PARTIAL REPLACEMENT OF COARSE AGGREGATE WITH PORCELAIN GRANITE TILE WASTE (PGTW) IN REINFORCED CONCRETE BEAM

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Thesis submitted in fulfilment of the requirements
for the award of the degree of
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JUNE 2016

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Dedicated to my parents,

for their love and endless support,

that has helped make me who I am today

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ABSTRACT

The demand of concrete in the construction industry increased rapidly due to the continuous development of countries around the globe. Extensive use of concrete leads to sacristy of natural aggregates. The reuse of construction waste and solid waste from manufacturing is an alternative way to preserve waste management problem as well as to reduce the depletion of natural resources. This research was conducted to investigate the flexural behaviour of partial coarse aggregate replacement with porcelain granite tile waste (PGTW) in reinforced concrete beam. In this study, PGTW was used to partial replace the coarse aggregate by 10%, 20% and 30%. All the concrete was design to strength of 25 N/mm^2 and all the specimens were cured for 7 days and 28 days. Compressive strength test was conducted to determine the compressive strength of hardened concrete. The results presented that 10% and 20% of PGTW concrete had higher compressive strength as compared to control concrete. For flexural behaviour, all the PGTW reinforced concrete beams behaved in the same way as control reinforced concrete beam in term of load and deflection.

ABSTRAK

Permintaan konkrit dalam industri pembinaan semakin meningkat kerana pembangunan yang berterusan di seluruh dunia. Pengunaan berterusan ini membawa kepada kekurangan agregat semula jadi. Penggunaan semula sisa pembinaan dan sisa pepejal dari industri adalah cara alternatif untuk menguruskan masalah pengurusan sisa dan juga untuk mengurangkan pengunaan terus sumber semula jadi. Kajian ini dijalankan untuk mengkaji kelakuan lenturan rasuk bertetulang yang menggunakan konkrit dengan penggantian sisa jubin (PGTW) sebagai agregat kasar. Dalam kajian ini, PGTW digunakan untuk menggantikan sebahagian agregat kasar sebanyak 10%, 20% dan 30%. Semua konkrit direkabentuk dengan kekuatan 25 N/mm^2 dan semua spesimen diawet selama 7 hari dan 28 hari. Ujian kekuatan mampatan dijalankan untuk menentukan kekuatan mampatan konkrit keras. Keputusan menunjukkan bahawa 10% dan 20% gantian PGTW dalam konkrit mempunyai kekuatan mampatan yang lebih tinggi berbanding konkrit kawalan. Bagi kelakuan lenturan semua rasuk PGTW bertetulang, didapati hubungan antara beban dan pesongan setiap rasuk tidak mempunyai perbezaan yang ketara dengan rasuk betetulang yang mengunakan konkrit kawalan.

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LIST OF SYMBOLS

%	Percentage
Mm	Millimeter
N/mm^2	Newton per millimeter square
Kg	Kilogram
N	Newton
kN	Kilonewton
kg/m^3	Kilogram per meter cubic
w/c	Water to cement ratio
mm^2	Millimeter square
m^3	Meter cubic
Pa	Pascal
MPa	Mega Pascal
Psi	Pounds per inch square
pH	Potential of Hydrogen

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standard
CC	Conventional Concrete
CEM	Certified Energy Manager
DOE	Department of Environment
IS	Indian Standard
LVDT	Linear Variable Displacement Transducer
LWA	Lightweight Aggregate
NWC	Normal Weight Concrete
OPKS	Oil Palm Kernel Shell
OPSC	Oil Palm Shell Concrete
P0	0% of Porcelain Granite Tile Waste
P1	10% of Porcelain Granite Tile Waste
P2	20% of Porcelain Granite Tile Waste
P3	30% of Porcelain Granite Tile Waste
PGTW	Porcelain Granite Tile Waste
RCA	Recycled Concrete Aggregate

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Construction industry is one of the major industries in Malaysia and had contributed much to the economic growth of the country (Olanrewaju & Abdul-Aziz, 2015). However, this industry produces a lot of wastes and causes negative impact to the environment. According to Yap & Foong (2013), it stated that about 15 - 30% of the daily production goes to waste in ceramic industry and the ceramic waste has high resistance toward chemical, physical and biological degradation forces. Hence, the ceramic waste generally managed by dumping in the landfill site or by incineration. One of the ways to address these problems is to recycle those waste materials and reuse them for other construction purposes. Meanwhile, depletion of the natural aggregates arises due to rapid urbanization in the developing country.

