NWC and LWC has positive effect on improving concrete permeability, but no significant difference has been detected when replacing normal aggregate with expanded clay.

2.2.4 Thermal insulation properties of LWC

Due to the higher porosity of lightweight aggregate, LWC possesses improved thermal insulation properties compared to normal aggregate concrete and can be applied in buildings as insulation materials.

Back to 1990, it has been proved that the use palm kernel shell aggregate has a significant positive effect on improving concrete thermal insulation properties (Okpala 1990). It has been reported that with the incorporation of palm kernel shell, the density of concrete can be reduced to 1450Kg/m^3, while the thermal conductivity can be reduced to 0.19W/mK, which enables energy saving in buildings when this type of concrete used as insulation material.

2.2.5 Acoustic insulation properties of LWC

It is commonly acknowledged that using of lightweight aggregate improves thermal insulation properties of concrete, previous research works also revealed that it is possible to enhance the acoustic insulation properties of concrete using LWA as aggregate.

Xu prepared lightweight hollow bricks from expanded polystyrene (EPS) (Xu et al. 2012), the bulk density of the EPS used was 30Kg/m^3, up to 25 vl.% EPS can be incorporated, and it was found out that the EPS had obvious benefits of absorbing sound characteristics as well as reducing the self-load of material.

Topcu reported that it is feasible to use expanded perlite aggregate (EPA) as aggregate to produce lightweight aggregate concrete with improved noise attenuation capacity (Topçu & Işikdağ 2008), 18dB sound insulation can be provided at the frequency of 125Hz when a type of EPA with rough density lower than 200Kg/m^3 was used as aggregate in concrete.

However, it was also reported (Kim & Lee 2010) that the cement flow, the size of aggregate and the thickness of specimens had more significant impact on the noise absorption coefficient of lightweight aggregate concrete while the porosity showed limited effect.

It was revealed in previous research works that using damping materials (e.g., rubber aggregate) is more effective in concrete acoustic insulation properties enhancement compared to the high porosity lightweight aggregates. Therefore, the effect of a type of recycled rubber aggregate has been investigated in this study (section 2.4.5).

2.3 Use of FBA in concrete

Previous research works have proved the feasibility of replacing natural aggregates by FBA to produce concrete (Kou & Poon 2009; Wongkeo et al. 2012). Natural resource efficiency is an important consideration to achieve sustainable development in the construction industry. Concrete mixtures prepared with high volumes of FBA as fine aggregates can alleviate pressure on finding space to dispose of FBA as well as help conserving natural aggregates.

FBA has a lower density and a higher porosity than common natural aggregates. Thus, as indicated by past research studies, using FBA together with light weight aggregate in concrete would render the concrete having poorer durability properties as indicated by the inferior resistance to chloride ion penetration (Zhang & Poon 2015). Using silica fume in the concrete matrix has been proved to be an effective means for improving the compressive strength (Siddique 2011) as well as the durability of the concrete (Bagheri et al. 2012; Bagheri et al. 2013). Previous study on use of high volume FBA in concrete showed that for the concrete mix prepared with 100% FBA replacing natural fine aggregate, a compressive strength of 32 MPa was achieved after 28 days hydration at a w/c ratio of 0.53 and the 28 days compressive strength could be further improved to 65 MPa when the w/c was decreased to 0.34 (Kou & Poon 2009). The use of bottom ash also attracted attention in Thailand. It has been demonstrated (Wongkeo et al. 2012) that the feasibility of using a ground bottom ash with similar chemical compositions to FBA to partially replace cement, and the result showed that 28 d compressive strength slightly increased from 9 MPa to 11 MPa with the increase of BA replacement ratio from 0 to 30% at a fixed w/c ratio. However, very limited research works have been conducted to investigate how the high porosity of furnace bottom ash could impact the properties of concrete. In this study, not only has high volume of FBA generated from local power plant been used in lightweight aggregate concrete to further improve the thermal insulation properties of concrete, but also the internal curing effect of FBA has been investigated.

2.4 Rubberised concrete

Scrap tires can be added into concrete to produce rubberised concrete. Generally rubber aggregate is classified into three types according to the size of aggregate: shredded or chipped rubber (length of 100-150mm, width of 100-230mm), crumb rubber (diameter 0.15-19mm), and ground rubber (particle size in the range of 0.075 to 0.475mm) (Youssf & ElGawady 2014).

2.4.1Fresh properties of rubberised concrete

Various researchers (Lv et al. 2015; Pacheco-Torgal et al. 2012) have reported that with the increase amount of rubber particles as fine aggregate in concrete, decreased slump value were detected. Severe workability loss was also observed by Pacheco-Torgal with the mixture contained up to 50% rubber aggregate.

Slump value test conducted by Batayneh and Asi (Batayneh et al. 2008) also proved the aforementioned conclusion, a series of rubberised concrete with high rubber content have been prepared, the w/c ratio was set as 0.56 for the control mixture, based on which 20 vol.%, 40 vol.%, 60 vol. %, 80 vol.% and 100 vol.% crumb rubber were used as fine aggregate in rubberised concrete mixtures. The slump test results indicated that the slump value for the control mix is about 75mm, and it decreased drastically with the increase of rubber content, when the total fine aggregate was rubber aggregate, the residual slump value was only 4.7mm.

Despite the use of rubber aggregate in conventional concrete, recently attention has been paid to investigate the effect of rubber aggregate incorporation in lightweight aggregate concrete by partially or fully replacing natural fine aggregate. Similar to the impact on conventional concrete fresh properties, rubber aggregate was also reported to have negative impact on lightweight aggregate concrete flowability. Lv (Lv et al. 2015) conducted research works on rubberised concrete by systematically replacing fine aggregate by recycled shredded rubber in lightweight aggregate concrete from 10vol.% to 100vol.%, the slump test results showed that incorporation of rubber aggregate led to a linear reduction of slump value, in this study, fresh lightweight aggregate concrete at w/c ratio of 0.35 had a slump value of 215mm, and when fine aggregate was fully replaced by the type of shredded rubber, the slump value significantly decreased to 125mm.

Though it is well recognized that the incorporation of rubber aggregate resulted in possible segregation and bleeding as well as decreased flowability of fresh concrete, it is possible to improve rubberised concrete workability by using proper additives or admixtures.

Ho prepared rubberised concrete aiming to improve the strain capacity (Ho et al. 2009), severe bleeding and segregation was observed in the rubberised concrete mixtures without admixtures. Yet it was found out that when a type of viscosity agent (Sika Stabilizer 300 SCC) was added, a more homogenous mixture can be achieved.

Proper additives or admixtures can also be applied to mitigate the poor workability of rubberised concrete as well as to modify the surface of rubber aggregate.

Rivas-Vásquez used 50 vol.% acetone and 50 vol.% methanol to modify the surface of shredded rubber aggregate produced from waste tires (Rivas-Vázquez et al., 2015), the slump test results showed that for the rubberised mixtures using as-received rubber aggregate, significant slump values reduction occurred when the amount of rubber increased, while when the methanol pre-treated rubber aggregate was used, only slightly slump loss, from around 120mm to about 100mm when 15% aggregate replaced by recycled rubber aggregate has been observed, and when use the acetone pre-treated rubber aggregate, the slump values remained the same level as the control mixture.

2.4.2 Mechanical properties of rubberised concrete

The compressive strength, the splitting tensile strength and the flexural strength are the commonly used parameters to evaluate the mechanical properties of rubberized concrete.

The incorporation of rubber aggregate into concrete leads to strength loss and stiffness loss, which can be attributed to the higher poison's ratio of rubber aggregate compared to natural aggregate. The Young's modulus of rubber aggregate is as low as around 1/3 of concrete, as a result, noticeable relative deformation can be expected which leads to initial cracks followed by cracks propagation, and strength loss occurred (Youssf & ElGawady 2014).

Najim and Hall produced self-compacting rubberised concrete using crumb rubber aggregate from waste tires with specific density of 1120Kg/m^3 (Najim & Hall 2012), the compressive strength test results showed that the use of rubber aggregate leads to strength reduction from 45MPa to 20-30MPa.

As for the stiffness indicated by the modulus of elasticity, it has also been summarized in the review work by Youssf and ElGawady that with rubber content of around 20% in rubberised concrete as aggregate, the reduction of concrete E-value reached 30% (Youssf & ElGawady 2014).

Ho prepared rubberised concrete with 20 vol.% to 40 vol.% recycled tire rubber as fine aggregate (Ho et al. 2009), the mechanical property test results showed that with 20% rubber, drastic strength reduction from 60MPa to 30MPa occurred;

and when the rubber content increased to 40%, the modulus of elasticity decreased from 35GPa to less than 20GPa.

Turatsinze prepared cement based mortar with rubber aggregate incorporation (Turatsinze et al. 2005), the rubber aggregate used was generated from recycled tires, the maximum size was 4mm and rubber aggregate had coarser particle size distribution compared to natural sand. A mortar stabilizer admixture was added to reduce bleeding and segregation. Rubber aggregate was added at two replacement ratio (20% and 30%) of natural sand, and 20Kg/m^3 or 40Kg/m^3 fiber was used for reinforcement. The compressive strength test results showed that the mixtures without rubber incorporation achieved 30MPa to 40MPa compressive strength, while replacing 30% of natural sand by recycled rubber aggregate led to drastic strength reduction to less than 10MPa, the trend for all mixtures were similar, despite of the existence of fiber in the mortar.

It is commonly noticed that the incorporation of rubber aggregate leads to drastic strength and stiffness loss to rubberised concrete, thus for most of the previously developed rubberized concrete the rubber content was intended to be controlled to less than 20% by volume.

Xie indicated that it is feasible to use 4 vol.% to 16 vol.% rubber aggregate to replace natural sand to produce green concrete (Xie et al. 2015), the mechanical properties test results of which showed that the cylinder compressive strength of concrete decreased linearly with the increase of rubber aggregate fraction, with 16 vol.% recycled rubber replacing sand, strength loss from 53.1MPa to

42.5MPa (20% reduction) was observed, and the incorporation of rubber aggregate also resulted in flexural strength reduction from 7.8MPa to 5.7MPa.

Holmes investigated the mechanical behavior of rubberised concrete with different formed or shaped rubber aggregate incorporation (Holmes et al. 2014), the 28 days compressive strength test results of which showed that at constant cement content (475Kg) and constant w/c ratio (0.475), the control mixture obtained 28 days compressive strength of 56MPa, the incorporation of 15 wt.% rubber aggregate led to obvious strength loss despite of the shape and form, though, the mixture with 15 wt.% 2-6mm rubber aggregate still showed nearly 40MPa compressive strength after 28 days curing while when dust formed rubber aggregate was used the residue strength was only 30MPa.

In recent years, research work has been conducted to mitigate the strength loss of rubberised concrete.

Pelisser investigated the effect of using silica fume to modify the properties of rubberised concrete. In the work conducted by Pelisser, three groups of mixtures have been prepared (Pelisser et al. 2011): reference mixtures without rubber aggregate (type RF), rubberised concrete with as-received rubber aggregate (type BR) and silica fume modified rubberised concrete (type BM), in each group three w/c ratio were used, the figure showed the compressive strength test results for all three groups mixtures after 7 days and 28 days strength development, it can be observed from the figure that compared to the reference mixtures, the use of rubber aggregate resulted in significant strength loss (averagely 67% reduction), while when silica fume was employed in the rubberised mixtures, the gap of compressive difference between reference mixtures and rubberised concrete became much smaller (averagely 14% reduction) after 28 days curing.

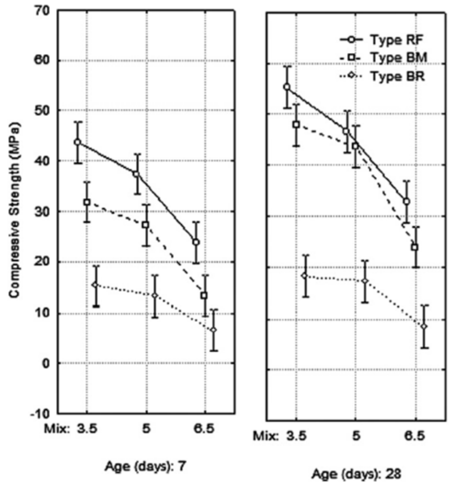


Figure 2-5 7 days and 28 days compressive strength test results of reference mixtures, rubberised concrete with/without silica fume (Pelisser et al. 2011)

The cement based mortar specimens with 20% or 30% recycled rubber aggregate replacing natural sand and with fiber reinforcement prepared by Turatsinze have been used for cracking behaviors tests and it was observed that rubber particles acted as crack arresters and the rubberised mortar showed high strain capacity before macro-cracking localization, and the post-crack ductility was further enhanced with the fiber reinforcement (Turatsinze et al. 2005).

It is well documented that use of fiber reinforcement in concrete improves level of deformation before macro-cracks appear. However, the use of rubber aggregate is an alternative way to mitigate the brittleness problem of concrete which is more environmentally beneficial when recycled rubber aggregate is used.

2.4.3 Durability properties of rubberised concrete

Other than the mechanical properties, the durability properties evaluation is also of great importance for the investigation on rubberised concrete. Compared to natural aggregate used in conventional concrete, recycled rubber has a totally different chemical composition, and rubber aggregate surface is hydrophobic, which may result a weak interfacial transition zone (ITZ) of rubber-cementitious (as illustrated by figure 2-6), thus the long term behavior evaluation of rubberised concrete must be conducted.

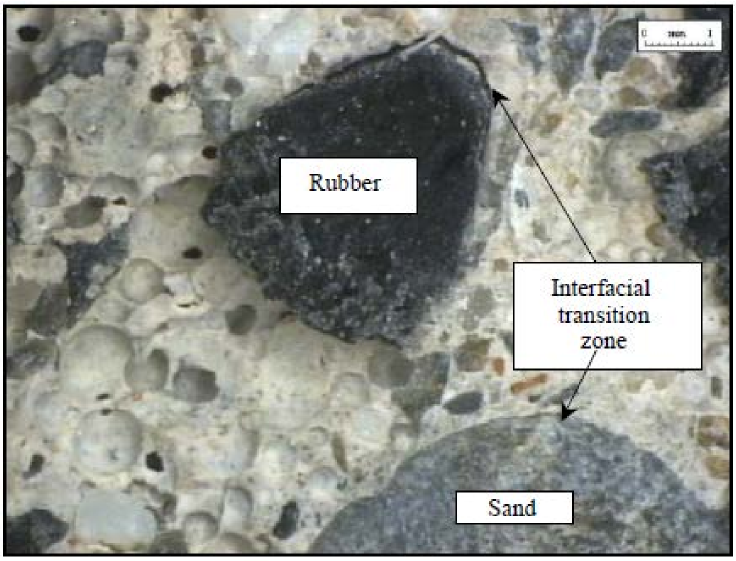


Figure 2-6 Interfacial transition zone between "cement paste and rubber aggregate'' and between ''cement paste and natural sand aggregate'' (Turatsinze et al. 2005)

Commonly used indicators of concrete durability properties evaluation include shrinkage test, permeability test, carbonation test, chloride ion penetration resistance test, high temperature resistance test, freezing-thawing test, chemical attack resistance test, etc.

Bravo and de Brito have investigated the durability-related performance of rubberised concrete with 5 vol.% to 15 vol.% recycled rubber aggregate in total aggregate. The durability properties test results showed that the use of rubber aggregate in concrete led to higher shrinkage value, increased water absorption, reduced chloride ion penetration resistance and linearly increased carbonation depth compared to conventional concrete, in the 91 days carbonation depth test, the reference mixture only showed 7mm carbonation depth, the value increased to 10mm with 15 vol.% recycled rubber as aggregate. It can be concluded from the work of Bravo and de Brito that the use of rubber aggregate has a negative impact on concrete durability properties (Bravo & de Brito 2012).

Topçu and Demir have investigated the durability properties of rubberised concrete (Topçu & Demir 2007), 10 vol.%, 20 vol.%. 30 vol.% and 40 vol.% crumbed rubber chips produced from recycled tires was used to replace natural sand, freeze-thaw resistance, seawater resistance and high temperature resistance have been evaluated. The results showed that after 30 freezing-thawing cycles, rubberised concrete showed similar weight loss and strength loss indicated by compressive strength compared to the control mixture. However, slightly higher stiffness loss was detected, which indicated that the incorporation of 10 vol.% to 30 vol.% recycled rubber aggregate had slightly negative impact on concrete freeze-thaw resistance; the sea water resistance test showed that rubberised concrete had more significant stiffness loss compared to conventional concrete; and the high temperature resistance test showed that upon 3 hours exposure to

400˚C, rubberised concrete and the reference mixture showed very similar strength loss and stiffness loss, thus, it was concluded by Topçu and Demir that this type of rubberised concrete has potential application in construction works where high strength is not required but durability is important.

It was reported that the use of silica fume is effective in enhancing the impermeability of rubberized concrete (Onuaguluchi 2015), with 42Kg/m^3 silica fume incorporation, the charge passed in the accelerated chloride ion penetration test of rubberized concrete was significantly reduced from 3000 coulombs to less than 500 coulombs.

Even though in various previous research works it has been observed that the incorporation of rubber aggregate into concrete has negative impact on concrete durability, though, in the review work of Youssf and ElGawady, it has been reported that compared to conventional concrete rubberised concrete showed improved durability properties (Youssf & ElGawady 2014).

2.4.4 Acoustic insulation properties of rubberised concrete

Previous research works revealed that incorporation of rubber aggregate in concrete leads to improved insulation properties, especially improved acoustic insulation properties of concrete.

Research works have been conducted to quantitatively analyze the decreased dynamic modulus and increased vibration damping coefficient of rubberised concrete compared to conventional concrete. Najim and Hall have prepared self-compacting rubberised concrete with 5 wt.%, 10 wt.% and 15 wt.% crumb rubber aggregate made from waste tires replacing fine/coarse aggregate (Najim & Hall 2012), the damping constant and dynamic modulus of elasticity have been measured and calculated the results showed that the dynamic modulus of elasticity decreased linearly and the damping constant increased linearly with the increase of rubber aggregate content in concrete, which explains the improved acoustic insulation properties of rubberised concrete compared to conventional concrete from the mechanism perspective.

Holmes investigated the sound absorption co-efficient in two frequencies ranges (63Hz-500Hz and 1000Hz to 8000Hz) of rubberised concrete with 7.5 wt.% or 15 wt.% rubber aggregate as fine aggregate (Holmes et al. 2014), the test results showed that under laboratory conditions, absorption co-efficient of the reference concrete was around 0.02, while when 15 wt.% rubber was used to as fine aggregate, the acoustic insulation was improved significantly despite of the shape and form of aggregate, absorption co-efficient around 0.13 can be achieved with 15 wt.% dust formed rubber as fine aggregate, and the index further increased to 0.14 and 0.16 when same fraction of 1-3mm rubber aggregate and 2-6mm rubber aggregate was used, respectively.

Aliabdo prepared rubberised concrete at cement content of $400Kg/m^3$ and w/c=0.45 to investigate the sound attenuation coefficient (Aliabdo et al. 2015), it was found out that with the increased amount of rubber aggregate replacing sand, the sound attenuation coefficient of concrete increased linearly from 0.75 to 1.25.

Abundant research works have been conducted on the improved insulation properties of rubberised concrete, meanwhile how to mitigate the strength loss and the weak bonding between rubber aggregate and matrix had become a new topic.

2.4.5 Rubber aggregate surface modification

The use of as-received rubber as aggregate in concrete is associated with strength loss and other negative impact on rubberised concrete, which can mainly be attributed to the poor adhesion between as-received rubber aggregate and the matrix. Youssf and ElGawady concluded that the poor adhesion is due to the hydrophobicity of rubber aggregate surface which is due to two reasons: the smooth surface and low hydraulic conductivity of rubber aggregate; and the soap layer that repels water caused by the existence of zinc stearate from manufacturing process (Youssf & ElGawady 2014).

Poor adhesion between aggregate and paste not only causes strength and stiffness loss, but is also associated with higher permeability of hardened rubberised concrete. Therefore, rubber surface treatment methods have been applied to mitigate the mechanical properties and durability properties of rubberised concrete. Some commonly used surface modification methods have been summarized in this sub-section.

Saturated NaOH Solution

In previous research works, saturated sodium hydroxide (NaOH) aqueous solution has been used for recycled rubber aggregate surface modifications.

Segre conducted surface treatment on recycled tire rubber (Segre et al. 2002), flat sections of tire was abraded lightly with sandpaper, rinsed with distilled water and then be placed in saturated NaOH aqueous solutions for 20 minutes to 144 hours with stirring, followed by rinsed and air dried under room temperature. The contact angles test, conducted by using a comparator microscope with a goniometer, showed that the saturated NaOH aqueous solution treatment resulted in an improved homogeneity, which can be attributed to the decrease of the zinc stearate on the treated rubber surface.

Li applied the NaOH treatment on recycled rubber aggregate surface modification (Li et al. 2004), rubber aggregate sized 25.4mm×25.4mm×5mm has been prepared from waste car tires and trunk tires, the control mixture without rubber aggregate incorporation was prepared with designed compressive strength of 40MPa and the recycled rubber chips were used to replace 15 vol.% of natural coarse aggregate in concrete, both un-treated rubber chips and surface pre-treated rubber chips were used, the surface treatment was conducted by immersing the rubber chips in saturated analytical grade NaOH solution for half an hour while stirring, the compressive strength test results showed that when 15 vol.% un-treated rubber chips were used as coarse aggregate, significant strength loss was detected, the rubberised concrete mixture only achieved 22.33MPa strength which is less than 60% compared to the control mix (39.08MPa), and the NaOH treatment only showed negligible enhancement, the mixture with NaOH treated rubber chips obtained 23.23MPa result in the compressive strength test.

In previous research works, NaOH has been proved to be effective in mitigation the poor bonding between rubber aggregate and other materials, though NaOH treatment had limited effect on improving mechanical properties of hardened rubberised concrete. Other chemical treatment on rubber surfaces was then proposed.

Silane Coupling Agent

Silane coupling agent is a bi-functional compound which attaches to organic material (e.g. rubber) at one end and attaches to inorganic materials (e.g. matrix or aggregate) at the other end, the chemical natural of silane coupling agent makes it possible to mitigate the bonding in rubberised concrete when applied to the surface of rubber aggregate (Huang et al. 2013).

In the year of 2013, Huang developed a novel scheme of recycled rubber aggregate surface treatment, as illustrated by figure 2-7. To complete the two staged treatment process, a silane coupling agent material (1:1 mixture of H_2NCH_2 CH_2NH CH_2 CH_2 $CH_2Si(OCH3)_3$ and O CH_2 CH_2 CH_2O CH_2 CH_2 CH_2 $Si(OCH3)_3$) was firstly used to modify rubber particle surface and to build chemical bonds with the paste, in this stage, crumb rubber aggregate with size smaller than 4.75mm was immersed into silane coupling agent ethyl alcohol aqueous solution for 20 minutes and heated to 85˚C for 15 minutes, then cement paste was used to coat the silane-treated particles as a second treatment, the treated rubber particles was dried at 110˚C for 12 hours before use.

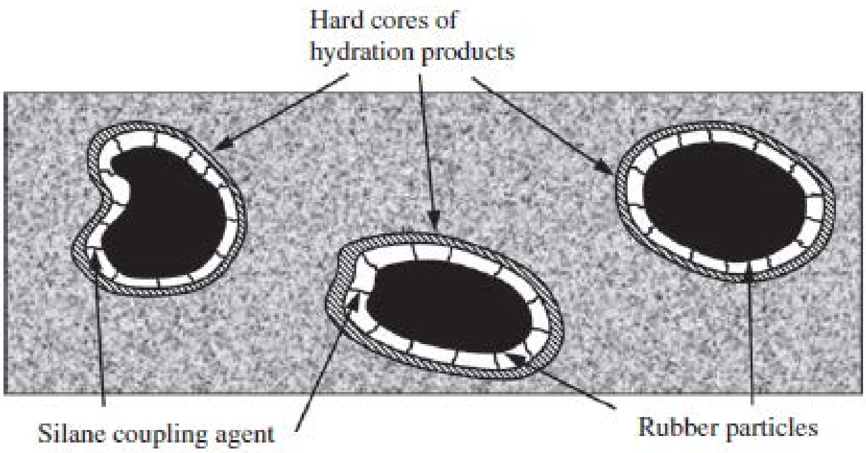


Figure 2-7 Two staged treated rubber aggregate in hardened rubberised concrete (Huang et al. 2013)

50mm×50mm×50mm cubes were prepared for compressive strength test, the test results showed that similarly to the previous research on the mechanical properties of rubberised concrete, at constant cement content and w/c ratio, the compressive strength decreased with the increase of recycled rubber aggregate content, and using only silane coupling agent treatment had very limited effect to compensate the strength loss. However, it was found out that when the two staged surface modification scheme was applied, noticeable strength enhancement was detected, effective for mixtures with rubber content 5 wt.% to 25 wt.% (see figure 2-8).

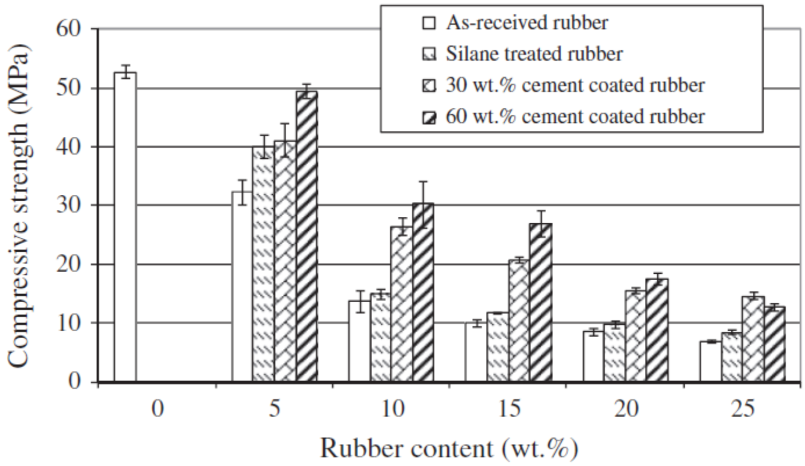


Figure 2-8 Compressive strength test results of rubberised mixtures with varies rubber aggregate treatment (Huang et al. 2013)

Other than applying on the rubber aggregate surface, the coupling agent can also be applied on bonding materials. Thongsang and Sombatsompop used a type of chemical coupling agent, named bis-triethoxysilylpropyl tetrasulfane (Si69), to mitigate the bonding between fly ash particles and rubber (Thongsang & Sombatsompop 2006), and it was reported that at a low concentration (2.0 to 4.0 wt.%) of Si69, the mechanical properties of the rubber-fly ash composites can be improved due to the increased of crosslink density.

Other Chemical Treatment

Despite of the two types of most commonly used chemical, NaOH and silane coupling agent, in recent years other chemicals have also been used for rubber aggregate surface modification.

Rivas-Vázquez (Rivas-Vázquez et al. 2015) have used two different solvents to modify the rubber surface and reported that enhancement of mechanical strength was observed when acetone was used on the waste tire rubber fiber. In

Rivas-Vázquez's work, the control mixture without rubber aggregate achieved around 220 MPa compressive strength after 28 days hydration, the strength decreased to about 170 MPa when 10% rubber aggregate was used; however, when the recycled rubber aggregate was pre-treated by acetone, the 28 days compressive strength was maintained to slightly higher than 200MPa, which indicated that acetone is an effective chemical for recycled rubber aggregate surface modification.

Cementitious Materials Coating

In this study, the use of recycled rubber aggregate is mainly aimed at improving concrete acoustic insulation properties, a simple coating pre-treatment method was applied for the rubber aggregate surface modification and was found effective to further improve the noise reduction effect of rubberised concrete.

Coating has also been reported in other research works as a modification method to rubber aggregate surface (see figure 2-9).

Figure 2-9 Recycled rubber aggregate before and after coating (Pacheco-Torgal et al. 2012)

Silica fume is a type of material with fine particle size and very high specific surface area. It is commonly recognized that the use of silica fume in concrete has positive impact on strength enhancement and impermeability improvement. It has also been employed in rubberised concrete/ mortar to compensate strength loss.

Onuaguluchi published his work on using a two staged approach for recycled rubber aggregate surface modification (Onuaguluchi 2015): coating the crumb rubber aggregate by limestone powder and adding silica fume in the mixture by 10 vol.% of cement. It was found out that similarly to previous research works on rubberised concrete, the use of as-received rubber aggregate led to strength loss, though when the surface pre-treatment was applied, rubberised mortar achieved comparable compressive strength and higher flexural strength of the reference mixture.

However, limited research works have been found regarding the coating method on the acoustic insulation properties of rubberised concrete.

2.5 Internal curing effect

2.5.1 Concept of internal curing effect

Water is pivotal for concrete in two aspects: securing strength increase during the curing process and preventing or mitigating the occurrence of shrinkage and cracks. The lack of external water supply during the curing age results in decrease in hydrating cement ratio as well as increase in water-vapor-filled capillary pores.

Surface water loss of concrete can be caused by air flow or temperature changes, insufficient water during curing process brings detrimental effects to concrete mechanical properties (e.g. strength loss) and durability properties (e.g. cracks).

Traditional concrete curing methods are focused on two aspects to secure sufficient water for concrete (Weiss et al. 2012): to provide external water to the surface of the concrete (e.g. to place the concrete specimens into water tank) and to avoid water loss from concrete (e.g. cover the specimens with plastic sheets). However, there are limitations of traditional external curing methods: the curing quality depends on the penetration degree of water, the dimension of the specimens and the quality of the specimens. Therefore, changing the water supply resource from outside to inside enables water supply more evenly, thus benefits the hydration process during curing age and improve concrete properties.

As illustrated by the figure 2-10, the definition of internal curing given by American Concrete Institute is: Internal curing is supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation (Weiss et al. 2012).

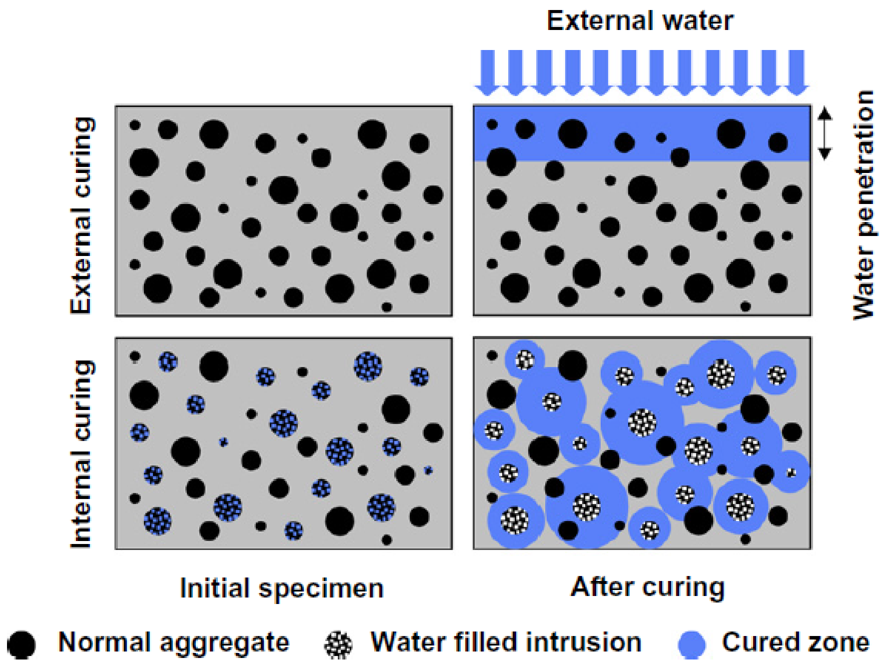


Figure 2-10 Conceptual illustration of the differences between external and internal curing (Weiss et al. 2012)

2.5.2 Reservoir effect of porous aggregate

Determine of lightweight aggregate mass in mix Proportion design was conducted according to the equation 2-1 (ACI Committee 2013):

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S \times \Phi_{LWA}} \quad (2\text{-}1)$$

Where M_{LWA} (kg/m^3) is the mass of LWA (in a dry state) that needs to be pre-wetted to provide water to fill in the voids created by chemical shrinkage; C_f (kg/m^3) is the binder content of the mixture; CS (mL of water per g of binder) is the chemical shrinkage of the binder; α_{max} (unit less) is the expected maximum degree of hydration (0 to 1); S (unit less) is the expected degree of saturation of the LWA and was taken to be 1 when the dry LWA was soaked for 24 h; and Φ_{LWA} (kg of water/kg of dry LWA) is the absorption capacity of the LWA (taken here as the 24 h absorption value).

Previous research works revealed that various types of porous aggregate can be served as the reservoir agent in concrete to provide the internal curing, some of the effective reservoir materials are listed as followings.

Table 2-2 List of dry density and 24h water absorption value of the aggregates as water supply source in internally cured concrete or mortar

Internal curing agent	Aggregate type	Aggregate dry density (Kg/m^3)	24h water absorption (%)	Source
Rotary kiln expanded shale	Fine aggregate	1380	17.5	(De la Varga et al. 2012)
Pumice aggregate	Coarse aggregate	635	16.0	(Kabay & Aköz 2012)
Expanded shale	Fine aggregate	920	15.0	(Cusson & Hoogeveen 2008)
Expanded shale	Fine aggregate	1540	24.7-30.0	(Browning et al. 2011)
Expanded shale	Fine aggregate	1800	23.8	(Henkensiefken et al. 2009)
Expanded shale	Fine aggregate	1611	10.5	
Leca	Coarse aggregate	1267	8.9	(Bentur et al. 2001)
Crushed returned concrete aggregate (CCA)	Fine aggregate	2150-2230	12.0-16.0	(Henkensiefken et al. 2009)
Porous Ceramic Waste	Coarse aggregate	2270	9.31	(Suzuki et al. 2009)
Lightweight Sand with irregular shape	Fine aggregate	1600	25.0-30.0	(Liu et al. 2011)
Spherical shale ceramsite	Coarse aggregate	1478	4.06	(Ji et al. 2015)

The impact of pre-wetting methods and the fractions of porous aggregate on the internal curing effect have been investigated. Ji prepared lightweight aggregate mixtures using spherical shale ceramsite produced in mainland China (Ji et al. 2015), the un-saturated or saturated ceramsite occupied 50% or 100% in total coarse aggregate, the 28-day compressive strength test results showed that at constant cement content and effective w/c ratio, increased lightweight aggregate fraction from 50% to 100% induced obvious strength reduction from 56MPa to 43MPa when un-saturated lightweight aggregate was used, and similar reduction (from 58MPa to 45MPa) was detected when in the ceramsite had been pre-wetted for 24 hours in both mixtures.

Ji's work also revealed that pre-wetting the lightweight aggregate has very limited benefits for concrete strength development when the cement content and effective w/c ratio kept constant. However, both the water absorption of aggregate and the saturated degree has been reported to have significant impact on concrete shrinkage.

2.5.3 Concrete shrinkage reduction

Internal curing enables water compensate from inner layers to the surface via water releasing from pre-wetted porous aggregates, also internal curing results in drastically reduction of capillary stress by refilling of hydrating cement paste in the pores of aggregate, thus reducing cracks and strength losses due to water evaporation of the surface layer (Weiss et al. 2012).

Abundant previous research works agreed that by using pre-wetted porous aggregate in mortar or concrete, the drying shrinkage and autogenous shrinkage can be reduced due to the more evenly dispersed water from the aggregate pores.

Ji investigated the early age autogenous shrinkage of concrete made with pre-wetted or not pre-wetted ceramsite as coarse aggregate (Ji et al. 2015), the test results showed that when 50% of coarse aggregate was lightweight aggregate, the total initial autogenous shrinkage was 1035με when the lightweight aggregate was not saturated, and the value decreased to 626με if the ceramsite had been pre-wetted for 24 hours; while when the lightweight aggregate fraction increased to 100% of coarse aggregate, the shrinkage reduction effect of internal curing was even obvious (from 1164με to 412με).

Bentur prepared lightweight aggregate concrete to investigate the autogenous shrinkage reduction provided by pre-wetted Leca aggregate with a ssd density of 1380Kg/m^3 and 24h water absorption value of 8.9% (Bentur et al. 2001), particle distribution concentrated within 4.5mm-9mm, cement usage for both reference concrete and lightweight aggregate concrete were 444Kg/m^3, water/binder ratio 0.33, lightweight aggregate at both ssd situation and air-dried situation (water absorption value of 5.8%) have been used to act as the reservoir for internal curing, the size of shrinkage specimens was 40mm×40mm×1000mm, after demolding, specimens were sealed by plastic sheet and been kept in the environment under a constant temperature of 30˚C, the results indicate that at the early age (tested after 6d of remolding) a slight expansion occurred in both LWC concrete and NWC concrete specimens, however, in terms of long terms autogenous shrinkage, LWC concrete prepared with 100% replacement ratio of fully-saturated Leca aggregate shown continuous expansion of specimens dimension, LWC concrete prepared with 100% replacement ratio air-dried Leca aggregate shown non obvious shrinkage after about 120 days of remolding, when the replacement ratio of Leca be reduced to 25%, the compensation effects to shrinkage also been correspondingly deducted, while for normal aggregate concrete, significant autogenous shrinkage can be detected just after 2 weeks of remolding, and the autogenous shrinkage value was almost 300um at the age of 168 days as a result of lack of water. Fully-saturated porous lightweight aggregate has prominent effects on autogenous shrinkage reduction.

Cusson and Hoogeveen prepared prismatic concrete specimens with the dimension of 200mm×200mm×1000mm to investigate the influence on critical value of net autogenous shrinkage associated with varies internal curing level (Cusson & Hoogeveen 2008), the result of which illustrated that internal curing realized by pre-wetted expanded shale partially replacing natural sand as fine aggregate significantly mitigates concrete autogenous shrinkage: a 20% reduction can be gained by a 6% replacement ratio on a weight basis, a 60% reduction can be achieved when the replacement ratio increased to 12%, when 20% natural sand replaced for internal curing, autogenous shrinkage was found only 10% compare to the control mix without lightweight aggregate.

Henkensiefken prepared mortar specimens containing various proportions of recycled concrete aggregate (sieved to 75μm to 4.75mm) and lightweight aggregate concrete with a density of 1800Kg/m^3, water absorption 23.8% to study the impact on shrinkage reduction caused by internal curing agent (Henkensiefken et al. 2009), water to cement ratio was set as 0.3 for all mixtures, the results indicate that compared to only using lightweight aggregate as internal curing agent, a combination of both lightweight aggregate (57% by dry mass) and recycled concrete aggregate (43% by dry mass) lead to a substantially further reduction of autogenous shrinkage determined by strain.

Henkensiefken also investigated the influence on concrete shrinkage and cracks brought by different levels of internal curing by preparing mortars incorporate 0 to 33% of total aggregate volume lightweight aggregate with density of about 1611Kg/m^3 and 24h water absorption of 10.5% to replace natural sand with a density of 2610Kg/m^3 (Henkensiefken et al. 2009), some of the main findings are: extra water brought with pre-wetted lightweight aggregate is able to provide an early age expansion to compensate the strain which may cause cracks; and a higher replacement ratio of lightweight aggregate results in improvement of long term shrinkage reduction.

2.5 Summary

Based on the literature review of previous research works on the properties of lightweight aggregate concrete and rubberised concrete, the following research gaps have been found:

The production of high strength effectiveness lightweight aggregate concrete is pending to be investigated;

Use of Furnace Bottom Ash (FBA) on the concrete mechanical properties and durability properties have been investigated, but limited works have been conducted on the thermal insulation properties of FBA incorporated concrete;

Use of pre-wetted lightweight aggregate to conduct internal curing in concrete has been proved to have positive impact on concrete shrinkage reduction, but limited works have been conducted regarding the internal curing effect of FBA;

Use of rubber aggregate produced from waste tires resulted in poor workability and strength loss, varies surface treatment methods have been investigated to improve fresh properties and mechanical properties of rubberised concrete, while limited works have been conducted to improve the acoustic insulation properties of rubberised concrete via rubber aggregate surface treatment.

In this study, works have been designed to fill these research gaps as well as to develop new green concrete with high volume of recycled aggregate incorporation.

Chapter 3. – METHODOLOGY

3.1Materials

An ordinary Portland cement (ASTM Type I) sourced locally was used in this study, the density of which was 3.16 g/cm^3 and the specific surface areas was 3,500 cm^2/g. The detailed chemical compositions of the cement are presented in Table 3-1.

Crushed granite with maximum sizes of 10 mm and 20 mm was used as natural coarse aggregate in the normal aggregate concrete, and a crushed fine stone with a fineness modulus of 3.5 was used as the fine aggregate for both the normal weight aggregate concrete and the lightweight aggregate concrete. The properties of the natural aggregates are listed in Table.

Two types of Lightweight expanded clay aggregate (LECA) have been used:

LECA 1 with a diameter ranged from 6 mm to 10 mm surface saturated dried density of the lightweight aggregate 1,192 kg/m^3, and the 24 hours water absorption value was 9.41%.

LECA 2 lightweight aggregate was with surface saturated dried density of 924 kg/m^3, and the 24 hours water absorption 21.40%.

Before casting, all lightweight aggregate was soaked in water for 24 h. After that the aggregate was scooped out, hanged in the air until a saturated surface dried (SSD) situation was obtained.

The rubber aggregate used in this study was sourced from mainland China, fabricated from waste tires. The Rubber particles produced from waste tires used in this study were rounded shaped with a relatively smooth surface, and the density was 1,569 Kg/m^3.

A superplasticizer ADVA 109 (Grace) was used to control the workability determined by the slump values of the fresh concrete mixtures. The amount of superplasticizer used in each mix proportion is listed in the mix proportions design tables.

Table 3-1 Chemical compositions of cement and FBA (%)

	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	SO_4	Na_2O	K_2O	TiO_2	Others	L.O.I.
Cement	19.61	3.32	7.32	63.15	2.54	2.13	-	-	-	-	-	2.97
FBA	52.10	11.99	18.34	6.61	4.85	-	0.72	2.43	1.57	0.87	0.52	4.13

The FBA used in this study was sourced from a local power generation plant. FBA is a by-product of coal fired power generation plants, and its density and water absorption values vary with different sources of coal and type of plants. FBA used in this series of experiment had a saturated surface dried density of 2,208 kg/m^3, 24 hours water absorption of 11.17%, and a fineness modulus of 3.3. The chemical compositions of the FBA are presented in Table 3-1, and the properties of FBA can be found in Table 3-2.

Table 3-2 Properties of aggregates

Properties	Size of sieve (mm)	Percentage passing (%) 20mm granite	10mm granite	Crushed fine stone	FBA
Sieve Analysis (according to ASTM C 136 06)	37.5	100	-	-	-
	20	97	-	-	-
	14	18	100	-	-
	10	4	96	100	100
	5	-	21	97	83
	2.36	-	4	67	61
	1.18	-	-	44	46
	0.6	-	-	27	36
	0.3	-	-	14	28
	0.15	-	-	6	19
Ssd density (Kg/m^3) (according to BS EN 1097-6:2000)	-	2652	2656	2670	2208
24h water absorption (%) (according to BS EN 1097-6:2000)	-	0.91	0.85	1.19	11.17

The NaOH (Sodium hydroxide) solution used for rubber aggregate surface modification was prepared from NaOH pellet sourced from a local supplier. The grade of the NaOH pellet is Analytical Reagent Grade. The purity of the NaOH pellet is ≥98%.

The Silane Coupling Agent (SCA) SCA is an organosilicon compound containing two different reactive groups. One functional group is organophilic, whereas the other polymerises and reacts with the surface of inorganic material. The formula of SCA is $YSi(OR)_3$, where Y is a non-hydrolytic group which tends to bond well the synthetic resin, rubber, and so on, in organic materials; OR is a hydrolysable group that will hydrolyse in water to generate a silanol (Si–O–H) group) which will chemically react with hydroxyl on the surface of inorganic materials (Su et al. 2015).

3.2 Mix design

In this study, various types of lightweight aggregate have been used to replace natural coarse aggregate in concrete, while two types of recycled aggregate, FBA and waste tires particles have been used to partially replace natural fine aggregate in concrete.

Three major groups of mixtures have been prepared:

The first group of concrete was targeted to produce lightweight aggregate concrete with improved thermal insulation properties and with FBA incorporation, in total 6 mixtures have been cast, one normal aggregate concrete and five mixtures of lightweight aggregate concrete with FBA replacing 0, 25%, 50%, 75%, and 100% crushed fine stone by volume;

The mixture proportions are listed in the table 3-3.

Table 3-3 Mix proportion designs of group 1: low strength lightweight aggregate concrete without silica fume incorporation and the normal aggregate concrete (NAC) as reference (kg/m^3)

Mix code	W/C	FBA	Cement	Water	Crushed Fine Stone	Coarse Aggregate 10mm	20mm	LECA 1	ADVA 109 (L/m^3)
NAC	0.6	0	325	195	1041	276	552	-	3.55
LWCF0	0.39	0	450	175	755	-	-	477	1.46
LWCF25	0.39	156	450	175	566	-	-	477	1.96
LWCF50	0.39	312	450	175	377	-	-	477	1.37
LWCF75	0.39	468	450	175	189	-	-	477	1.86
LWCF100	0.39	624	450	175	0	-	-	477	1.76

The second group of concrete was targeted to investigate the internal curing effect in concrete shrinkage reduction. Five mixtures of normal aggregate concrete and five mixtures of lightweight aggregate concrete have been prepared, while silica fume was added to compensate strength loss as well as to improve durability properties of concrete.

The mixture proportions are listed in the table 3-4.

Table 3-4 Mix proportions design of group 2: high strength lightweight aggregate concrete and normal aggregate concrete with silica fume and FBA incorporation (Kg/m^3)

Mix code	W/C	FBA	Cement	Silica Fume	Water	Crushed Fine Stone	Coarse Aggregate			ADVA 109 (L/m^3)
							10mm	20mm	LECA 1	
NACF0	0.34	0	550	55	187	669	354	707	0	6.38
NACF25	0.34	132	550	55	187	502	354	707	0	6.38
NACF50	0.34	264	550	55	187	335	354	707	0	6.38
NACF75	0.34	395	550	55	187	167	354	707	0	6.38
NACF100	0.34	527	550	55	187	0	354	707	0	6.38
LWCF0	0.34	0	550	55	187	669	0	0	477	3.20
LWCF25	0.34	132	550	55	187	502	0	0	477	3.20
LWCF50	0.34	264	550	55	187	335	0	0	477	3.20
LWCF75	0.34	395	550	55	187	167	0	0	477	3.20
LWCF100	0.34	527	550	55	187	0	0	0	477	3.20

The third group of concrete was targeted to investigate the acoustic insulation properties of rubberised concrete with waste tire particles incorporation as well as to investigate the mechanism of rubber aggregate surface pre-treatment effect on noise reduction. In this group, nice preliminary mixtures have been cast, one control mix of lightweight aggregate concrete using a second type of LECA as coarse aggregate and FBA as fine aggregate, rubber aggregate was used to replace 25% to 100% of FBA as fine aggregate by volume, while for each replacement ratio, both as-received rubber aggregate and pre-treated rubber aggregate have been used for making comparison. Besides, four extra mixtures have been prepared and proved that when use crushed fine stone instead of FBA in concrete as fine aggregate, pre-treated rubber aggregate also showed better noise reduction effect than as-received rubber aggregate.

The mixture proportions are listed in the table 3-5.

Table 3-5 Mix proportions design of group 3: rubberised concrete with FBA incorporation (Kg/m^3)

Mix code	W/C	FBA	Cement	Water	LECA 2	Rubber	ADVA 109 (L/m^3)
CTR	0.34	637	550	187	392	0	4
R25 u	0.34	478	550	187	392	113	4
R25 p	0.34	478	550	187	392	113	4
R50 u	0.34	319	550	187	392	226	4
R50 p	0.34	319	550	187	392	226	4
R75 u	0.34	159	550	187	392	340	4
R75 p	0.34	159	550	187	392	340	4
R100 u	0.34	0	550	187	392	453	4
R100 p	0.34	0	550	187	392	453	4

3.3Rubber aggregate surface modification

In this study, a few surface modification methods have been applied on the recycled rubber aggregate: Coating by cement slurry, immersion in saturated NaOH solution, and immersion in Silane Coupling Agent (SCA) solution.