In order to preserve waste management problem and depletion of natural resources, the alternative way to overcome the issue is by utilizing potential ceramic waste material such as Porcelain Granite Tile Waste (PGTW) as coarse aggregate. Therefore, research on the performance of concrete with PGTW must be determined with the purpose of identify whether the ceramic waste is suitable to be used as a substitution for the coarse aggregate material in concrete.

1.2 BACKGROUND OF STUDY

Replacing coarse aggregate with other materials over of conventional one is one of the ways to reuse and recycle the waste materials. Moreover, concrete with recycled waste materials is able to perform as well as the conventional one. Some of the recycled waste materials used in concrete are cockle shell, oil palm kernel shell, recycled concrete aggregate and ceramic. These materials are common agricultural and construction wastes. Besides that, construction wastes are non-biodegradable. Hence, the common ways to dispose them are to bury these materials in landfills, where in the long term pose threats to the natural environment.

Based on the research done by Kalpavalli (2015), the result exhibited that the compressive strength of the recycled aggregate concrete is closed to conventional concrete. Alengaram (2013) stated that the splitting tensile strength of oil palm kernel shell concrete is similar to conventional concrete. Besides that, Sekar et al. (2011) mentioned that ceramic aggregate concrete can exhibited similar strength in compression, flexure and split tensile as conventional concrete.

From past studies (Alengaram et al., 2013; Kalpavalli, 2015; Muthusamy et al., 2012; Sekar et al., 2011), concrete made of recycled waste materials generally have shown satisfying results, including increased compressive strength, increased flexural strength at certain percentage of replacement on coarse aggregates. These properties are deemed beneficial to the overall performance of concrete. Hence, it is favourable to use recycled waste materials as a substitution for the coarse aggregate in concrete while still being able to perform as satisfactory as the conventional ones.

However, the structural performance of concrete with ceramic aggregate remains unknown. Ceramic waste arguably does make an ideal substitution material to be used as aggregate in reinforced structural member. Nevertheless, not much research has been conducted on replacing coarse aggregate of concrete with ceramic waste in term of structural performance.

1.3 PROBLEM STATEMENT

The high demand of concrete production will lead to high extraction of aggregates from natural resources (Serres et al., 2015). Coarse aggregate is a non-renewable resource in the production of concrete. Sustainable issue arises as this non-renewable natural resource will be depleted eventually due to the huge demand in the construction sector. In addition, the cost of materials for producing concrete had been rising yearly. This is mainly caused by increasing demand of the materials while at the same time increased difficulties to obtain the materials. This has been worsened by the activity of illegal harvesting of these materials.

Construction activity had produced a lot of construction and demolition waste especially ceramic materials and it usually disposed in the landfill (Juan et al., 2011). According to Pacheco-Torgal & Jalali (2010), reutilization of ceramic waste in construction industry is a potential to develop a sustainable concrete. It contributes an alternative method to waste disposal by recycle the waste material instead of incineration or landfilling. In addition, it also directly helps in decreasing the use of natural aggregate in production of concrete.

But little is known about the mechanical performance of ceramic waste concrete with regard to its suitability as a substitute of coarse aggregate, and how well would ceramic waste concrete performs with compare to conventional concrete in terms of structural performance. Thus, research on the performance of concrete with ceramic waste must first be conducted in order to identify the suitability of ceramic waste as coarse aggregate in concrete.

1.4 RESEARCH OBJECTIVES

i. To determine the compressive strength of PGTW concrete
ii. To study the flexural behaviour of reinforced concrete beam with PGTW
iii. To compare performance of conventional concrete with various percentages of replaced aggregate in concrete.