3.3.1 Chemical pre-treatment

The saturated NaOH solution was prepared by dissolving 110g NaOH pellet (Analytical Reagent Grade) in 100mL water at ambient temperature. To conduct the surface modification via NaOH pre-treatment, the rubber aggregate was soaked into the saturated NaOH solution for 24 hours, rinsed under tap water and air dried for 24 hours in laboratory conditions before casting.

The SCA solution was prepared by dissolving 5 units SCA liquid in 100 units water. To conduct the surface modification via SCA pre-treatment, the rubber aggregate was soaked into the SCA solution until the entire surface was coated by the agent before casting.

NaOH and SCA modification showed negligible effect on noise attenuation effect and strength reduction compared to specimens prepared from as-received rubber aggregate, detailed results are listed in Chapter 4. Therefore, in this study, only cement paste coating method has been studied systematically.

3.3.2 Coating pre-treatment

Cement paste was prepared to conduct surface modification on the recycled rubber aggregate via coating. As illustrated by figure 3-1 and figure 3-2, the rubber aggregate was coated evenly by a cement paste and air-dried for 7 days before used for casting.

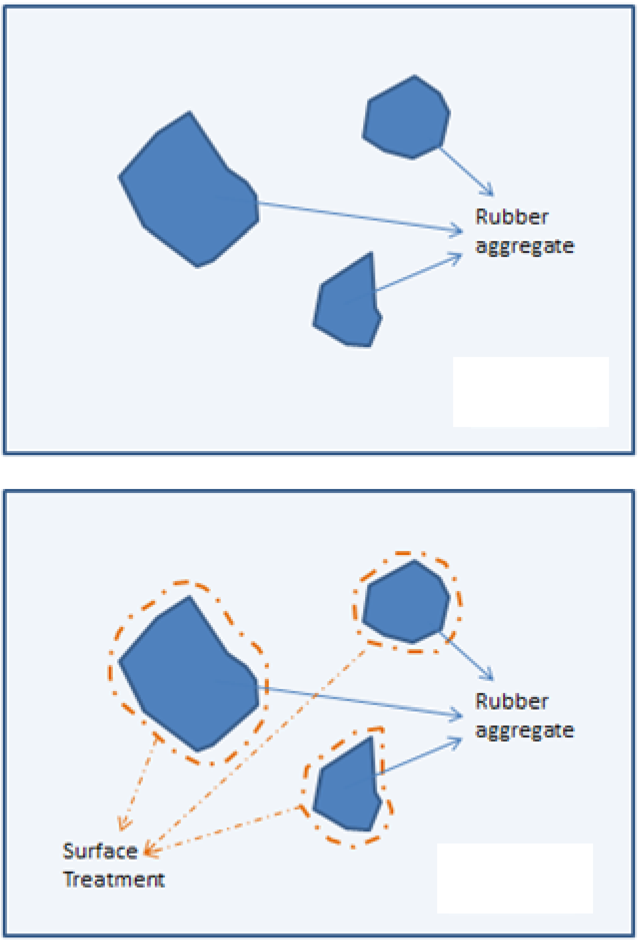


Figure 3-1 Illustration of surface treatment

Figure 3-2 Applying the coating method on the surface of recycled rubber aggregate

Trial mixtures have been casted to determine the water/cement ratio and cement/rubber aggregate ratio of the paste used for coating. Paste was prepared at w/c from 0.5 to 1.0 and c/r from 1/4 to 1/10. 100×100×100mm cubes have been casted and compressive strength tests was conducted. The test results are listed in Table 3-6.

Table 3-6 Compressive strength test results of rubberised concrete prepared with cement paste coating pre-treatment

Trial mix code	Mix Design			1d f_c (MPa)
	Rubber as fine aggregate	Water/cement of coating	Cement/rubber of coating	
1	50%	-	-	8.4
2	50%	0.5	1/6	6.9
3	50%	0.6	1/6	7.1
4	50%	0.7	1/6	6.8
5	50%	0.8	1/6	7.2
6	50%	1.0	1/6	6.2
7	50%	0.8	1/4	7.2
8	50%	0.8	1/8	7.0
9	50%	0.8	1/10	6.1

It can be seen from the table 3-6 that when the coating method applied, strength loss occurred despite of the water/cement ratio and cement/rubber ratio of coating. When 1/6 cement/rubber used to prepare the coating, strength loss at water/cement=1.0 is more obvious than mix 2-5; and from mix 5, 7-9 it can be seen that at 0.8 water/cement ratio, when 1/4, 1/6, or 1/8 cement was used for prepare the coating, strength reduction was less significant compared to when only 1/10 cement was used. When the water/cement ratio of 1.0 was used, excessive paste has been observed after applying the coating.

The paste used for rubber surface pre-treatment was prepared at a water/cement ratio of 0.8 and the cement usage was set as 1/8 of treated rubber aggregate by weight.

To conduct the surface treatment, the rubber aggregate and the freshly prepared paste was mixed using a mortar mixture machine, then coated rubber aggregate was placed on plastic sheets for air dry process before the casting of rubberised concrete.

3.4 Curing

In this study, two different curing methods have been applied: air curing and water curing.

All the water cured specimens were demolded after 24 hours of casting and cured in a water tank at a temperature of 23 ± 2 °C until the test ages.

All the air cured specimens were demolded after 24 hours of casting and cured in a chamber with a constant temperature of 23 ± 2 °C and with a constant relative humidity of 50±5%. Air curing was adopted to investigate the influence of water on concrete strength development.

3.5 Testing – For structural applications

In this study, as illustrated in the subsection of specimen's preparation, two types of applications are targeted: external wall as structural materials and partition wall as insulation materials. Therefore, the testing methods were also designed to fulfill the general requirements of these two types of applications. For the structural applications, fresh properties, mechanical properties, durability properties, the shrinkage and the thermal insulation properties were evaluated, while for the concrete targeted to be used as partition wall materials, sound insulation properties indicated by noise attenuation values was tested and analyzed.

3.5.1 Fresh properties and mechanical properties test

Slump test was performed to evaluate the workability of the fresh concrete in accordance with BS EN 12350-2:2009;

The cubic specimens with dimensions of 100 mm×100 mm× 100 mm at the surface saturated dried condition were used for the density test, in accordance with BS EN12390-7:2009;

Cubic specimens with sizes of 100 mm×100 mm× 100 mm were used for the compressive strength test carried out at the ages of 1 d, 3 d, 7 d, 28 d and 90 d in accordance with BS EN 12390-3:2009;

Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were prepared for conducting the static modulus of elasticity test at the ages of 28 d and 90 d in accordance with BS 1881-121.

3.5.2 Durability properties testing

The accelerated chloride ion permeability test was conducted at the curing ages of 28 d and 90 d in accordance with the standard test method presented by ASTM C 1202, the specimens with sizes of 100 mm diameter and 50 mm thickness were cut from the cast cylinders with 100mm diameter and 200mm height. Samples had been pre-conditioned with a vacuum pump for 6 hours and then placed in water tank for 18 hours before the test, the standard solution used in this test were 3.0 wt.% sodium chloride solution and 0.3N sodium hydroxide solution, after connected to a constant voltage of 60±0.1V, the current was recorded and the charge passed (coulombs) will be calculated.

The classification of chloride ion penetrability is evaluated following the classification presented by the table 3-7.

Table 3-7 Standard classification of chloride ion penetrability

Charge Passed (Coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

3.5.3 Thermal insulation properties testing

Thermal conductivity test conducted according to BS EN 1934:1998, three identical 300mm×300mm×60mm slabs were prepared for each mix. They were cured in a water tank for 28 d, followed by placing them in an oven for 24 h at 105 °C to drive out the free moisture. The equipment used for measurement the K value was fabricated according to BS EN 1934:1998. The temperatures of the cold and the hot side of the chamber were set at 23 °C and 53 °C, respectively. The thermal conductivity K-value is calculated by the equation 3-1:

$$K = \frac{Q}{A} \times \frac{L}{\Delta T} \tag{3-1}$$

Where K is thermal conductivity value, in $W \cdot m^{-1} \cdot K^{-1}$;Q is heat flux through tested specimen, in W;A is the area of heat flux, in mm^2;L is the thickness of the slab, in m; and ΔT is the temperature difference of two surfaces of tested specimen, in K..

The setup of the thermal conductivity test is illustrated in the figure 3-3

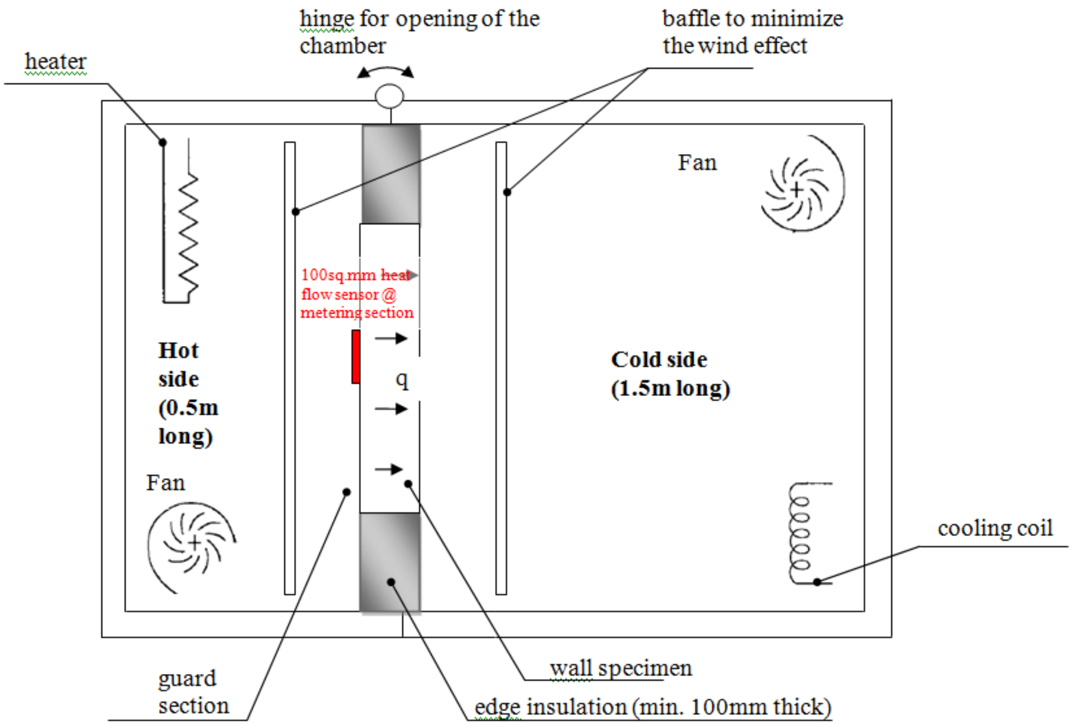


Figure 3-3 Schematic of thermal conductivity test setup

3.5.4 Shrinkage testing

For the drying shrinkage test, for each designed concrete mixture, three 75 mm×75 mm×285 mm concrete prisms were cast according to BS ISO 1920-8. The cast specimens were removed from the molds, put into a water tank for 7 days at 23±2 °C, and after which the length of specimens were measured as the initial length. Following this, the specimens were stored in an environmental chamber at a temperature of 23±2 °C and a relative humidity of 50%. The length change of the specimens was measured at 1, 3, 7, 14, 28, 56, and 112 days after the initial reading.

To assess the autogenous shrinkage of the specimens, three 75 mm×75 mm×285 mm concrete prisms for each mix were cast, and they were taken out from the molds after 1 day, and immediately wrapped by two layers of plastic sheet to eliminate water loss, and then wrapped by two further layers of aluminum foil to prevent heat exchange with the environment. After that, the specimens were transferred to an environmental chamber with controlled conditions (temperature of 23 ± 2 °C and relative humidity of 50%). The length changes of the specimens were measured at 1, 3, 7, 14, 28, 56, and 112 days.

For both types of shrinkage tests, the results were calculated by the equation 3-2:

$$S = \frac{S_n - S_i}{L_i} \tag{3-2}$$

Where
S is the shrinkage value;
S_n is the length deformation data tested after n days;
S_i is the initial length deformation data;
L_i is the length of the prism specimen.

3.6 Testing – For sound insulation applications

In this study, due to the limitation of laboratory conditions, a modified testing method has been applied in testing concrete noise reduction effect. 400mm×400mm×40mm slabs were prepared. Then impact sound reduction experiment was conducted to determine the noise reduction effects of each slab compared to the background experiment results. In this study, noise level caused by hitting the specimens with a metal ball was determined in the frequency range from 100Hz to 3150Hz. Noise level data was captured at an interval of 0.2s, and the total duration was 3s to ascertain that the maximum noise level be captured and recorded. Each test was repeated 3 times to obtain the average noise level. Figure 3-4 shows the diagram of sound insulation test method used in this study.

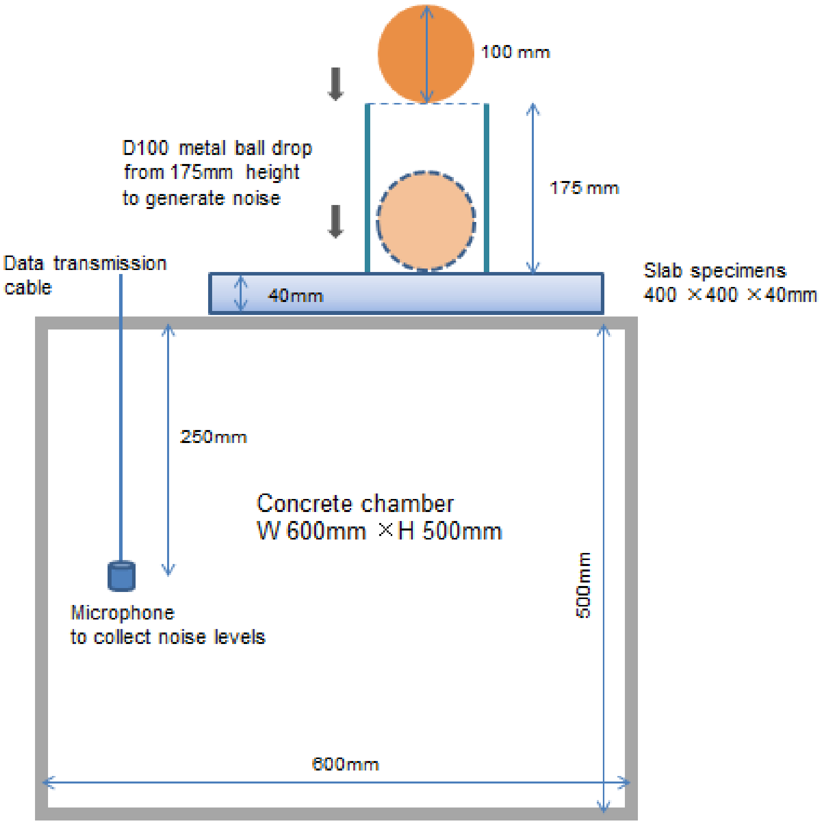


Figure 3-4 Schematic of noise reduction test setting

The dynamic modulus of rubberised concrete produced was determined in accordance with ASTM 1876. The test set up can be found in figure 3-5; a steel ball connected to a polymer rod was used to create the vibration, and the resonance frequency could be detected from the vibration curves captioned by a microphone sensor attached to the antinode of the specimen. The bar specimens were cut from the 400mm×400mm×40mm slabs, and the dimensions and the mass of each specimen were measured and recorded. The two points of support were located at 0.224L (90mm) from each end as required by standard. The dynamic Young's modulus was calculated by the equation 3-3 (Czichos et al. 2007):

$$E = 0.9465(m f_f^{\,2}/b)(L^3/t^3)T_1 \qquad (3\text{-}3)$$

Where E is the dynamic Young's modulus in Pa;
m is the mass of tested slab in g;
f_f is the resonance frequency of material in Hz;
b is the width of specimen in mm;
L is the length of specimen in mm;
t is the thickness of specimen in mm; and
T1 is the correction factor.

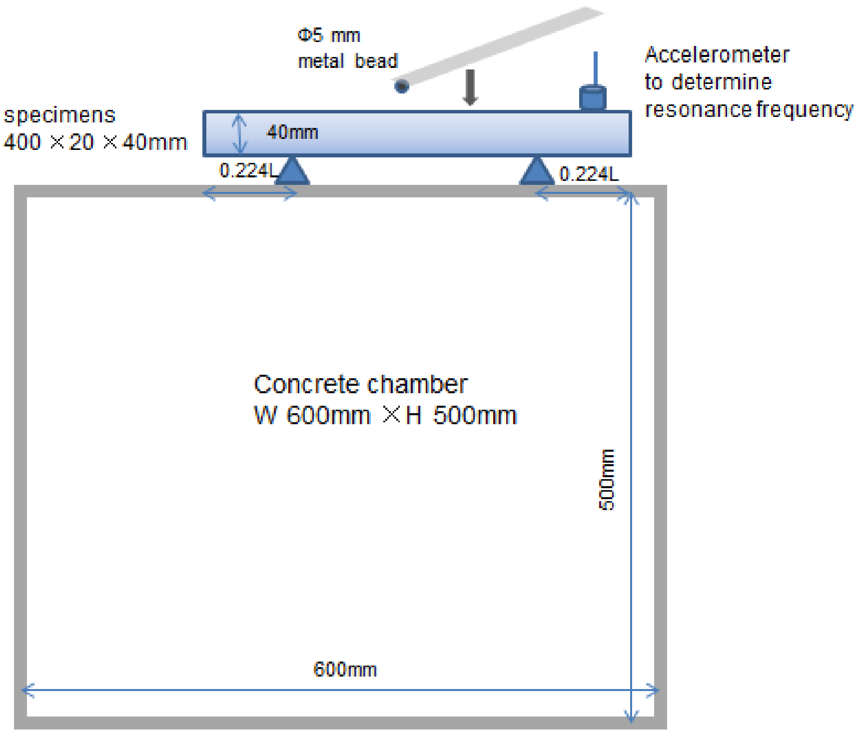


Figure 3-5 Schematic of resonance frequency test

Chapter 4. – RESULTS AND DISCUSSION

4.1 For lightweight aggregate concrete targeted at external wall applications

4.1.1 Workability

Proper fresh properties are essential for external walls constructions. The workability of lightweight aggregate concrete with FBA incorporation has been evaluated by determining the slump value of fresh mixtures. As illustrated by figure 4-1, with proper amount of superplasticizer added, it is feasible for lightweight aggregate concrete to achieve comparable slump value of conventional concrete, and with FBA incorporation, it is possible to produce lightweight aggregate concrete with 100mm to 200mm slump values.

And it can be seen from the mixture design that lightweight aggregate concrete required less amount of superplasticizer to obtain acceptable slump values than conventional concrete, which can be attributed to the round shape and smooth surface of the lightweight aggregate.

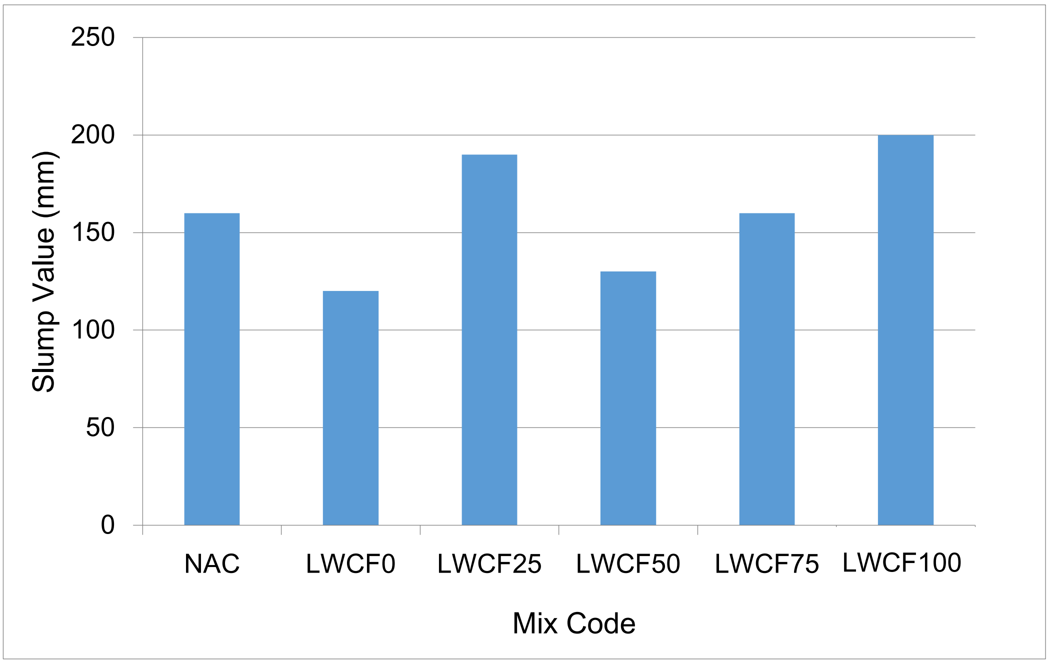


Figure 4-1 Slump test results of normal aggregate concrete and lightweight aggregate concrete without silica fume incorporation

The slump test of group 1 mixtures proved that it is possible to produce FBA incorporated lightweight aggregate concrete with acceptable workability for common construction works, while in group 2, as illustrated by the mixture design, the w/c ratio for normal aggregate concrete and lightweight aggregate concrete were kept constant (0.34), and with different FBA content, the amount of superplasticizer were also kept constant for NAC (6.38L/m^3) and for LWC (3.20L/m^3), the figure 4-2 shows the slump test results for both NAC and LWC as 0 to 100% fine aggregate, it can be seen from the figure 4-2 that the increased FBA content resulted in higher slump value. At the dosage of superplasticizer mentioned above, lightweight aggregate concrete mixture with 50% or higher FBA replacing natural fine aggregate showed no less than 100mm slump values.

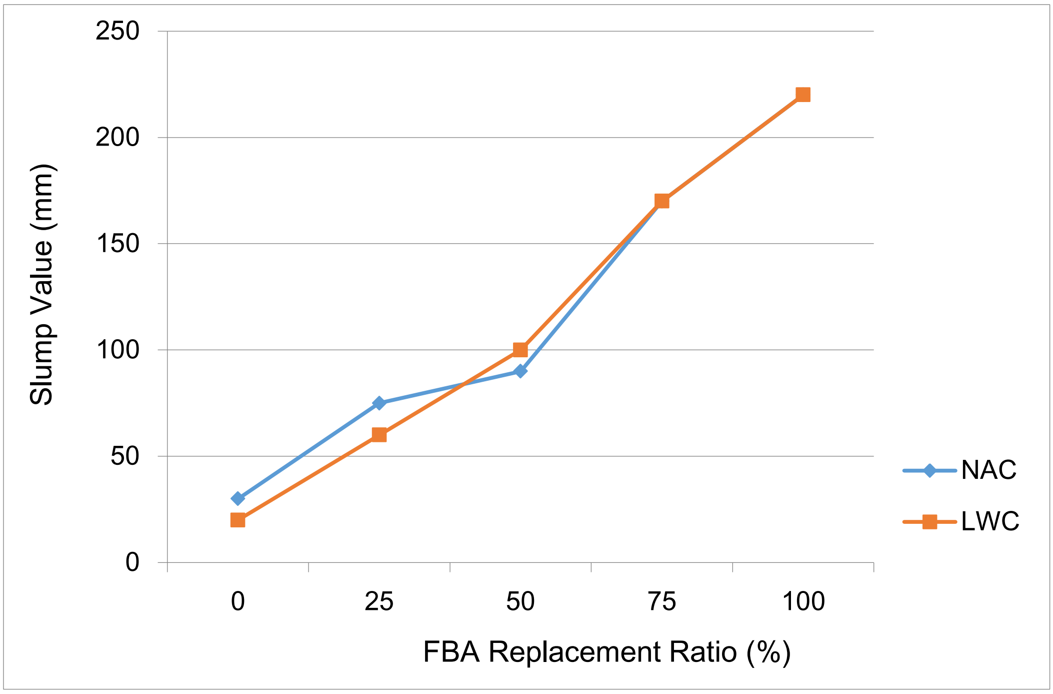


Figure 4-2 Correlation between slump value of fresh concrete mixtures and FBA replacement ratio in normal aggregate concrete and high strength lightweight aggregate concrete with silica fume incorporation

4.1.2 Density

The density is another important index for external walls materials as a lower self-load helps to reduce the labor cost as well as the transportation cost. The density test results of the lightweight aggregate concrete developed in this study aimed for external walls applications are presented by figure 4-3 and figure 4-4. The data illustrated in the figure 4-3 indicated that by using lightweight aggregate to replace natural coarse aggregate, the concrete density can be lowered from about 2,300 kg/m^3 to about 1,800 kg/m^3. Furthermore, when using a higher volume of FBA to replace natural crushed fine stone, the concrete specimens can attain an oven-dried density value of about 1,500 kg/m^3 as a reasonable result due to the lower density of FBA than crushed fine stone which is used as natural fine aggregate in this study.

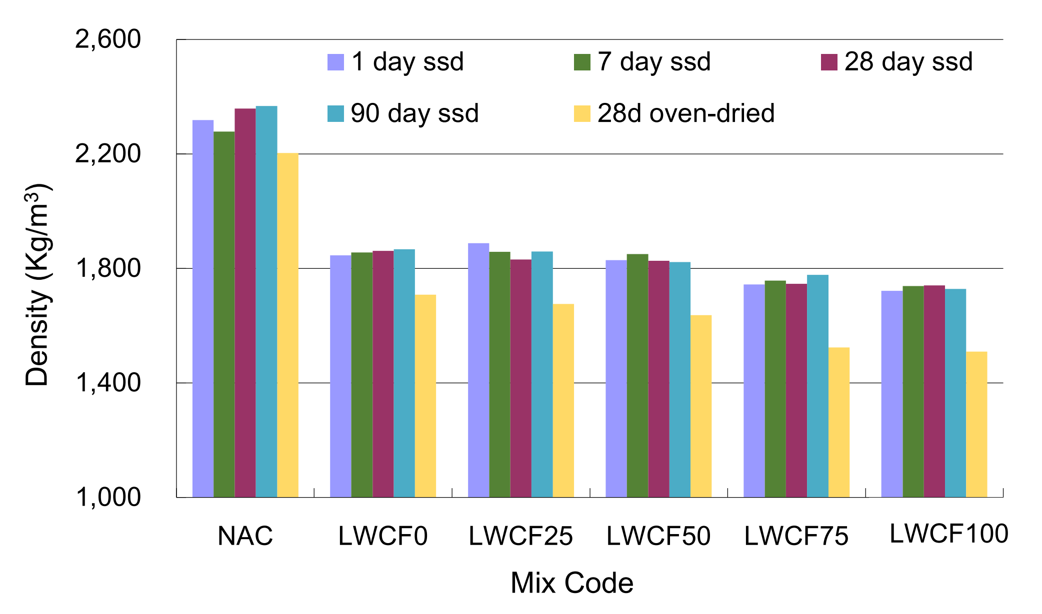


Figure 4-3 Surface Saturated Density and Oven-dried Density test results of normal aggregate concrete and lightweight aggregate concrete without silica fume incorporation

The data illustrated by the figure 4-4 indicated that when the natural coarse aggregate was replaced by the lightweight aggregate, the 28-day surface-saturated density (ssd density) can be lowered from 2,365 kg/m^3 to 1,864 kg/m^3. When FBA was used to replace crushed fine stones as the fine aggregates, the ssd density can be further reduced to 2,279 kg/m^3 in the NAC series and 1,733 kg/m^3 in the LWC series.

In terms of oven-dried density (od density), the NAC with 100% FBA incorporation (mixture coded NAC_F100) had an od density of 2,205 kg/m^3 after 28 days of curing, while for the LWC series, the od density can be lowered to 1,618 kg/m^3.

The results of the density test show that decreased density values were noted with an increase in FBA content, which was due to the lower density of the FBA aggregate compared to the natural crushed fine stone. Similarly, due to the lower density of the lightweight aggregate, at the same FBA replacement ratio, the concrete in the LWC series always showed lower density than the counterpart specimens in the NAC series.

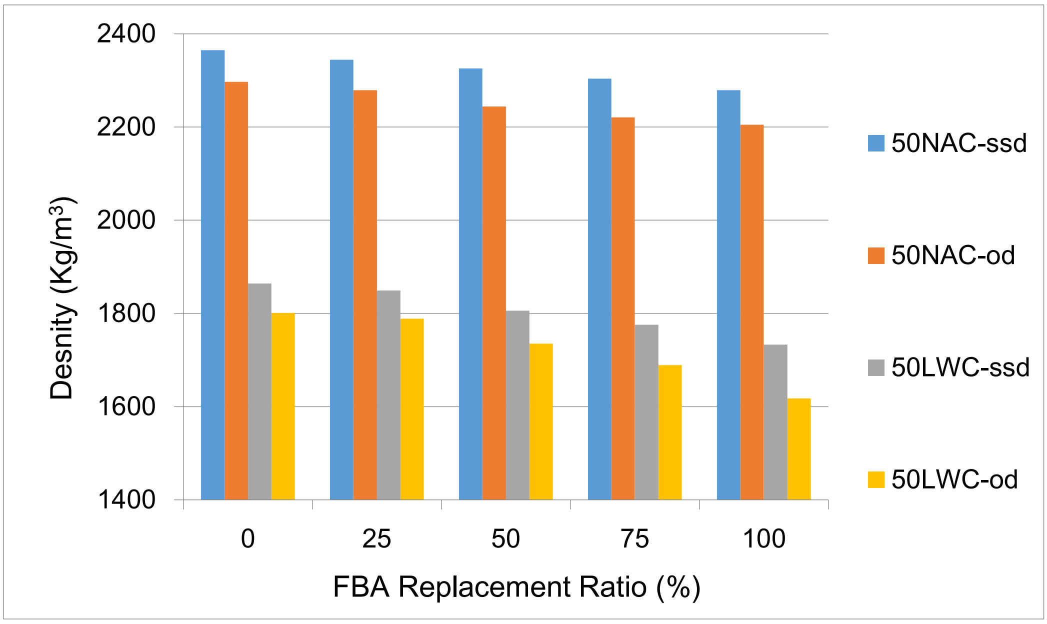


Figure 4-4 Surface Saturated Density and Oven-dried Density test results of water cured normal aggregate and high strength lightweight aggregate concrete specimens with FBA incorporation at 28 days curing age

4.1.3 Compressive strength

As external walls, proper strength shall be achieved in order to support the structure. In this study, the compressive strength of the mixtures was tested as the one of the most important parameters to evaluate the mechanical properties of concrete.

The figure 4-5 shows the compressive strength test results for low strength lightweight aggregate concrete without silica fume incorporation.

From the figure 4-5 it can be seen that with increased curing age, the compressive strength of the concrete mix increased gradually. The data illustrated in the figure also indicated that the concrete with a higher volume of FBA incorporation had lower compressive strength.

However, even when 100% FBA was used to replace natural fine aggregate, a 28 d compressive strength of higher than 30 MPa could still was achieved.

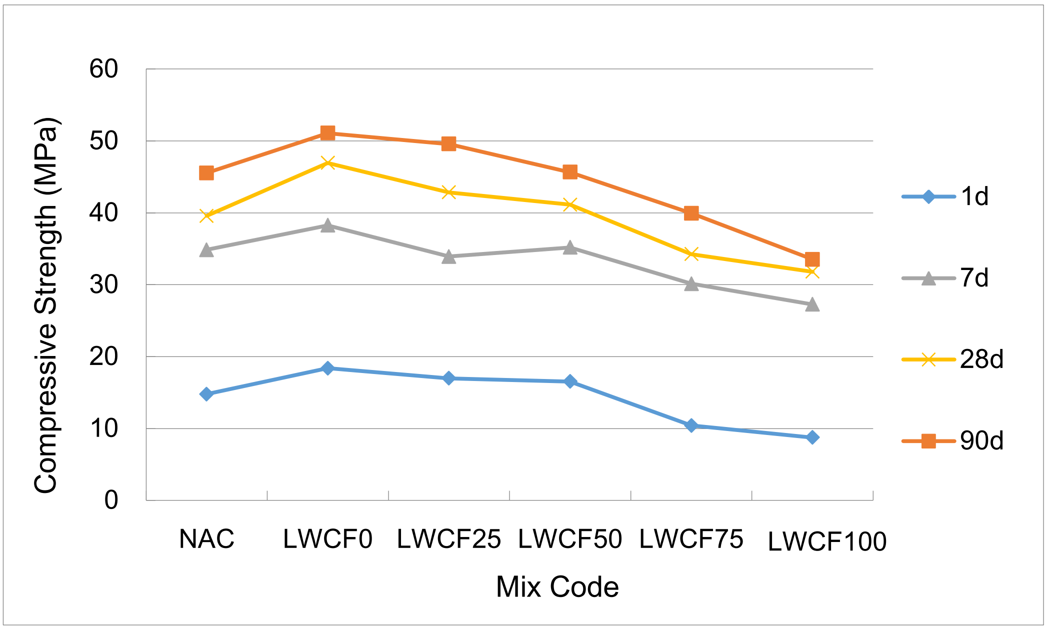


Figure 4-5 Compressive strength test results of normal aggregate concrete and low strength lightweight aggregate concrete without silica fume incorporation

According to American Concrete Institute (ACI) Committee Report 213 “Guide for Structural Lightweight-Aggregate Concrete” (Ries et al. 2010) lightweight aggregate concrete with a 28 d compressive strength of higher than 17 MPa can serve as structural concrete, which means that even with silica fume incorporation the lightweight aggregate concrete produced in this study already had acceptable strength for some construction works. With silica fume incorporation higher strength can be achieved.

The 28 days and 90 days compressive strength test results of high strength normal aggregate concrete and lightweight aggregate concrete is presented by figure 4-6 and figure 4-7.

Duplicated samples of the silica fume incorporated mixtures were prepared and both water curing and air curing were applied, in the figures, the water cured samples are coded "-w" and the air cured samples are coded "-a". It can be seen that with the incorporation of 10% (by weight of cement) silica fume, concrete obtained relatively high compressive strength compared to the compressive strength the lightweight aggregate concrete without silica fume obtained.

After 28 days of curing, even with 100% FBA incorporation, the NAC concrete attained compressive strength values of about 70 MPa, and the LWC concrete also showed no less than 45 MPa in compressive strength test. These indicate that all the concrete mixtures prepared are suitable for structural uses in terms of compressive strength. Also, as the curing age increased to 90 days, all the concrete mixtures experienced further strength development.

The figures also show that, for concrete in the NAC series, when small amounts (less than 50%) of FBA were incorporated to replace natural crushed fine stone, the concrete showed slightly higher compressive strength than the control mix without FBA incorporation. But when higher volumes of FBA were added, strength loss occurred. For the concrete mixtures prepared with FBA replacing 100% natural fine aggregate, more than 10MPa strength reduction was noted compared to the mixture with 25% FBA aggregate incorporation. In LWC series, only a slight difference in the compressive strength values of the mixtures prepared with different amounts of FBA was noticed. The test results indicated that FBA is suitable to replace natural fine aggregate in concrete, especially in the lightweight aggregate concrete, without inducing severe strength loss.

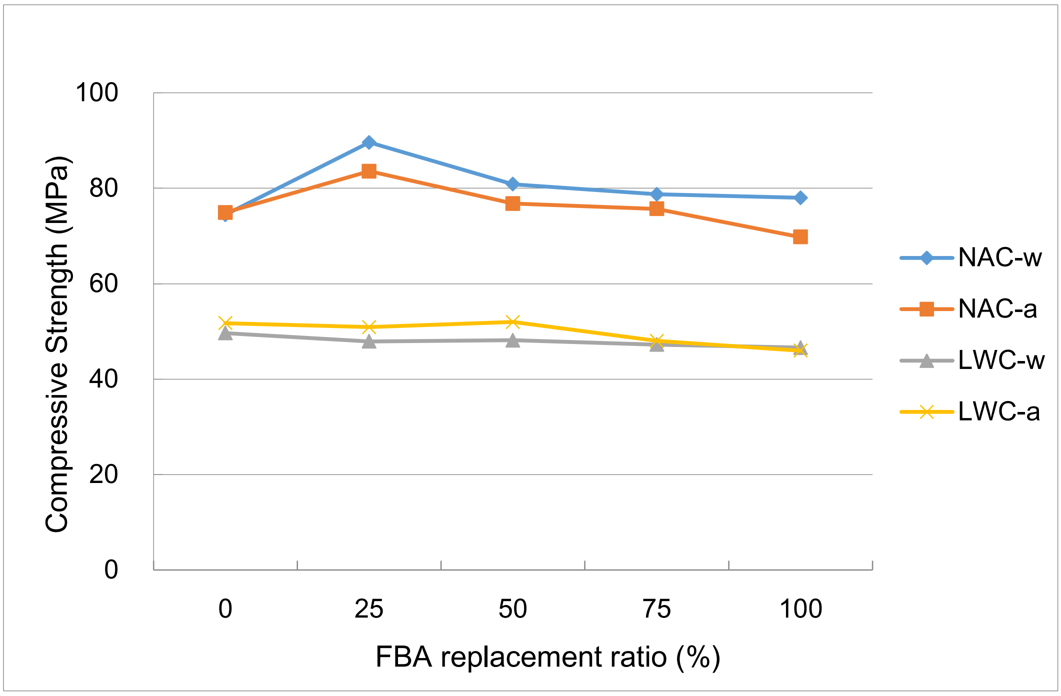


Figure 4-6 28 days Compressive strength test result of normal concrete and high strength lightweight aggregate concrete specimens with FBA incorporation cured at two different conditions

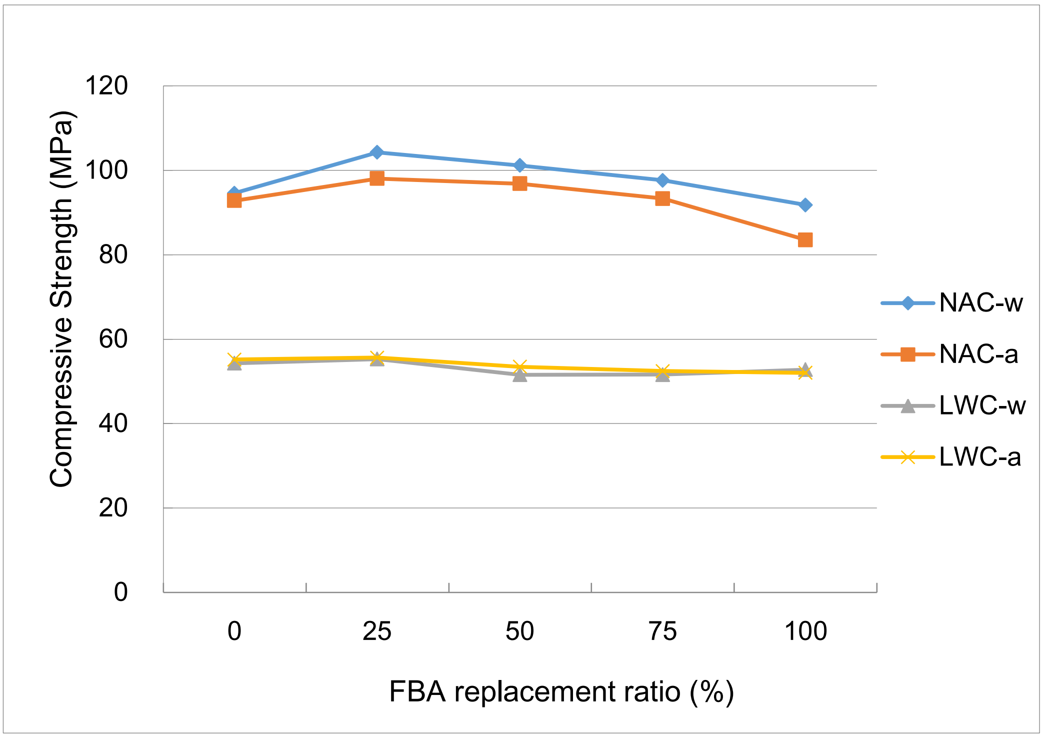


Figure 4-7 90 days Compressive strength test result of normal concrete and high strength lightweight aggregate concrete specimens with FBA incorporation cured at two different conditions

A non-linear relationship between FBA replacement ratio and concrete strength is noticed. It can be seen from the slump test results that the slump values for each mixture were different; the slump value for the NAC without FBA was low, while the slump values of NAC with 25% FBA and 50% FBA were higher than the control mix. Besides the lower density and different chemical compositions, the FBA aggregate used also had a different particle size distribution compared to the crushed fine stones, as listed in the table 4-1, it can be seen that FBA incorporation changed the grading of the fine aggregates.

Table 4-1 Calculation of grading indicated as cumulative retained and Fineness Modulus for each FBA replacement ratio as a combination of FBA and natural fine aggregate

Mix proportions		F0C100	F25C75	F50C50	F75C25	F100C0
Cumulative	10 mm	0.0	0.0	0.0	0.0	0.0
Retained	5 mm	3.1	6.6	10.1	13.5	17.0
(%)	2.36 mm	33.2	34.6	36.0	37.3	38.7
	1.18 mm	55.9	55.6	55.2	54.8	54.4
	600 um	73.2	70.9	68.7	66.4	64.1
	300 um	85.9	82.4	79.0	75.5	72.1
	150 um	93.7	90.4	87.1	83.9	80.6
	PAN	100.0	100.0	100.0	100.0	100.0
Fineness of Modulus		3.450	3.405	3.360	3.314	3.269

Figure 4-7 also illustrates the differences in compressive strength between the samples cured under different conditions. It can be seen that air cured specimens in the NAC series had slightly lower compressive strength compared to the corresponding water cured samples. For the LWC series, FBA incorporation also resulted in a slight decrease in compressive strength at both 28 days and 90 days curing ages. But air curing did not cause obvious negative impacts on concrete strength development, and after 90 days, the air cured specimens showed slightly higher compressive strength than the corresponding water cured specimens. This can be explained by the effective internal curing provided by the pre-wetted lightweight aggregate.

Similar results had been reported (Mouli & Khelafi 2008) in previous research works, it was found out that when a type of natural pozzolanic materials sourced from natural deposits in North West of Algeria was used to replace natural aggregate in concrete, when the replacement ratio was 20%, the optimal strength was achieved, whilst when the replacement ratio was higher than 40%, strength loss occurred compared to the control mix.

4.1.4 Modulus of elasticity

As external wall materials, the stiffness of concrete is also of great importance in terms of concrete mechanical behavior evaluation. In this study, modulus of elasticity (E-value) was selected as the indicator of concrete stiffness.

The figure 4-8 shows the test results of 28 days and 90 days E-values of the low strength lightweight aggregate concrete prepared with no silica fume incorporation.

The data illustrated in the figure 4-8 shows that by using the lightweight aggregate, a significant decrease in E-values was noticed due to the lower density of the lightweight aggregate compared to the natural aggregates. Regarding the effect of FBA replacement ratio, the E-values of the concrete mixtures further was decreased linearly with the increase of FBA content. The data also shows that for all the concrete mixes, after 90 days curing, higher E-values were achieved compared to the specimens tested after 28 days curing, attributed to the continued hydration process of the cementitious systems. However, for the lightweight aggregate mixture with 100% FBA replacing the natural fine aggregate, the 28 days and 90 days E-value decreased to less than 15GPa, which were only about half of the E-value of the conventional concrete (29GPa at 90 days test age). Even though the compressive strength of lightweight aggregate concrete with high content of FBA was acceptable for structural use, the stiffness needs to be further improved.

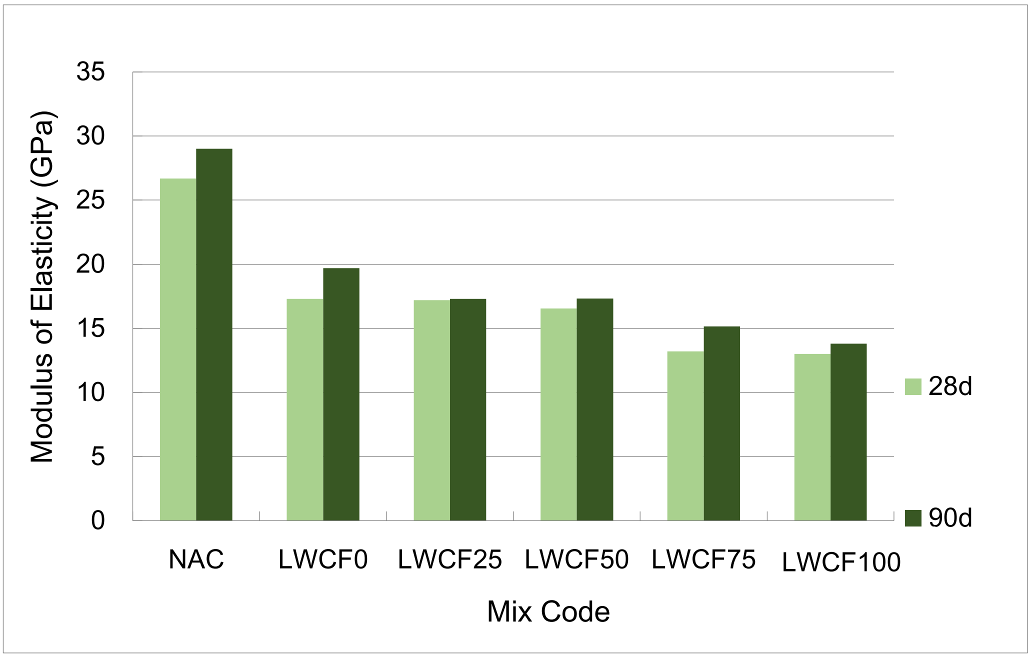


Figure 4-8 Modulus of Elasticity test results of low strength lightweight aggregate concrete without silica fume incorporation

The E-value of high strength lightweight aggregate concrete and the E-value of normal aggregate concrete is presented by figure 4-9.

It can be seen from figure 4-9 that the concrete stiffness was improved as the curing age increased, and the specimens tested after 90 days curing showed higher E-values than the 28 days curing. The results also indicate that FBA incorporation led to lower stiffness values for both NAC and LWC concrete. In NAC series, when all the fine aggregate was natural aggregate, an E value of more than 40 GPa was attained after 90 days of water curing; but the E-value decreased to less than 30 GPa when all the fine aggregate was replaced by FBA. Similarly, in the LWC series, FBA incorporation led to a stiffness reduction of about 30% when FBA was used to replace the natural fine aggregate. For the high strength lightweight aggregate concrete with 100% FBA as fine aggregate, even after 90 days water curing, only less than 20 GPa E-value was achieved.

When comparing the concrete mixtures prepared with the same FBA replacement ratio, it can be seen from figure 4-9 that the NAC series concrete had higher stiffness than the LWC concrete, which can be attributed to the lower stiffness of the lightweight aggregate.