1.5 SCOPE OF STUDY

The scope of this study will be focused on the laboratory test to analyse the performance of concrete with different percentages of PGTW as coarse aggregate replacement. The PGTW is one of the ceramic waste and it will be used in this study is collected from the construction waste at kk4, Universiti Malaysia Pahang. The collected PGTW will be broken into size of 5 – 20 mm as coarse aggregate.

The percentages of coarse aggregate replacement by PGTW are 10 %, 20 % and 30 %. The dimension of cube specimens is 150 mm x 150 mm x 150 mm whereas the dimension of beam specimens is 150 mm x 200 mm x 1500 mm. All specimens will undergo curing process and will be tested at the age of 7 and 28 days. The tests to be carried out on this study are concrete density test, compressive strength test and flexural test.

1.6 RESEARCH SIGNIFICANT

Ceramic waste, besides being a waste material, it is also a potential aggregate replacement material that can contribute to the concrete structure. The study is likely to contribute to the reduction in construction expenses where the cost of concrete production will be lowered. With the ceramic waste increasing year by year, the waste material is readily available and can be obtained easily from the industries.

The ceramic waste is selected as a replacement material in concrete to reduce the landfill of solid waste and minimize using the scarcity of natural aggregate like gravel. Besides that, this study will also indirectly reduce the problem of handle huge amount of ceramic wastes generated that has to be taken seriously. Therefore, the environment can be preserved and ecological system will be left undisturbed.

This research is able to analyse the feasibility of ceramic waste application in the concrete. Through this research, the performance of ceramic waste as coarse aggregate replacement in concrete are determined. The strength of replaced aggregate concrete is anticipated to be as similar as conventional concrete. As a result, it can be accepted by industry player and applied to the concrete technology in the future.

1.7 CONCLUSION

In short, the research on Porcelain Granite Tile Waste (PGTW) as potential coarse aggregate replacement in concrete will be performed. It is to determine its compressive strength in concrete as well as flexural behaviour in reinforced concrete beam structure. All the brief introduction of this study will be discussed in this chapter. This chapter consist of background of the study and highlight the research objective as well as the scope of the study. The significance of this research is also included in this chapter. The literature review and previous study of other researches will be discussed on the next chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter includes the review of previous relevant literature such as composition of concrete used and study on the replacement of aggregate with other product, to be utilized in the concrete. In addition, waste material as the aggregate replacement in the concrete mixture will be the focus of this topic. All the data and information from the previous studies will be summarized in order to figure out the scope of this study. Furthermore, comparison between different by-products that can be used as aggregate replacement materials in the concrete mixture will be discussed in this chapter as well.

2.2 CONCRETE

Concrete is a composition of materials, comprising of cement, coarse and fine aggregates, and water, which are mixed in a particular proportion in order to achieve the desired strength. Concrete is widely used in construction field due to its high durability characteristic and excellent resistance to water. The other reason for the popularity of concrete is its ability to be formed into various of sizes and shapes for required structural concrete element, and its raw materials is readily available (Nagaraj, 2015).

The demand of concrete in the construction industry is increasing rapidly due to the continuous development of countries around the globe (Shafigh et al., 2014). Apart from strength and durability, concrete is ideal building material that can be mould in aesthetically pleasing forms. The concrete is strong in compressive but poor in tensile.

In order to overcome this problem, reinforcement is provided to resist the tensile stress and also can used to increase the compressive capacity. Reinforced concrete is defined as concrete strengthened by steel bars. The concrete industry can develop a sustainable future for coming generations with sustainable concrete structures and infrastructure.

With increasing awareness on the sustainability in future development, concrete industry has considered a practical interpretation of sustainability for production of concrete. The concrete industry can make substantial discussions with the short and long-term environmental impacts of concrete materials, structures, and construction works. Intensely emphasis on massive consumption of natural resources such as gravel, sand and water, and wide spread waste generation from demolished concrete structures is on the desk of the concrete industries (Matthies and Sugiura, 2014).