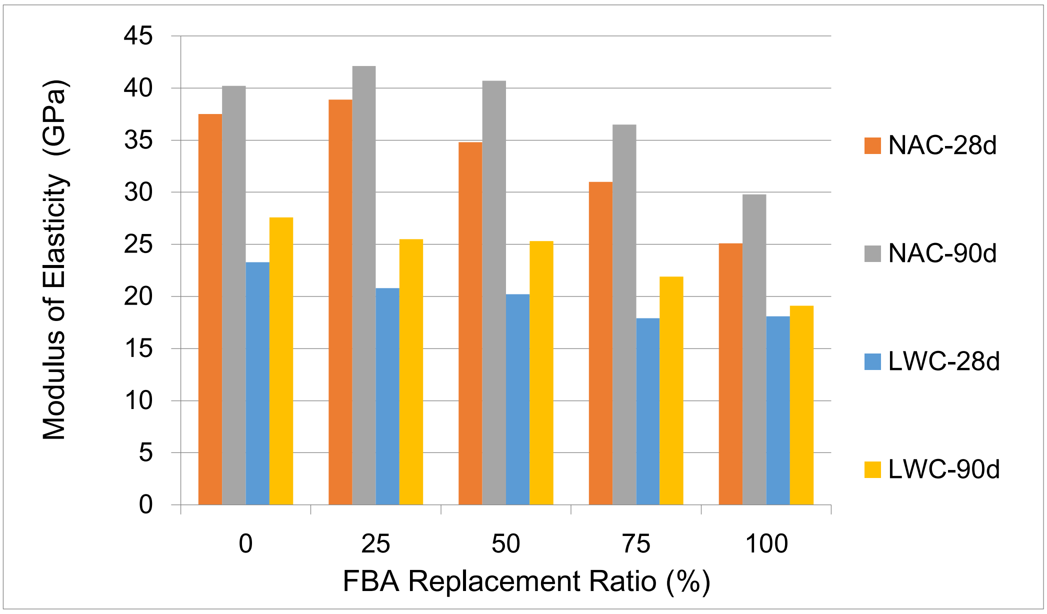


Figure 4-9 Coefficient between the FBA incorporation rate and modulus of elasticity of high strength normal aggregate concrete and lightweight aggregate concrete at 28 days and 90 days

Though, by comparing the E-value test results of the lightweight aggregate concrete with and without silica fume incorporation, it can be seen that adding silica fume in the mixture at an amount of 10% of cement content led to higher stiffness. For example, for the lightweight aggregate concrete with no FBA incorporation, the mixture without silica fume only achieved slightly less than 20GPa E-value after 90 days water curing, the mixture with silica fume achieved 25.5GPa E-value at the same curing age; the lightweight aggregate concrete with FBA replacing all natural fine aggregate had an E-value of 13.8GPa at 90 days test age while when silica fume added the detected E-value increased to 19.1GPa, which was around 38% enhancement.

The E-value test results for the two groups of mixtures in this study showed that silica fume has obvious stiffness enhancement effect on this type of lightweight aggregate concrete.

4.1.5 Strength effectiveness

In the previous subsections, both the density and the compressive strength of concrete have been tested. In this subsection, the strength effectiveness of the mixtures prepared in this study is evaluated.

The parameter used to evaluate the strength effectiveness is f_c/D ratio calculated as the compressive strength in MPa divided by ssd density in g/cm^3, which indicates the level of strength provided by a unit weight of concrete.

The strength effectiveness of the lightweight aggregate concrete prepared without silica fume is presented by figure 4-10.

The strength effectiveness of the high strength normal aggregate concrete and the lightweight aggregate concrete is presented by figure 4-11. Both the water cured specimens and the air cured specimens were evaluated.

The figure 4-10 shows the correlation between FBA incorporation and f_c/D ratio of the low strength lightweight aggregate concrete without silica fume incorporation. With FBA replacing 0 to 100% natural fine aggregate, the lightweight aggregate concrete produced in this group achieved f_c/D ratios of 18.3 to 25.2 after 28 days water curing, and the ratio increased to 19.4 to 27.4

after 90 days curing.

A negative linear relationship between the FBA incorporation and the strength effectiveness of concrete was found as showed by the trend line in Figure 4-10. With the increased amount of FBA, the strength effectiveness of lightweight aggregate concrete decreased, which indicated that FBA has a less strength effectiveness than the natural fine aggregate used in this study (crushed fine stone), this is mainly because of that FBA aggregate had a surface saturated dried density of 2208Kg/m^3, which was about 80% of the density of crushed fine stone, and thus it had less obvious effect on concrete unit weight reduction compared to the lightweight aggregate.

Compared to the values obtained by some of previous research works listed in Chapter 2, the present study is able to produce lightweight aggregate concrete with comparable or higher strength effectiveness.

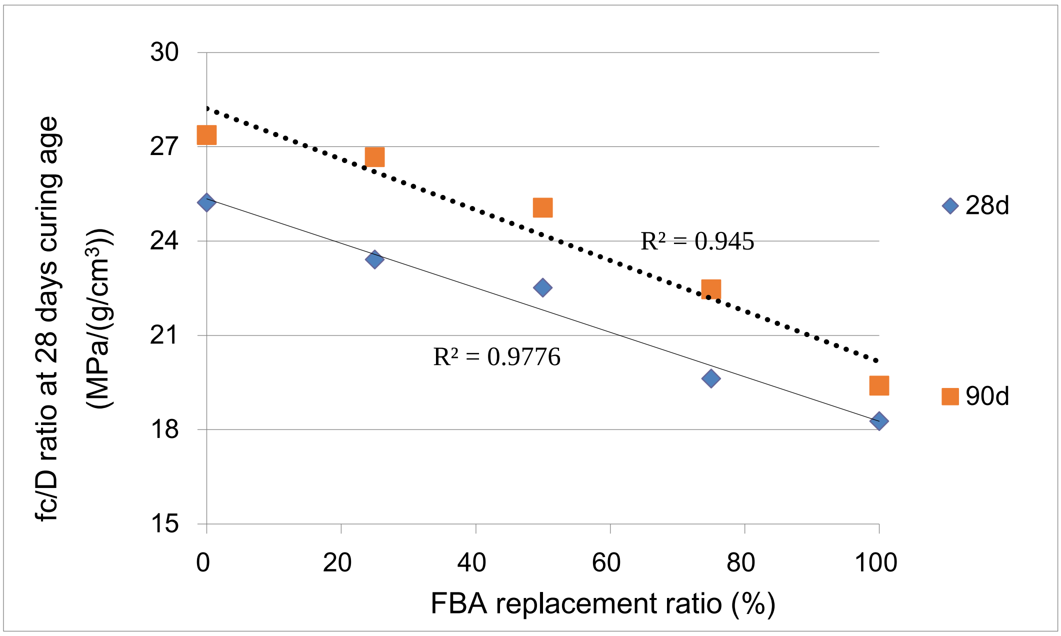


Figure 4-10 Correlation between fc/D ratio and FBA incorporation in low strength lightweight aggregate concrete without silica fume incorporation

As illustrated by figure 4-11, the silica fume incorporated concrete mixtures showed satisfactory f_c/D values after 28 days water curing, which indicates that all the concrete mixtures are mechanically effective.

While when comparing the strength effectiveness of the normal aggregate concrete and the high strength lightweight aggregate concrete with silica fume, it can be seen from figure 4-11 that with the same cement content and w/c ratio, a unit weight of normal aggregate concrete provided higher compressive strength than the lightweight aggregate concrete, which can be attributed to the lower stiffness of the lightweight aggregate.

However, unlike shown by figure 4-10, there is no obvious linear relationship between the FBA incorporation and the strength effectiveness detected for the high strength lightweight aggregate concrete and normal aggregate concrete as illustrated by figure 4-11.

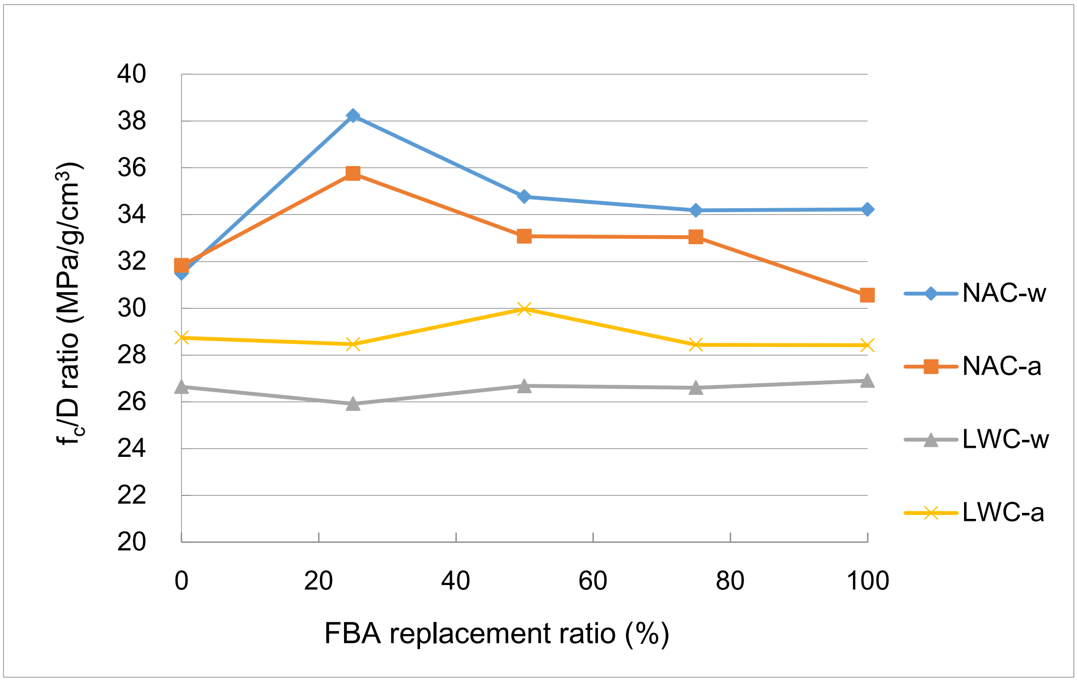


Figure 4-11 f_c/D ratio of concrete in high strength normal aggregate concrete and lightweight aggregate concrete with silica fume incorporation at 28 days curing age under water curing and air curing schemes

The strength effectiveness evaluation in this study showed that for the low strength lightweight aggregate concrete with similar slump values, the incorporation of FBA aggregate showed negative impacts on the concrete strength effectiveness; while for the silica fume incorporated high strength mixtures with a constant dosage of superplasticizer but different slump values, FBA replacement ratio of natural fine aggregate showed non linear coefficient on the strength effectiveness of the concrete mixtures.

4.1.6 Chloride ion penetration

As external wall materials, durability properties are important to ascertain proper service life as the concrete has bigger chance to be exposed to chemical attacks. In this study, the chloride ion penetrability is used for concrete durability evaluation.

The accelerated chloride ion penetration test results of both low strength lightweight aggregate concrete and high strength mixtures are illustrated by the figures 4-12 and 4-13.

From the figure 4-12, it can be seen that by using lightweight aggregate as the coarse aggregate, high level chloride ion penetrability was resulted even after 90 days of hydration, when the lightweight aggregate was used as coarse aggregate, the charge passed of all mixtures exceeded 4000 coulombs as a result of the porous structure of the lightweight aggregate. A positive linear correlation between the replacement ratio of natural fine aggregate crushed fine stone by FBA and the detected charge passed (coulombs) can also be seen from the figure, which demonstrated that higher volumes of FBA incorporation had a negative impact on the concrete durability properties.

The reduced resistance to chloride ion penetration with an increase in FBA aggregate content can be attributed to the higher volume of pores and the higher water absorption characteristics of the FBA aggregate compared to that of the natural crushed fine stone.

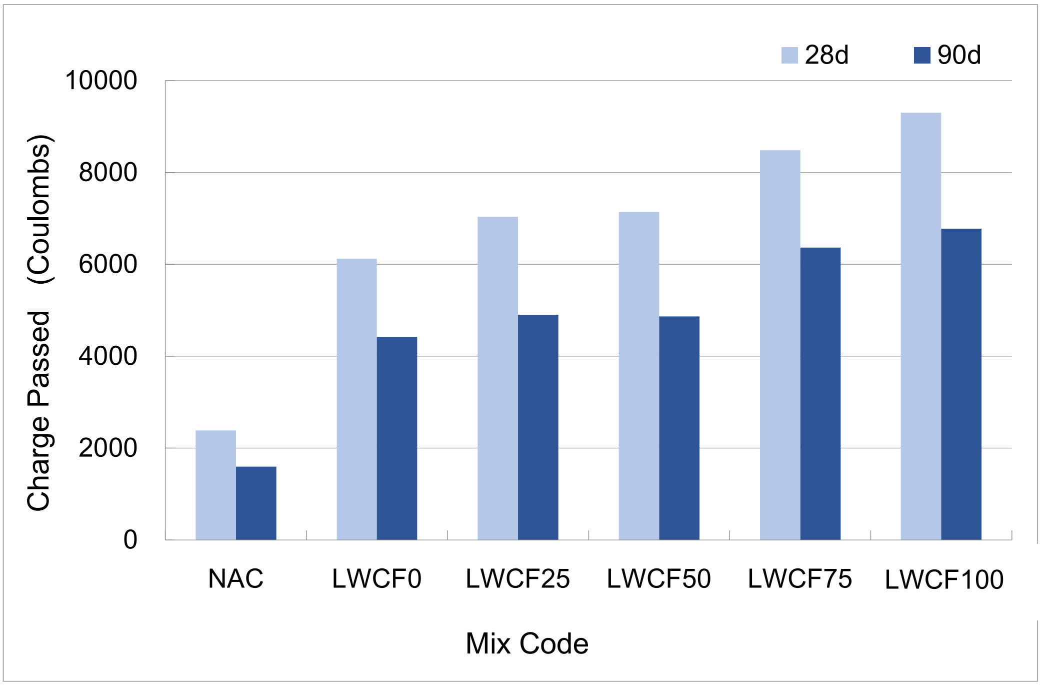


Figure 4-12 Chloride ion permeability test results of low strength lightweight aggregate concrete without silica fume incorporation

The accelerated chloride ion penetration test results of high strength normal aggregate mixtures and lightweight aggregate mixtures from figure 4-13 showed that the use of silica fume not only had positive impact on the hardened concrete strength and stiffness enhancement but also showed significant effect on improving the impermeability of concrete mixtures.

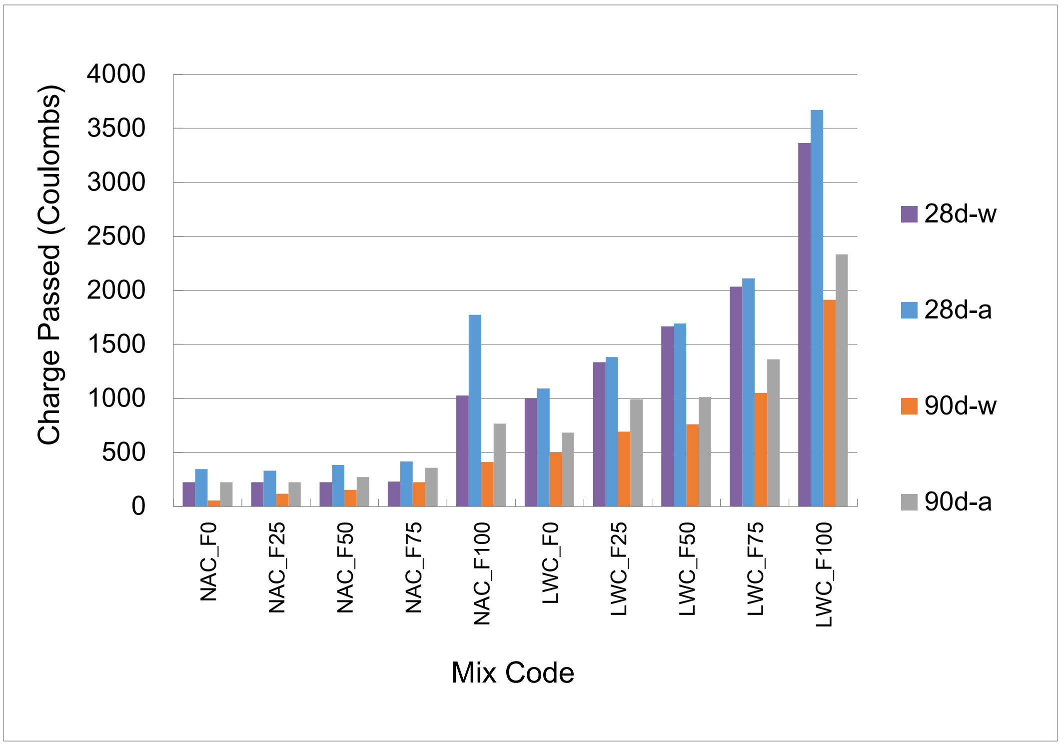


Figure 4-13 Chloride ion penetration test result of normal aggregate concrete and high strength lightweight aggregate concrete with FBA incorporation

As shown by the figure 4-13, when lightweight aggregate was used to replace the natural aggregate, the chloride ion permeability was increased.

FBA incorporation increased the chloride ion permeability due to the porous nature of FBA. It can be seen from the figure that for normal aggregate concrete and for lightweight aggregate concrete under either water curing or air curing conditions, higher charge passed volume was detected with higher FBA content. This is consistent with the findings in previous research work (Kou & Poon, 2009). It was also noticed that the increased charge passed volume from 75% FBA to 100% FBA was steeper than the increase rate between the concrete mixtures with lower FBA contents.

Different curing conditions also affected the permeability. For both normal aggregate concrete and lightweight aggregate concrete, it was noticed that the air cured specimens always showed higher permeability than the water cured specimens.

Comparing the accelerated chloride ion penetration test results for the low strength lightweight aggregate concrete and for the high strength mixtures, it can be seen that at each FBA replacement ratio, silica fume reduced the charge passed volume of the lightweight aggregate mixtures significantly. For example, for the lightweight aggregate concrete mixture with 0 FBA, after 90 days of hydration, the specimen without silica fume incorporation had 4422 coulombs charge passed volume; but with 10% silica fume (weight of cement) added, the value decreased to 410, which was less than 10% compared to the specimen without silica fume incorporation. Even when all the fine aggregate was replaced by the porous FBA aggregate, 10% silica fume helped to decrease the charge passed volume from 6774 coulombs to 1914 coulombs, which changed the ASTM C1202 classification of chloride penetrability level from “high” to “low”.

A conclusion can be drawn that the use of silica fume in the concrete mixes decreased the chloride-ion permeability significantly. Actually for all the silica fume incorporated mixtures, after 90 days of hydration, all the specimens achieved “moderate” or better level classification.

4.1.7 Thermal insulation properties

In subtropical regions like Hong Kong, a large percentage of total energy input is being consumed for air cooling systems in buildings. With improved thermal insulation properties, the FBA incorporated lightweight aggregate concrete can be used as building envelop materials to save energy use in buildings.

One advantage of using lightweight aggregate in concrete is the improved insulation properties of LWC, including both acoustic insulation and thermal insulation. In this subsection, thermal insulation properties of lightweight aggregate concrete will be investigated and discussed.

As illustrated by figure 4-14, under the constant temperature difference and relative humidity conditions, the normal aggregate concrete had a higher heat flux value than the lightweight aggregate concrete, which indicates that the lightweight aggregate concrete had better thermal insulation properties than the normal aggregate concrete.

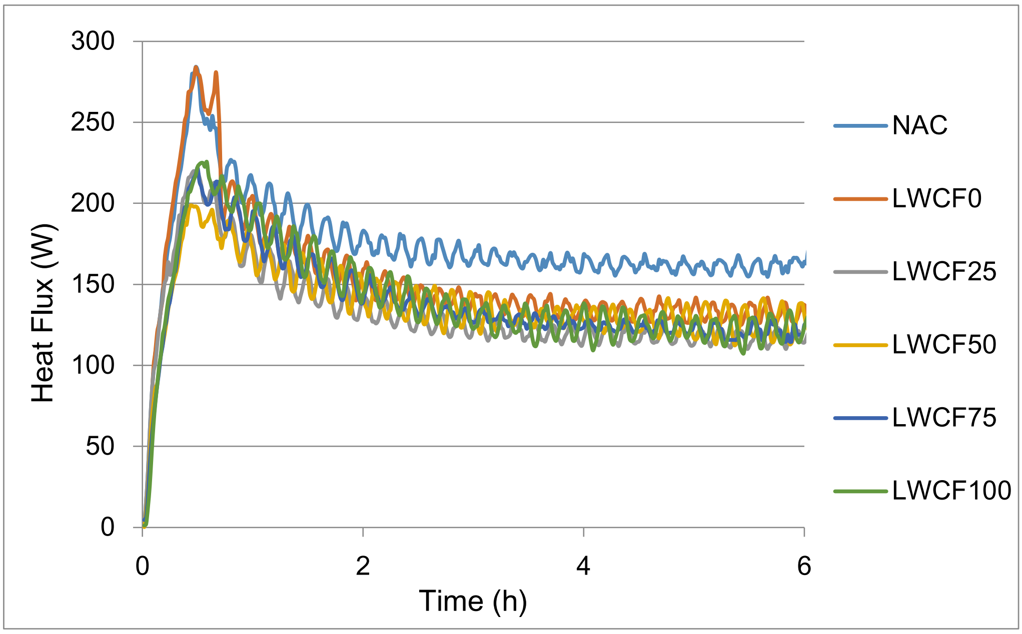


Figure 4-14 Heat flux of normal aggregate concrete and low strength lightweight aggregate concrete without silica fume incorporation

After the temperature difference reached stable, the surface temperature of slabs was tested and the thermal conductivity (K-value) of the slabs was calculated.

The coefficient between K-value and the FBA incorporation in low strength lightweight aggregate concrete is plotted as illustrated by the figure 4-15, It can be noticed from the figure 4-15 that by replacing natural coarse aggregate with lightweight aggregate, the K-value can be lowered from more than 0.9 W/mK to around 0.65 W/mK. With FBA incorporation, the thermal conductivity decreased with increasing FBA content, which can be attributed to the lower density and higher porosity of FBA compared to the natural crushed fine stone. When 100% FBA was used to replace natural fine aggregates, the thermal conductivity was further reduced to less than 0.5 W/mK.

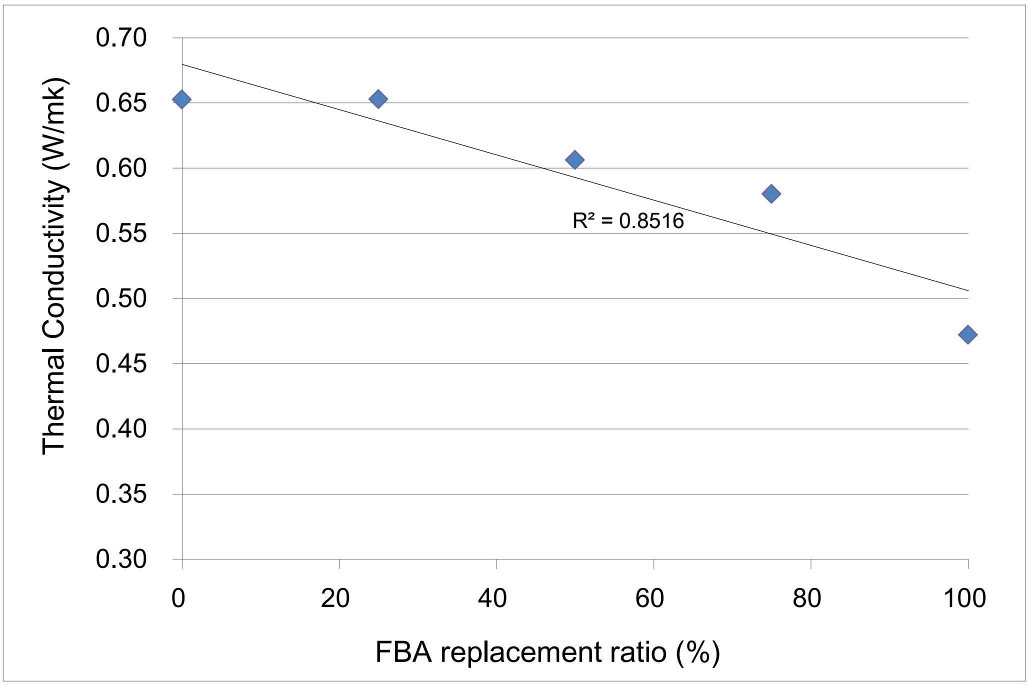


Figure 4-15 Correlation between FBA incorporation % and thermal conductivity values in low strength lightweight aggregate concrete without silica fume incorporation

The correlation between concrete oven-dried density and thermal conductivity is illustrated in figure 4-16.

An ACI guide suggested that concrete thermal conductivity is associated with the oven-dried density as illustrated by the equation 4-1 (ACI 122R-02 2002):

$$K = 0.072\ e^{0.00125d} \qquad (4\text{-}1)$$

Where K is the thermal conductivity in W/mK; and d is the oven-dried density of concrete in kg/m^3.

This equation reveals that in general a lower oven-dried density of concrete leads to a lower thermal conductivity. It can be seen from the figure 4-16 that the test results in the group 1 concrete in this study matches the trend proposed by the ACI guide on Thermal Properties of Concrete and Masonry Systems. This trend has been further proven in the thermal insulation properties test results of the high strength normal aggregate concrete and lightweight aggregate concrete prepared in this study.

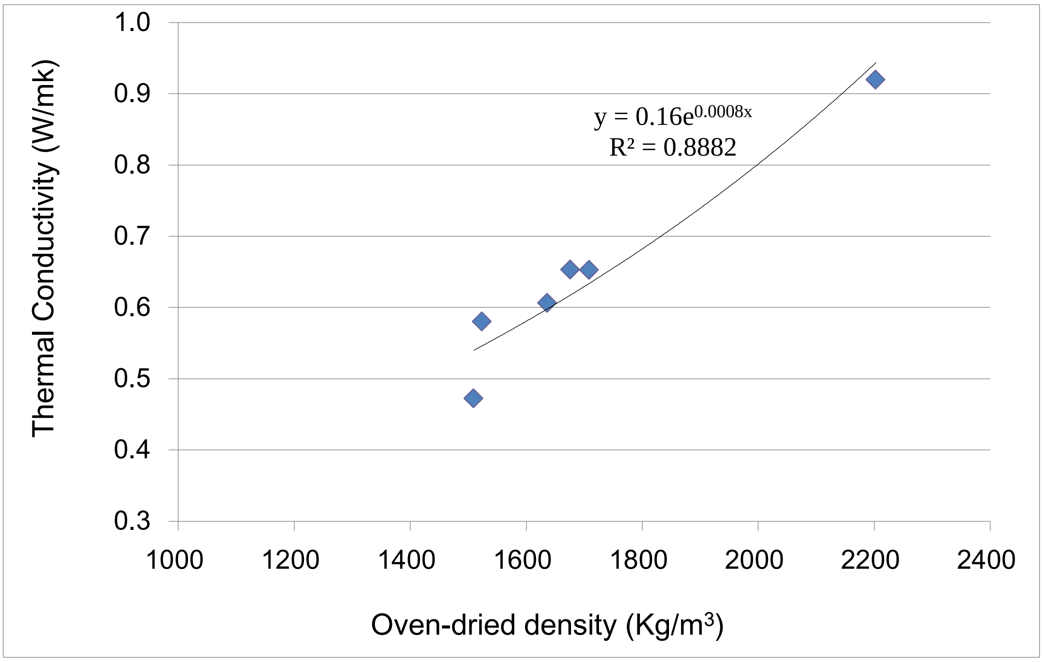


Figure 4-16 Correlation between concrete 28d oven-dried density and thermal conductivity values in low strength lightweight aggregate concrete

The heat flux test results of high strength concrete in this study are shown by figure 4-17. From figure 4-17 it can be seen that similarly to the heat flux test results obtained in the test of the low strength concrete slabs, higher heat flux was recorded for the NAC specimens than in the LWC specimens, which further proved that the lightweight aggregate concrete had better thermal insulation properties than the normal aggregate concrete.

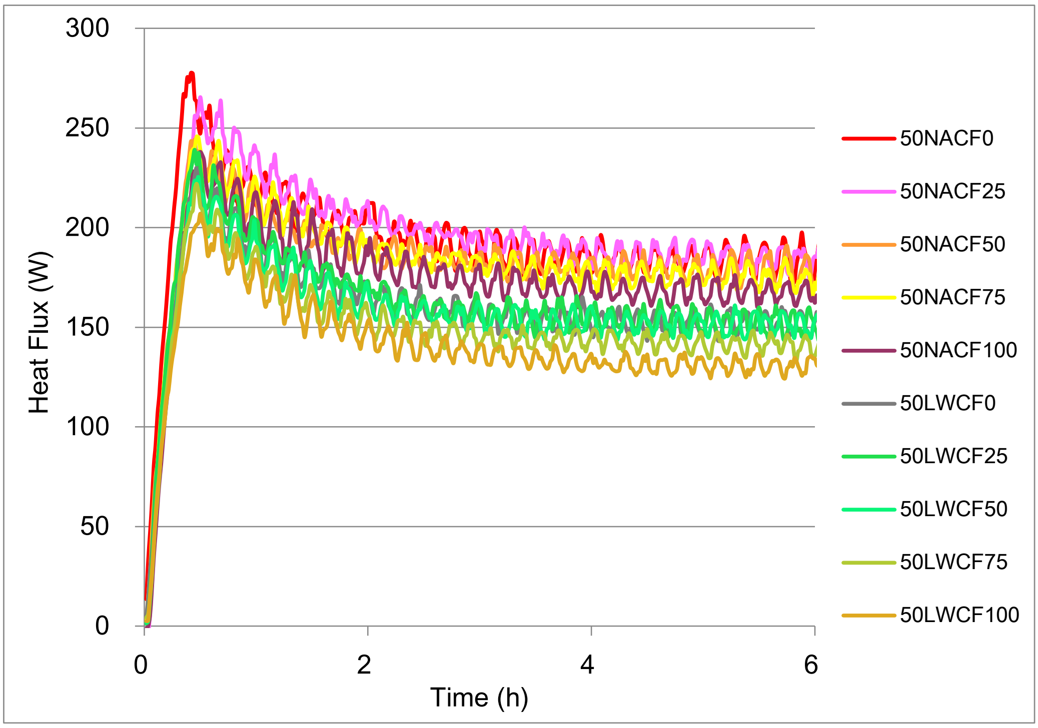


Figure 4-17 Heat flux of high strength normal aggregate concrete and lightweight aggregate concrete with silica fume incorporation

The figure 4-18 shows that the thermal conductivity K-value decreased with the increase in FBA incorporation in both the NAC and the LWC series, which was due to the lower density and higher porosity of FBA aggregate. For the NAC series, the mix with 100% FBA replacing natural crushed fine stone attained a K-value of 0.633W/mk, which was about 68% of that of the concrete without FBA. In the LWC series, the concrete prepared with all the fine aggregate replaced by FBA attained a K-value of 0.420W/mk, which is significantly smaller than the K-value of 0.622W/mk for the LWC without FBA incorporation.

The K-value test results show that both lightweight aggregate and FBA aggregate had positive effects on improving the thermal insulation properties of the concrete.

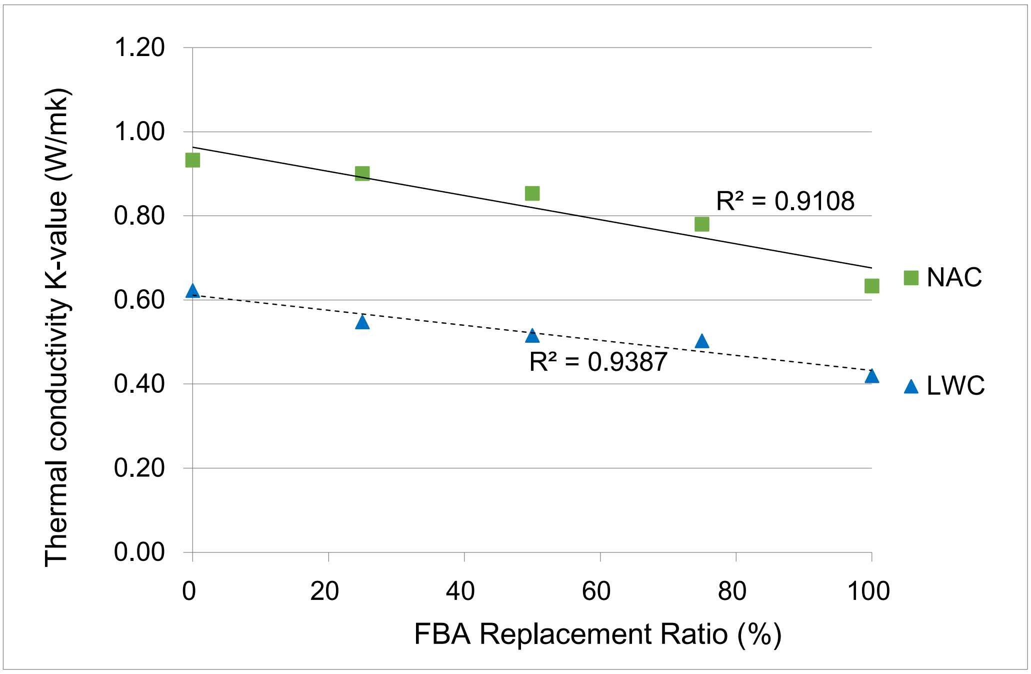


Figure 4-18 Correlation between FBA incorporation and thermal conductivity in normal aggregate concrete and high strength lightweight aggregate concrete

The correlation between concrete oven-dried density and thermal conductivity of high strength lightweight aggregate concrete and normal aggregate concrete is illustrated by figure 4-19.

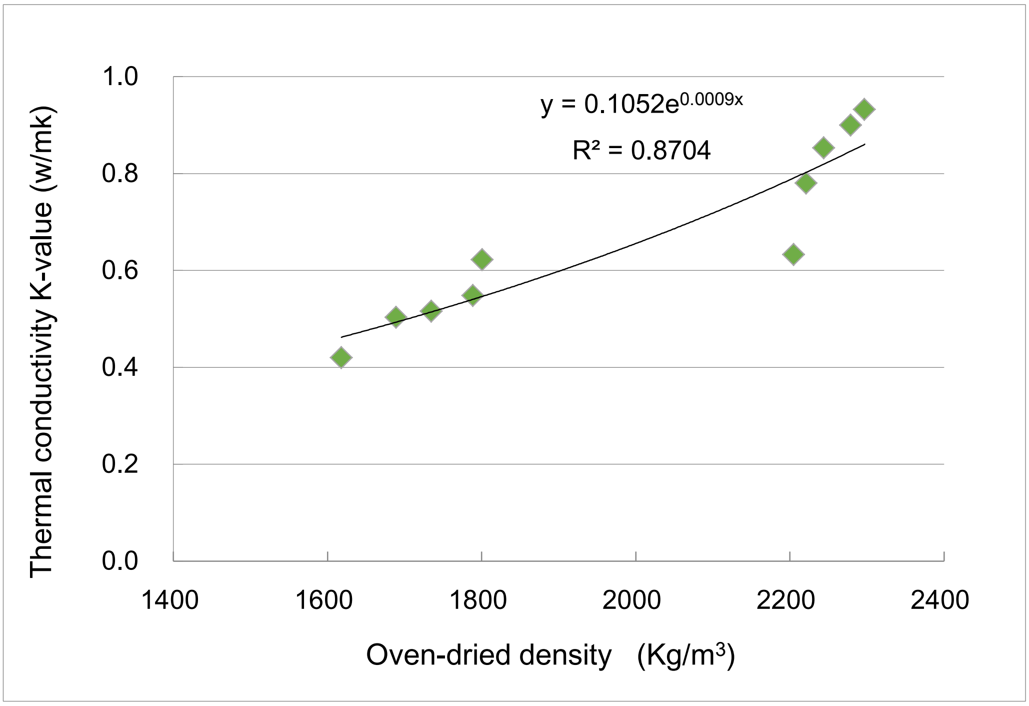


Figure 4-19 Correlation between concrete 28 days oven-dried density and thermal conductivity in normal aggregate concrete and high strength lightweight aggregate concrete with FBA incorporation

Similarly to the results obtained in the low strength concrete slabs test, it shows that lower oven-dried density values led to lower K-value and improved thermal insulation properties.

4.1.8 Shrinkage & internal curing effect

According to the previous studies as listed in the literature review chapter, the most significant effect of internal curing is the shrinkage reduction effect. In this study, drying shrinkage and autogenous shrinkage of high strength normal aggregate concrete and lightweight aggregate concrete were tested. The results are illustrated by the following figures.

The results of the drying shrinkage test from 1 day to 112 day are shown by figure 4-20 and figure 4-21 for NAC series mixtures and for LWC series mixtures, respectively. Comparing the NAC and LWC mixtures prepared with the same FBA content, it can be seen that before 14 days, the LWC mixtures showed lower drying shrinkage values than the NAC mixtures; whilst after 14 days, more length changes occurred in the LWC than in the NAC. Before 14 days, the LWC series showed less drying shrinkage due to the dispersion of water inside the system provided from the pores of the pre-wetted lightweight aggregate. But after 14 days, the LWC series exhibited higher drying shrinkage value which can be attributed to the accelerated water loss resulted from the chamber conditions.

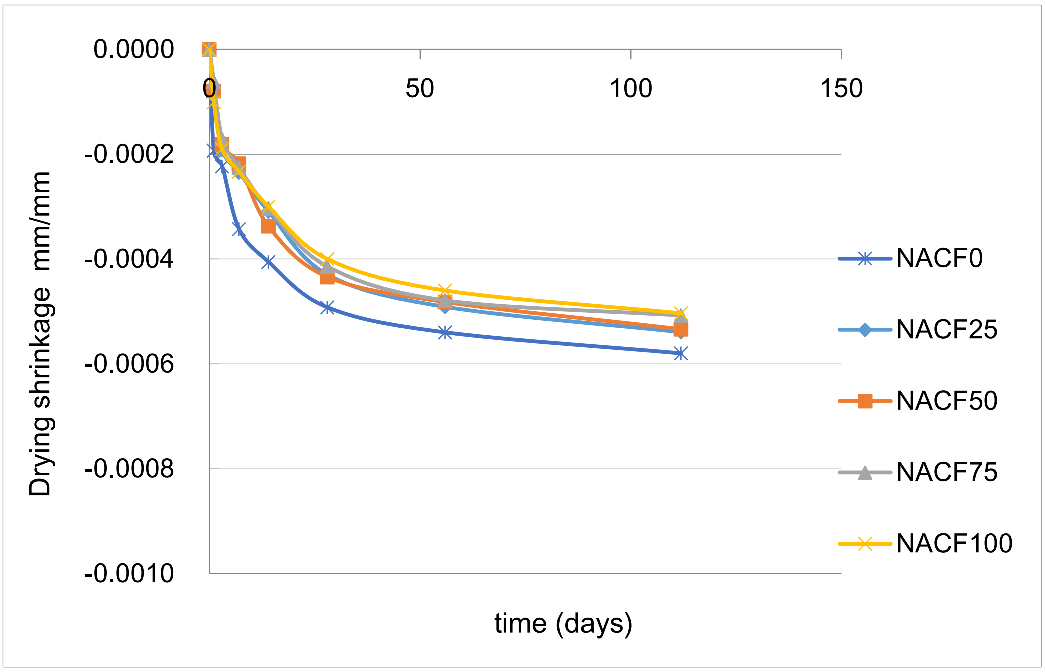


Figure 4-20 Drying shrinkage test results of high strength normal aggregate concrete with FBA incorporation

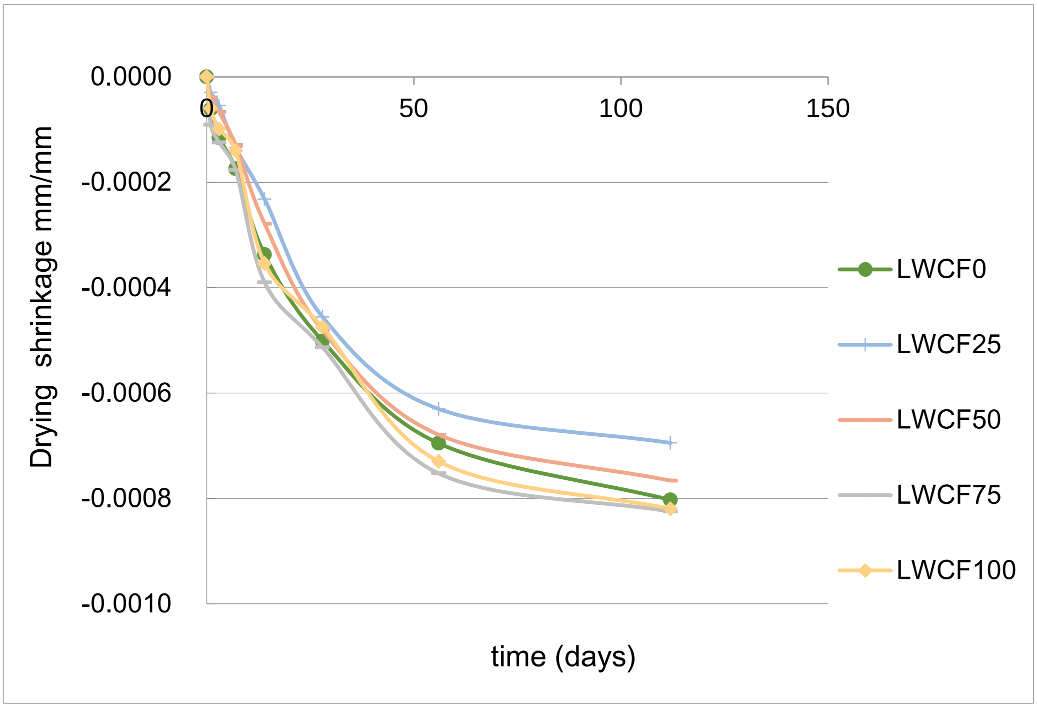


Figure 4-21 Drying shrinkage test results of high strength lightweight aggregate concrete with FBA incorporation

The ultimate drying shrinkage values are plotted in the figure 4-22. It can be seen that in the high strength NAC series, with the increase of FBA content, the drying shrinkage decreased linearly, which indicated that FBA incorporation had a positive impact in reducing the drying shrinkage of normal aggregate concrete; while for the mixtures in LWC series, the low correlation factor indicates no significant correlation between FBA incorporation ratio and the 112 days drying shrinkage value as the contribution of water containing in the pores of FBA had less impact compared with those contained in the pores of the LWA.

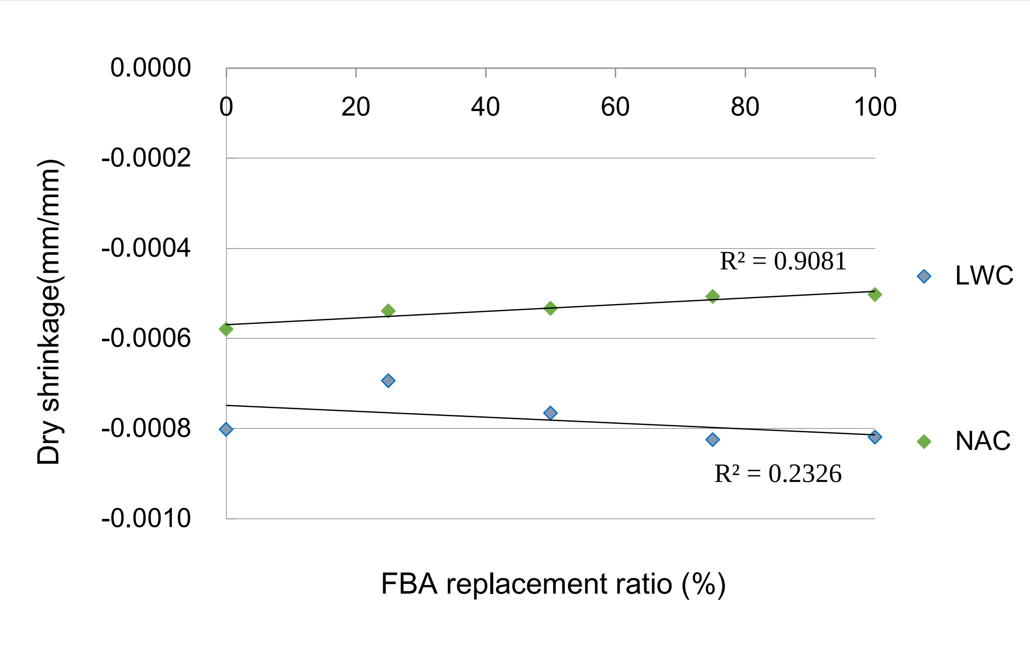


Figure 4-22 Correlation between FBA replacement ratio and ultimate drying shrinkage in normal aggregate concrete and in high strength lightweight aggregate concrete with silica fume

The results of the autogenous shrinkage test are presented by figure 4-23 and figure 4-24.

FBA incorporation also showed positive impact on concrete autogenous shrinkage reduction, function in both NAC series (as illustrated by figure 23) and LWC series (as illustrated by figure 24). The autogenous shrinkage values were decreased with the increase of FBA content, which indicated that FBA incorporation had positive effects on reducing the autogenous shrinkage of all mixtures prepared in this study. This can be attributed to the provision of water from the pores of the porous FBA particles.

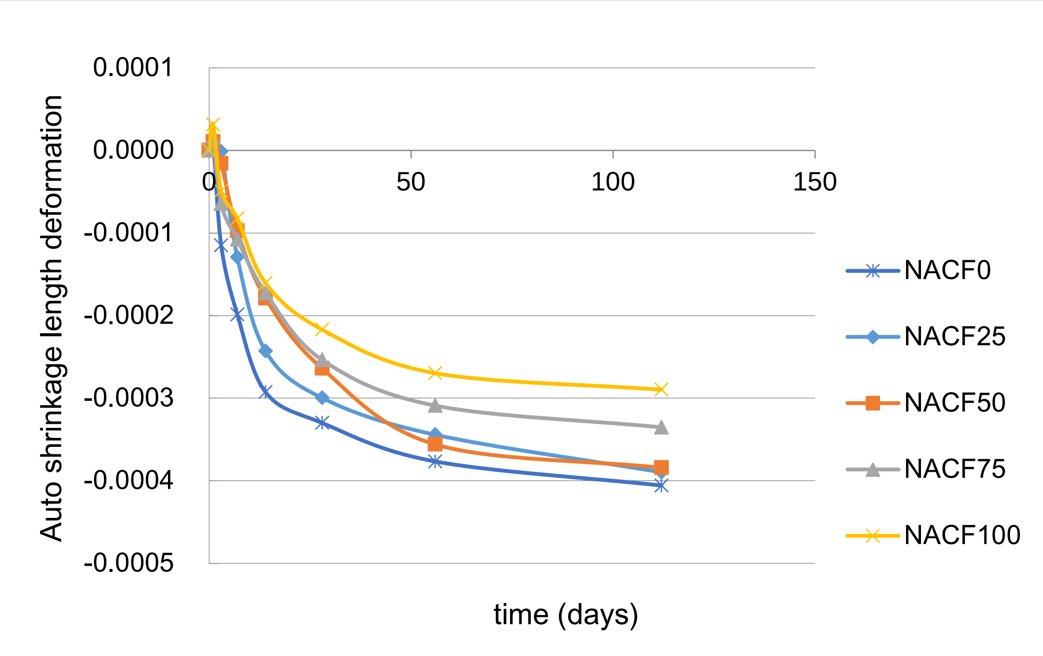


Figure 4-23 Autogenous shrinkage test results of normal aggregate concrete with FBA incorporation

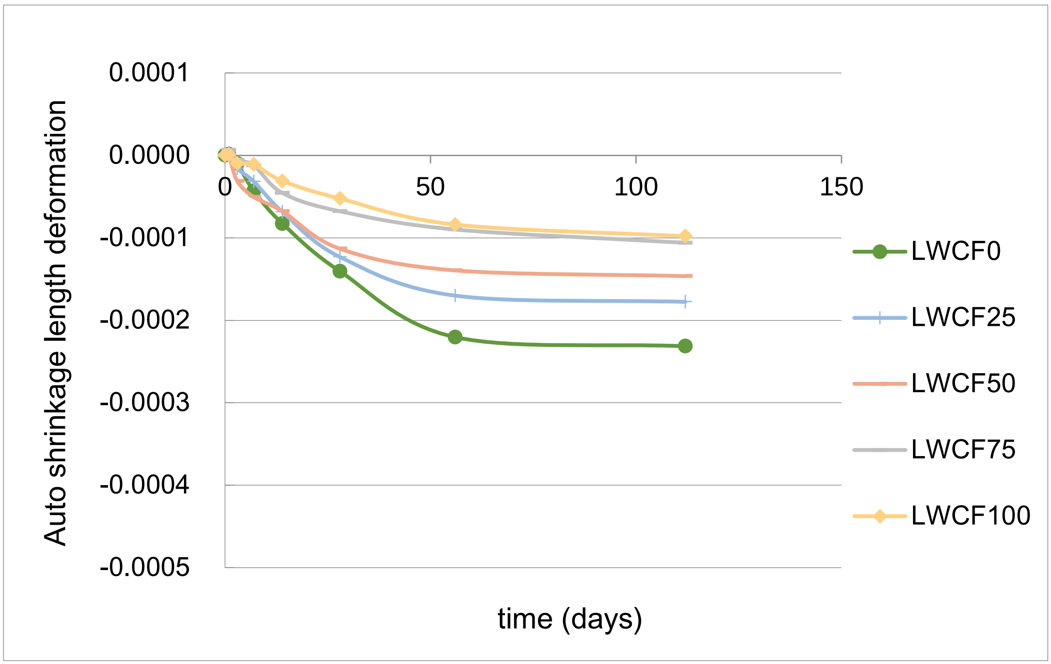


Figure 4-24 Autogenous shrinkage test results of lightweight aggregate concrete with FBA incorporation

The figure 4-25 showed the correlation between FBA replacement ratio and 112 days length change values for all the high strength normal aggregate concrete and lightweight aggregate concrete mixtures.

Comparing the autogenous shrinkage test results of the two series in figure 4-25, it can be seen that at each FBA replacement ratio, concrete in NAC mixture showed higher autogenous shrinkage values than the LWC mixture, which can be attributed to the internal curing effect realized by pre-wetted lightweight aggregate in LWC.

Comparing the results of the drying shrinkage as shown by figures 4-20, 4-21 and 4-22 with the autogenous shrinkage test as shown by figures 4-23, 4-24 and 4-25, it can be seen that for each high strength concrete mixture, the autogenous shrinkage values were less than the drying shrinkage ones. That can be attributed to the reason that despite of the hydration process, the low relative humidity in the test chamber also contributes to drying shrinkage.

Similarly to the results obtained in the drying shrinkage test, the incorporation of FBA resulted in decreased autogenous shrinkage values for all the high strength normal aggregate concrete mixtures. While for LWC series, contrary to the results obtained in the dying shrinkage test, a high correlation between FBA incorporation ratio and reduction in autogenous shrinkage values was detected, which shows the bigger contribution of FBA in reducing the autogenous shrinkage than the drying shrinkage.

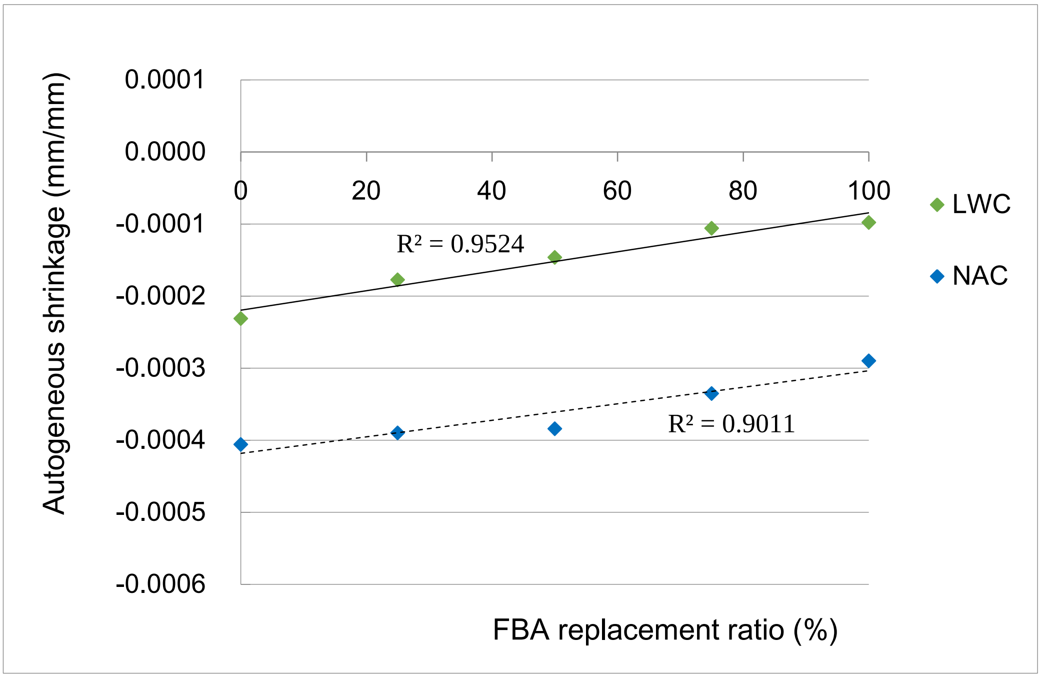


Figure 4-25 Correlation between FBA replacement ratio and ultimate autogenous shrinkage in normal aggregate concrete and in high strength lightweight aggregate concrete with silica fume

The shrinkage test results of high strength normal aggregate concrete and lightweight aggregate concrete showed that the incorporation of FBA not only helped mitigate the solid waste problem but also reduced the autogenous shrinkage.

The test results presented in the subsection of thermal insulation properties of lightweight aggregate concrete with FBA also showed that it is feasible to produce concrete with high volume FBA that possesses improved thermal insulation properties than conventional concrete. The test results presented in the subsection of mechanical properties of FBA incorporated normal aggregate concrete and lightweight aggregate concrete showed that even with high replacement ratio to natural fine aggregate, concrete with FBA incorporation maintained acceptable strength and stiffness.

The experimental test results in this study showed that it is feasible to produce normal aggregate concrete and lightweight aggregate concrete with high sustainability by using FBA as fine aggregate.

Other than the porous aggregates such as the furnace bottom ash used in this study, superabsorbent polymers (SAP) has also been used in concrete as a type of reservoir agent to compensate the autogenous shrinkage.

A type of SAP sized 2.4mm was used in cement paste prepared with water/cement ratio of 0.50 and 0.35 (Breugel 2006), it was found that the maximum distance the extra water released from SAP reached were 2.2mm and 2.5mm, respectively. Meanwhile with SAP sized 800μm, the maximum water providing distance was reduced to 740μm.

Based on the experimental studies conducted with incorporation of SAP into cementitious materials as internal curing agent, internal curing models at both meso-level and macro-level have been proposed.

In this model, assumptions have been made to assume that the water fills the empty pore spaces instantaneously and completely and released in the system uniformly.

In this model, the capillary pressure is calculated by the following equation 4-2 (Breugel 2006):

$$\dot{m}_{IC}(P^C) = \frac{\eta}{1-\eta}\rho^W \frac{\partial s_W^{IC}}{\partial p^C}\frac{\partial p^C}{\partial t} \tag{4-2}$$

Where η is the volume ratio of the material occupied by water reservoirs, $\partial s_W^{IC}/\partial p^C$ is the volume averaged mass of water transported from reservoirs materials to the unit volume of cured material due to the increase of capillary pressure in the paste.

In this study, the maximum aggregate size of the by-product FBA is 2.36mm, the incorporation of pre-wetted FBA was found effective on shrinkage reduction, it is believed that the FBA was acted as internal curing agent in the cementitious materials.

In the future, it is possible to detect the maximum water disperse distance from the reservoir aggregate (FBA) and more detailed comparison can be made in between high absorbent materials and industrial by-products.

4.2 For rubberised concrete targeted at partition wall applications

Other than FBA, another typical solid waste which causes a negative impact on the environment is rubber from waste tires. Therefore, in this study, rubber aggregate produced from waste tires was also used in concrete as an alternative fine aggregate. Rubberised concrete mixtures have been produced by using 25% to 100% as-received (coded as Rx u) and pretreated (coded as Rx p) rubber aggregate replacing FBA in lightweight aggregate concrete, normal aggregate concrete (coded as nac) and control mixture lightweight aggregate concrete with 100% FBA as fine aggregate (coded as ctr) have also been prepared as reference mixtures.

4.2.1 Density

The ssd density test result of rubberised lightweight aggregate concrete is presented in the figure 4-26.

The data indicate that the ssd density of the concrete in this study ranged from 1500 Kg/m^3 to 1712 Kg/m^3 with a linear reduction according to the amount of rubber added. The reduction in density is attributed to the lower density of the rubber aggregate compared to FBA aggregate. According to ACI lightweight aggregate concrete guide (Ries et al. 2010) all the rubberised concrete prepared in this study can be classified as lightweight aggregate concrete which are suitable for insulation uses.

It can also be seen from the figure that no significant difference in density value was detected when the pre-treatment was applied.

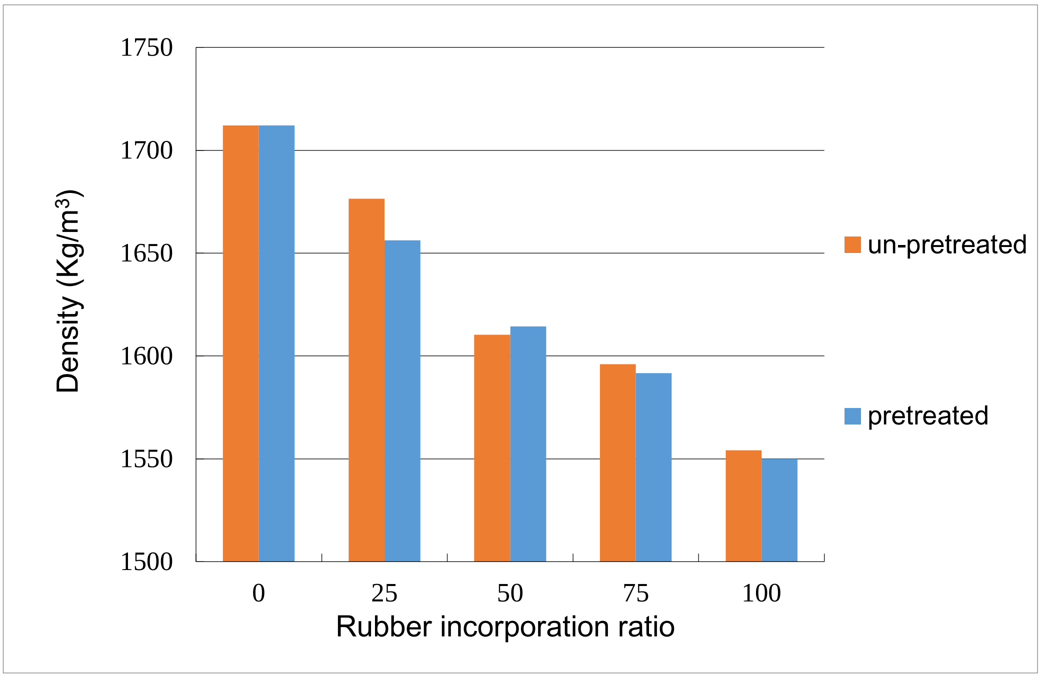


Figure 4-26 Saturated surface dried Density test results of rubberised concrete mixtures

From all the density test results obtained in this study, a conclusion can be drawn that the density of concrete decreases with the decrease of aggregate density, while the aggregate processing had limited impact on the density of concrete.

4.2.2 Thermal insulation properties

The K-value of rubberised concrete prepared in this study was tested as presented by the table 4-2. It can be seen the when using recycled rubber aggregate to replace FBA in the lightweight aggregate, no obvious change of thermal conductivity properties determined by K-value was observed. However, the use of recycled rubber aggregate had positive effects on concrete acoustic insulation properties and the test results will be discussed in the following subsections.

Table 4-2 Thermal conductivity test results of rubberised concrete compared to normal aggregate concrete

Mix Note	K-value (W/mk)		
NAC	1.0391	±	0.0336
R25 u	0.4183	±	0.0099
R25 p	0.3346	±	0.0057
R50 u	0.3614	±	0.0062
R50 p	0.3555	±	0.0087
R75 u	0.4064	±	0.0139
R75 p	0.3423	±	0.0110
R100 u	0.3929	±	0.0047
R100 p	0.3720	±	0.0238

4.2.3 Noise reduction effect

As illustrated by figure 4-27, impact noise reduction tests were conducted and the noise reduction effect of concrete slabs was analyzed, the targeted frequencies range was 630Hz to 3150Hz.

In this test, sound insulation was determined by overall noise reduction in dB (A), which was calculated by the difference of the received noise level between the blank test (no slab as barrier when hitting the metal ball) and the test conducted with the respective concrete slabs acting as noise barriers. In the figure 4-27, positive values indicate effective noise reduction.

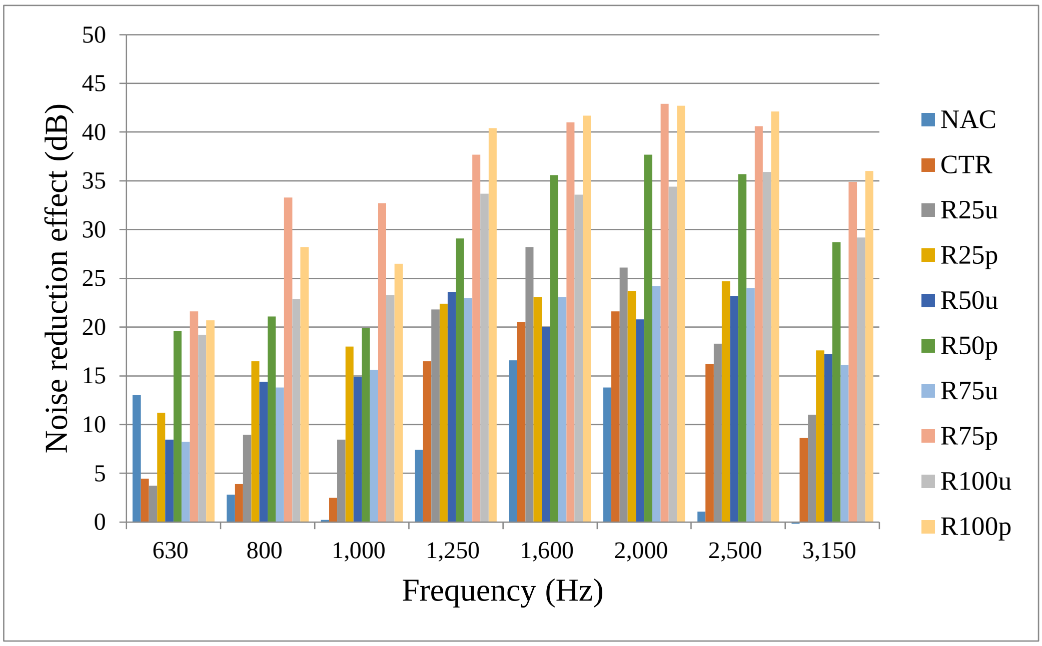


Figure 4-27 Noise reduction effect of rubberised concrete and normal aggregate concrete from 630Hz to 3150Hz

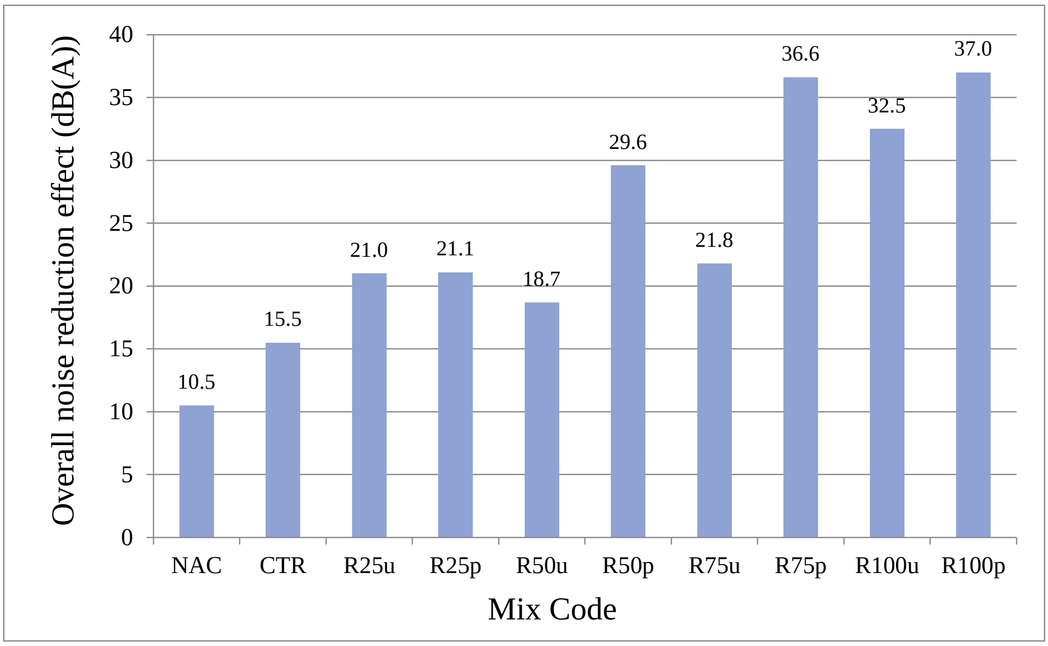


Figure 4-28 Overall noise reduction effect of rubberised concrete and normal aggregate concrete

From figure 4-28, it can be seen that all the prepared concrete in this study had better noise reduction effect than the normal aggregate concrete, and with the increase of rubber aggregate content, the sound insulation property of concrete was improved. When all the fine aggregates of the control mixture was replaced by the as-received rubber aggregate, the overall sound reduction level reached 32.5dB (A), which was significantly higher than the noise reduction effect of 21.0 dB (A) achieved by the lightweight aggregate concrete without rubber incorporation, and the 10.5dB (A) achieved by the normal aggregate concrete.

4.2.4 Rubber aggregate surface treatment

NaOH and SCA modification

Sodium hydroxide (NaOH) solution and Silane coupling agent (SCA) solution were used as rubber aggregate surface modification agents. The chemical pre-treatment was realized by soaking the rubber aggregate into the solutions for 24 hours, rinsing the aggregate under flowing water, and then air dry the aggregate. As-received rubber aggregate that constituted 50% of the fine aggregate was selected as the control mix. Compressive strength test and noise reduction test were conducted. The results within frequencies range 630Hz to 3150Hz can be found in figure 4-29 and the overall noise reduction effect is illustrated by figure 4-30.

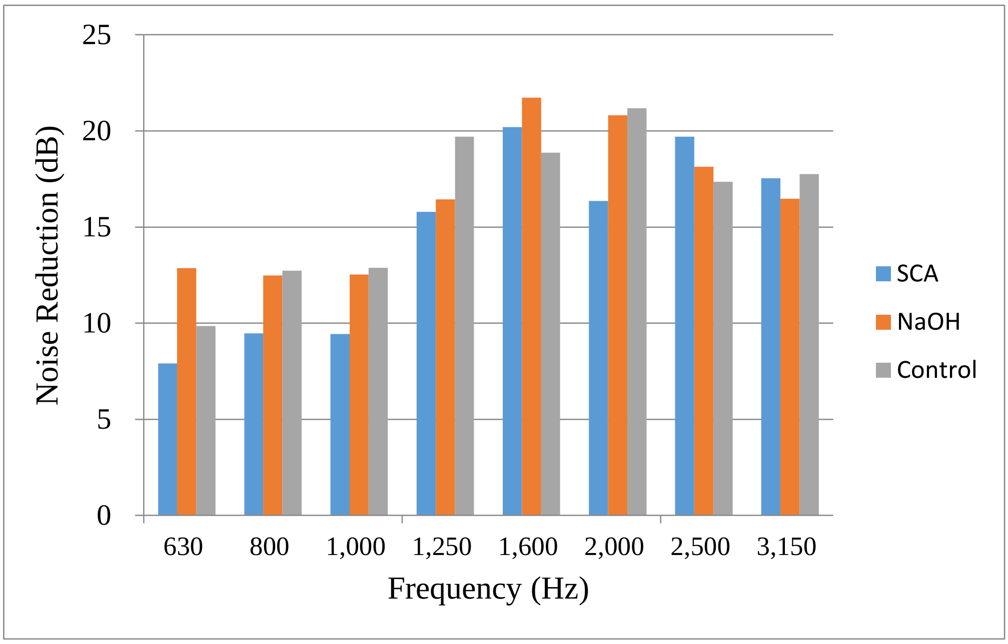


Figure 4-29 Noise reduction effect of rubberised concrete prepared with as-received rubber aggregate and chemical modified rubber aggregate

It can be seen that rubberised concrete prepared with NaOH/SCA treated rubber aggregate exhibited no improved noise attenuation capacity within the frequency range 630Hz to 3150Hz.

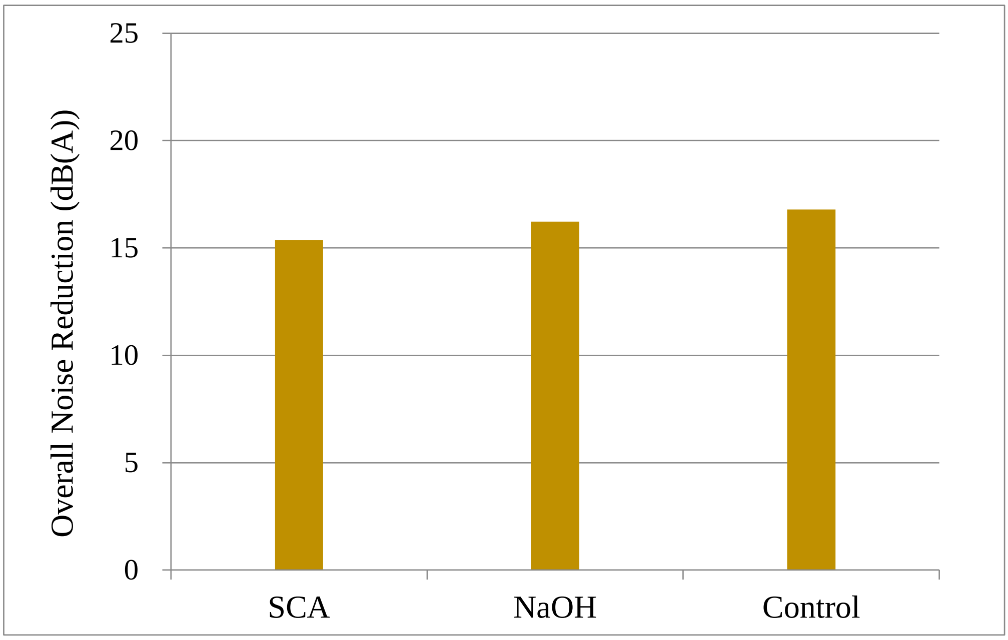


Figure 4-30 Overall noise reduction of rubberised concrete prepared with as-received rubber aggregate and chemical modified rubber aggregate

As shown by figure 4-30, the overall noise reduction of the rubberised concrete slab prepared from the as-received rubber aggregate and the NaOH/SCA treated rubber aggregate showed no significant difference.

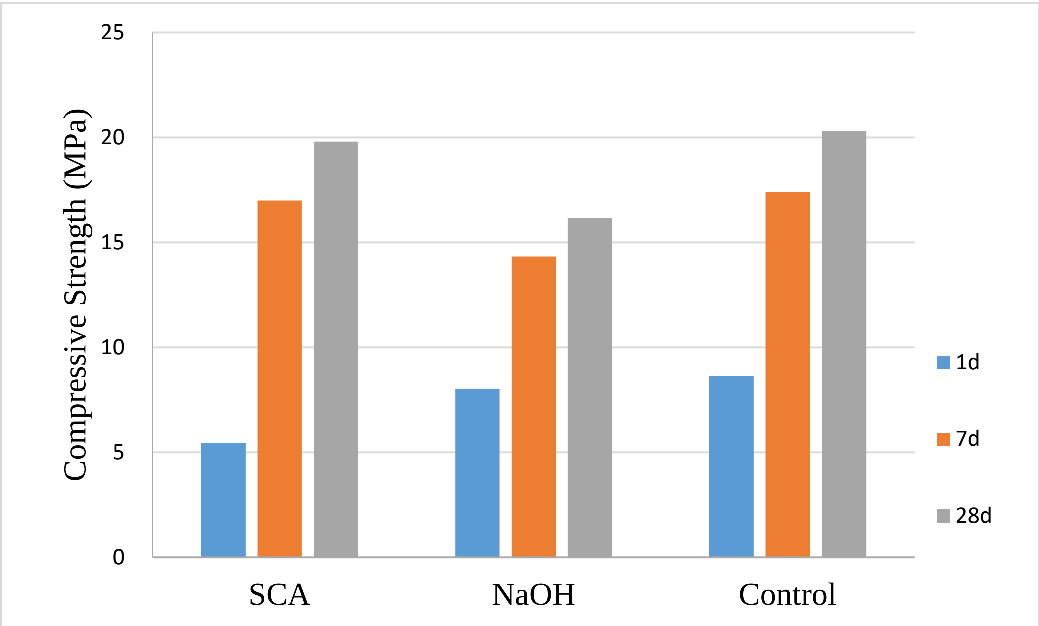


Figure 4-31 Strength development of SCA/NaOH treated rubberised concrete compared to Control mix prepared with as-received rubber aggregate

As shown by the figure 4-31, strength loss was detected when the treated rubber aggregate used compared to the mixture prepared with the as-received rubber aggregate.

Considering sustainability, cost effectiveness and the potential hazard associated with the chemical solutions, NaOH/SCA modification is less practical than the cement paste coating method (discussed below).

Effect of rubber aggregate surface coating

The effect of cement paste coating at water/cement=0.8 and cement/rubber=1/8 was studied.

During the mixing, segregation and poor workability was observed when high volumes (>50%) of the as-received recycled rubber aggregate was used (see figure 4-32), when the rubber aggregate was pre-treated by the coating method, the segregation of fresh mixtures was mitigated (see figure 4-33).

This can be explained by the fact that the surface of the as-received rubber aggregate is hydrophobic, while after coating the aggregate surface became hydrophilic, which was more compatible with the cementitious materials.

Figure 4-32 Inconsistency of fresh mixed rubberised concrete with high volume recycled rubber aggregate incorporation

Figure 4-33 Improved workability when surface modification applied to rubber aggregate

It was also observed that applying the pre-treatment method led to a better surface finish of rubberised concrete slabs, especially when the rubber content was high (see figure 4-34).

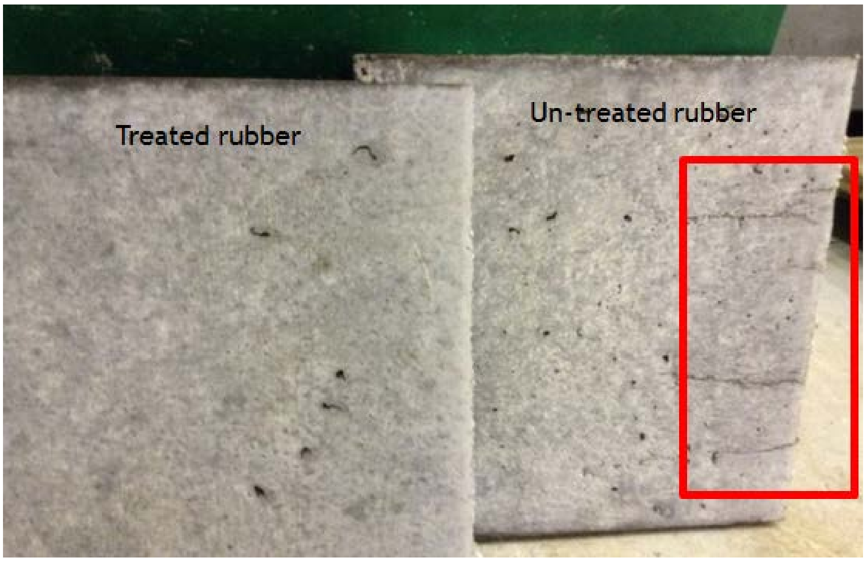


Figure 4-34 Finish of rubberised concrete slabs with 75% pre-treated rubber aggregate/ as-received rubber aggregate as fine aggregate

Figure 4-35 shows the effect of the coating method used in this study on the rubberised concrete acoustic insulation properties. The data in the figure 4-35 was calculated from the difference in noise reduction levels achieved by the concrete specimens prepared by the pretreated and untreated rubble particles. Similar to the test results shown in the previous subsection, the positive values in figure 4-35 indicate positive effects on impact noise reduction.

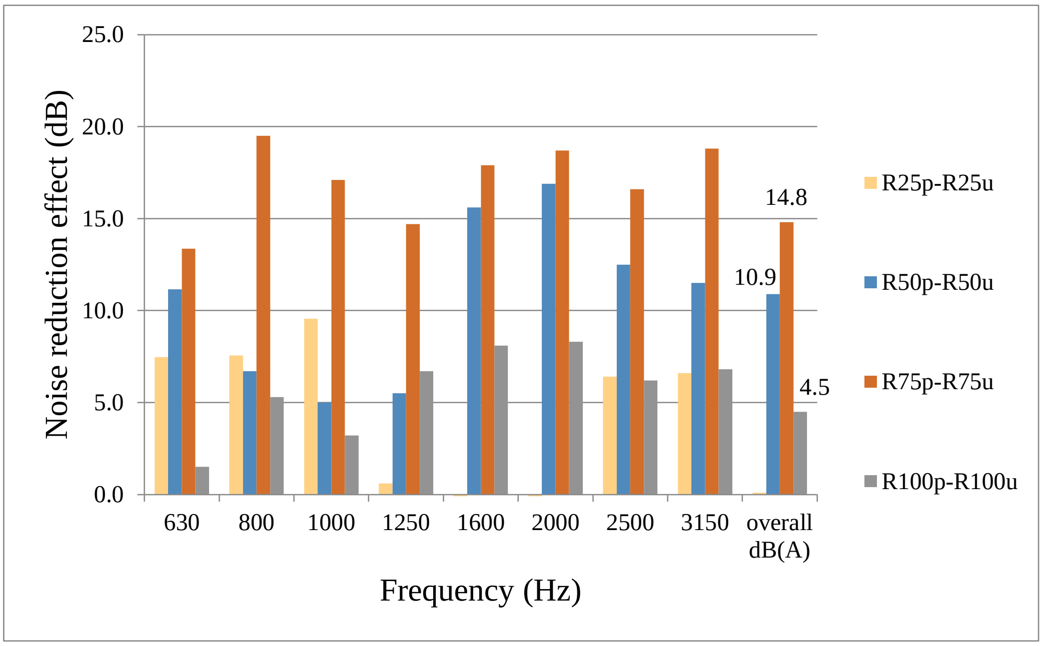


Figure 4-35 Noise reduction effect of surface pretreatment

It can be seen from figure 4-35 that at each replacement ratio of rubber aggregate, when the pre-treatment method was applied, the noise reduction effect of concrete was further improved. Among which the lightweight aggregate concrete with 75% rubber incorporation as fine aggregate showed the most significant pretreatment effect.

The noise reduction effect of material is affected by the mass, the stiffness and the damping. The density test results of the slabs showed that the density of concrete decreased with increased rubber contents, but the pre-treatment caused negligible difference to the density of the concrete. Therefore, for specimens cast by the same dimension molds, the mass of the mixture with the as received rubber aggregate and the pre-treated rubber aggregate can be assumed to be the same, which meant that the improved noise reduction effect was not due to mass differences.

On the other hand, the damping ratio was calculated from the test results of noise decay rate dB/s. The setting of the decay rate test was the same as the noise reduction test. Four parameters were recorded: The time needed for noise reduction of 10dB, 20dB, 30dB and 60dB in the frequency ranges from 100Hz to 3150Hz, represented as T_{10}, T_{20}, T_{30}, and T_{60}. T_{60} was the standard decay interval for calculation of the noise decay rate. Though, in this study, the minimum difference of the recorded noise level upon metal ball hitting and the background noise level was 19.1dB, which was smaller than 20dB. Therefore, to obtain more accurate results, T_{10} was used to calculate the decay rate and damping ratio.

The damping ratio was calculated according to equation 4-3 (Czichos et al. 2007):

$$\xi = \frac{\Delta}{2 \times 27.3 \times f} \qquad (4\text{-}3)$$

Where ξ is the damping ratio of material; Δ is the decay rate at a given frequency dB/s; and f is the given frequency Hz.

When damping ratio is less than 0.1, generally the vibration response of the tested material is not damping controlled.

As illustrated by the figure, no significant difference in damping ratio was detected for all the rubberised concrete mixtures.

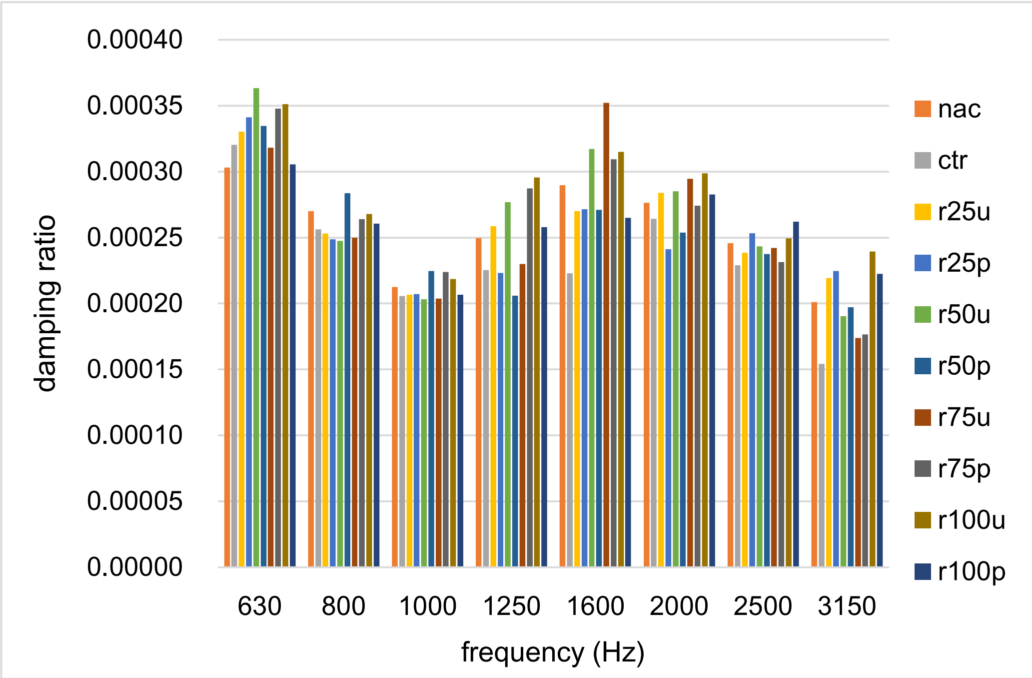


Figure 4-36 Damping ratio test results

Hence, the mechanism of noise reduction improvement caused by the pretreatment method probably can be explained by the reduced dynamic modulus of the mixture when the pretreatment method was applied.

The dynamic modulus of rubberised concrete produced in this study was determined in accordance with ASTM 1876. The dimension and the mass of each specimen were measured, and the resonance frequencies of the specimens were tested. Then the dynamic Young's modulus was calculated by equation 4-4 (Czichos et al. 2007):

$$\mathrm{E} = 0.9465(\mathrm{m}{f_f}^2/b)(L^3/t^3)T_1 \qquad (4\text{-}4)$$

Where E is the dynamic Young's modulus in Pa; m is the mass of tested slab in g; f_f is the resonance frequency of material in Hz; b is the width of specimen in mm; L is the length of specimen in mm; t is the thickness of specimen in mm; and T_1 is the correction factor.

The results of the dynamic Yong's modulus test are listed in the table 4-3. It can be seen from table 4-3 that a low E-value corresponded to better sound insulation property for the rubberised concrete at the same rubber aggregate content.

Table 4-3 Dynamic Young's Modulus test results and overall noise reduction of normal aggregate concrete and rubberised concrete

Slab code	Resonance frequency (Hz)	Mass (g)	b (mm)	L (mm)	t (mm)	Dynamic Modulus (GPa)	Overall Noise Reduction (dB(A))
NAC	530	791.6	39.6	401	22.6	30.3	10.5
R25U	467	493.4	39.5	411	21.3	18.9	21.0
R25P	449	578.0	39.9	416	22.8	17.1	21.1
R50U	534	523.9	40.7	402	22.2	21.0	18.7
R50P	496	554.8	40.8	386	24.7	12.4	29.6
R75U	486	531.1	41.8	405	22.2	17.6	21.8
R75P	313	515.4	39.8	415	22.5	7.7	36.6
R100U	378	441.2	39.8	388	20.0	11.1	32.5
R100P	400	489.2	40.8	391	22.7	9.5	37

From the noise reduction test and the dynamic Young's modulus test results, it can be seen that the improved noise reduction was associated with the decreased dynamic young's modulus value. When the pre-treatment method was applied, the concrete dynamic Young's modulus was effectively reduced. The results are consistent with previous findings (Najim & Hall 2012).

The bonding strength between rubber aggregate and the cement paste was investigated. Cubic samples were cast to simulate the bonding between the as-received rubber-paste and the pre-treated rubber-paste. The casting scheme is illustrated by figure 4-37: (a) cast the matrix part in the steel mold; and (b) after 24 hours, removed the wood and cast the rubberised concrete part.

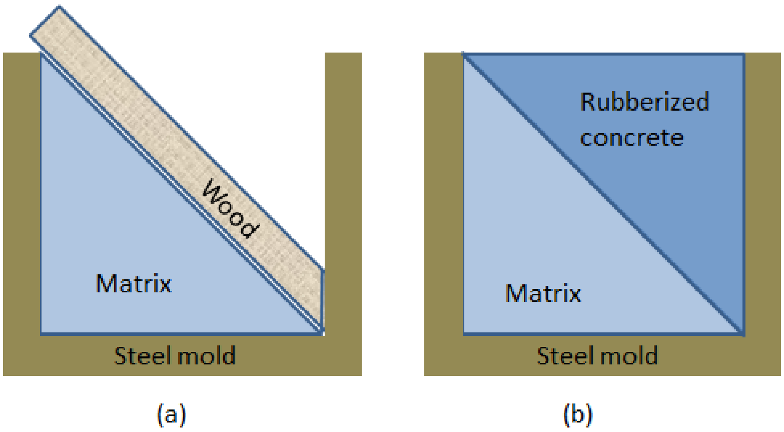


Figure 4-37 Sample preparation for bonding strength test

For the rubberised concrete part, both the as-received rubber aggregate and the pre-treated rubber aggregate were used. The mix proportions are listed in the table 4-4.

Table 4-4 Mixture design of rubberised concrete for bonding strength test (Kg/m^3)

Mix code	w/c	FBA	Cement	Water	LWA	Untreated Rubber	Pre-treated Rubber	ADVA 109 (L/m^3)
Rubberised concrete	0.34	319	550	187	392	226	0	4.0
	0.34	319	550	187	392	0	226	4.0
LWC	0.34	638	550	187	392	0	0	4.0

The cubic specimens were demolded and cured in water for 28 days, and then loads were applied to compare the strength of the bonding between the matrix and the rubberised concrete part. The testing scheme is demonstrated by the figure 4-38.

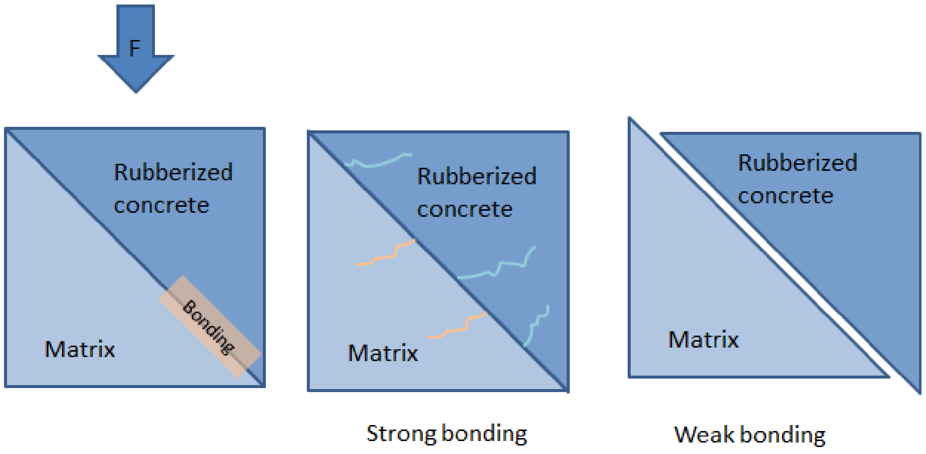


Figure 4-38 Strong bonding (cracks occur before bonding failure) and weak bonding (bonding failure before cracks occur) after force applying

Figure 4-39 shows the samples failure patterns after the bonding strength test. It can be seen that when pre-treated rubber aggregate was used, the bonding failed before major cracks occurred, while when the as-received rubber aggregate was used, major cracks occurred first before failure.

The bonding strength test showed that when the cement coating treatment was applied, the bonding strength between recycled rubber aggregate and the cement paste was weaker.

(a) Pre-treated rubberized concrete-matrix bonding failure

(b) As-received rubberized concrete-matrix bonding failure

Figure 4-39 Bonding strength test results

The cement paste used to modify the surface of the recycled rubber aggregate was prepared by using a high w/c ratio (0.8), and compared to the cement paste, the coating layer had a lower strength. The introduction of a weaker layer in the system resulted in poorer bonding between rubber aggregate and the cement paste. The weaker bonding led to decreased stiffness. Consequently, the energy from a constant vibration can be absorbed more quickly and easily by the rubberised concrete prepared from the pre-treated rubber aggregate compared to the counterpart specimens prepared with the as-received rubber aggregate. The rubberised concrete with the pre-treated rubber aggregate showed improved noise reduction effects.

The correlation between the dynamic young's modulus and the acoustic insulation properties had been investigated and revealed in previous research works (Kim et al. 2010). In Kim's work, a multi layers floor slab sized $4.6\times5.1m^2$ was prepared from a reinforced concrete slab, a resilient isolator and damping materials, a lightweight concrete and finishing mortar.

Kim et al. concluded that at the frequency ranges from 16Hz to 1000Hz, the multi-layer floor structure prepared from the material with a low dynamic modulus and loss factor was effective to reduce floor impact sound.

The theory developed by Kim can be applied in this study: the recycled rubber aggregate, as a type of damping material, was effective on the acoustic insulation properties enhancement in concrete. Therefore, the overall noise reduction level of rubberized concrete increased as the increase of rubber aggregate incorporation; the pre-treatment method applied in this study led to reduced dynamic modulus due to the introduction of a weaker layer (low strength cement slurry), and as the reduced dynamic modulus and loss factor had positive impact on improving the effectiveness of impact sound reduction, the rubberized concrete prepared from the pre-treated rubber aggregate exhibited better sound insulation properties compared to the specimens prepared with the as-received rubber aggregate.

4.3 Summary & Highlights

In this chapter, the laboratory test results of the two types concrete have been presented and analyzed:

a. The lightweight aggregate concrete with FBA incorporation targeted for application as external walls; and

b. The rubberized concrete with rubber aggregate surface treated targeted for application as partition walls.

The highlights of the findings from this study are as followings:

i) The effect of Furnace Bottom Ash (FBA) on the thermal insulation properties of lightweight aggregate concrete has been revealed;

ii) The internal curing effect of FBA in the silica fume incorporated lightweight aggregate concrete has been investigated; and

iii) A pre-treatment method has been developed for further enhancing the acoustic insulation properties of rubberized concrete with high volume rubber aggregate incorporation.

Chapter 5. -CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results presented in Chapter 4, the following conclusions can be drawn:

1. It is feasible to fabricate lightweight aggregate concrete with high volume FBA incorporation. The slump of concrete increased as the increased amount of FBA replacing natural fine aggregate. 25% replacement ratio of FBA led to slightly higher compressive strength compared to the lightweight aggregate concrete with no FBA incorporation, while higher replacement ratio of FBA led to strength loss. Both lightweight aggregate and FBA incorporation resulted in higher permeability and poorer durability performance, addition of silica fume is effective on mitigation of durability problems.

2. Lightweight aggregate concrete possessed improved thermal insulation properties compared to normal aggregate concrete. The thermal conductivity of concrete reduced with the increase of FBA aggregate incorporation. The K-value of conventional concrete is about 1.0W/mK, the lightweight aggregate concrete with 100% FBA replacing natural fine aggregate achieved K-value about 0.4W/mK. The 28-day compressive strength of this

concrete was over 45MPa. This type of structural lightweight aggregate concrete has potential application as building envelopes for energy saving purposes, and the high volume of industrial by-product's incorporation enhances the sustainability of the material.

3. The pre-wetted porous lightweight aggregate, acting as a reservoir, helped to reduce the autogenous shrinkage of concrete via the internal curing effect. Lightweight aggregate concrete showed lower autogenous shrinkage compared to normal aggregate concrete. When 100% natural fine aggregate replaced by FBA, the autogenous shrinkage of normal aggregate concrete reduced from 0.041% to 0.029%, while the autogenous shrinkage of lightweight aggregate concrete reduced from 0.023% to 0.010%. The FBA aggregate with water absorption higher than 10% acted as reservoir in both normal aggregate concrete and lightweight aggregate concrete and showed internal curing effect.

4. Recycled rubber aggregate incorporation led to improved noise reduction. When 100% fine aggregate was replaced by recycled as-received rubber aggregate, the overall noise reduction of concrete slabs increased to 32.5 dB(A), which was significantly better than the 15.5 dB(A) of the lightweight aggregate concrete without rubber aggregate.

5. When a cement paste coating method applied on recycled rubber aggregate surface modification, the noise reduction effect of rubberised concrete was

further improved. When the as-received recycled rubber aggregate replaced 75% of fine aggregate, the overall noise reduction was 21.8 dB (A), while when 75% pre-treated rubber aggregate was used, the overall noise reduction level further increased to 36.6 dB(A). However, rubberised concrete prepared with NaOH or Silane Coupling Agent modified rubber aggregate showed no noticeable impact on noise reduction compared to rubberised concrete prepared with as-received rubber aggregate.

6. The dynamic Young's modulus test results showed that rubberised concrete prepared with cement paste coated rubber aggregate exhibited lower modulus compared to the rubberised concrete prepared with same amount as-received rubber aggregate, and the bonding strength test results showed that when the cement paste coating was applied, the bonding between the rubber aggregate and cement paste became weaker. The mechanism has been proposed: cement paste coating on rubber aggregate led to a weaker bonding and a decreased dynamic young's modulus, thus upon vibration the specimen with pre-treated aggregate absorbs energy more quickly and easily, and consequently this pre-treatment method leads to enhanced noise attenuation capacity of rubberised concrete.

5.2 Limitations and recommendations for future works

1. Only two types of LECA were used in this study. In the future, it is feasible to use another commonly used lightweight aggregate Lytag for production

of lightweight aggregate concrete with industrial by-products and/or recycled aggregate incorporation;

2. In this study, pre-wetted FBA aggregate was found to have internal curing effect and led to decreased autogenous shrinkage. It is possible to investigate the internal curing effect of other by-product materials or waste materials with equivalent (11.17%) or higher water absorption;
3. In this study, silica fume was used to enhance the durability properties of lightweight aggregate concrete. Silica fume may also be used to improve the mechanical properties and durability properties of rubberised concrete. However, the acoustic insulation properties of rubberised concrete may be affected due to the filler effect of silica fume;
4. Silane coupling agent and saturated NaOH solution has been applied to modify the surface of recycled rubber aggregate, no further noise reduction effect has been achieved and no positive impact on strength enhancement has been detected. However, in future works, the two-staged pre-treatment method can be applied (chemical modification followed by cement paste coating), and the acoustic insulation properties of rubberised concrete with the two-staged method modified rubber aggregate can be investigated;
5. In this study no quantitative tests have been conducted to evaluate the bonding strength between rubber aggregate and cement paste. In the future, more comprehensive and systematic tests can be conducted to investigate the rubber aggregate-paste bonding and the impacts of rubber aggregate

surface modification, including chemical modification, coating, and two-staged pre-treatment.

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