Development of eco-friendly technology with an effective resource management in construction industry is a need to overcome the exploitation of natural resources. Green technology is not something new in research when it comes to finding substantial natural resources as a replacement in concrete production, reducing the negative impact on the environmental. Consequently, many researches had been done to seek for waste materials, which are compatible, to partially replace aggregate in concrete in order to achieve the intention of green concrete.

2.2.1 CEMENT

Cement is the most important basic ingredient of concrete which is act as binder to set, hardens, and binds other materials together. It is a powdery material with adhesive and cohesive properties. Generally, cement can be categorized into two types: hydraulic cement and non-hydraulic cement. Hydraulic cement is a type of cement that turns into the solid product in the presence of water due to occurrence of hydration process whereas non-hydraulic cement hardens without the contact with water.

The most commonly cement used in construction worldwide nowadays is the hydraulic-type Portland cement. According to The Cement and Concrete Association of Malaysia (2009), Portland cement is a common type powdery cementitious material made by heating the lime, alumina, iron oxide, magnesia, and silica mixtures together in a kiln and is then pulverized. It is transformed into the concrete when mixed with water and aggregates.

The standards and specifications of cement in Malaysia is shown in Table 2.1. The Portland Composite Cement, quality assured by the SIRIM certification of BS 197-1:2000 CEM II/B-M cement, is used in this study due to its usage in the construction industry for general purpose.

Table 2.1: Standards and specifications of cement in Malaysia (Cement and Concrete Association of Malaysia, 2009)

Main Type	Notation		Clinker Content (%)	Content of other main constituents (%)
CEM I	Portland cement	CEM I	95 to 100	0 to 5
CEM II	Portland-slag Cement	CEM II/A-S	80 to 94	6 to 20
		CEM II/B-S	65 to 79	21 to 35
	Portland-silica fume cement	CEM II/A-D	90 to 94	6 to 10
	Portland-Pozzolanic Cement	CEM II/A-P	80 to 94	6 to 20
		CEM II/B-P	65 to 79	21 to 35
		CEM II/A-Q	80 to 94	6 to 20
		CEM II/B-Q	65 to 79	21 to 35
	Portland-fly ash cement	CEM II/A-V	80 to 94	6 to 20
		CEM II/B-V	65 to 79	21 to 35
		CEM II/A-W	80 to 94	6 to 20
		CEM II/B-W	65 to 79	21 to 35
	Portland-burnt shale cement	CEM II/A-T	80 to 94	6 to 20
		CEM II/B-T	65 to 79	21 to 35
	Portland-limestone cement	CEM II/A-L	80 to 94	6 to 20
		CEM II/A-LL	80 to 94	6 to 20
		CEM II/B-L	65 to 79	21 to 35
		CEM II/B-LL	65 to 79	21 to 35
	Portland-composite cement	CEM II/A-M	80 to 94	6 to 20
		CEM II/B-M	65 to 79	21 to 35
CEM III	Blastfurnace cement	CEM III/A	35 to 64	36 to 65
		CEM III/B	20 to 34	66 to 80
		CEM III/C	5 to 19	81 to 95
CEM IV	Portland fly ash cement	CEM IV/A	65 to 89	11 to 35
	Pozzolanic fly ash cement	CEM IV/B	45 to 64	36 to 55
CEM V	Composite cement	CEM V/A	40 to 64	36 to 60
		CEM V/B	20 to 38	62 to 80

2.2.2 AGGREGATES

Aggregate is the one of the raw materials in concrete. Osei (2013) had mentioned that the three-quarters of the concrete are composed of aggregates, highlighting the point that the strength of concrete is limit by the quality of the aggregates. According to Skripkiunas et al. (2013), aggregates is the contributor for the durability of the concrete with higher density and chemical resistance. The function of the aggregates is to reduce the heat of hydration in concrete since aggregates are normally chemically inert and act as a heat sink for hydrating cement. In addition, it can reduce the shrinkage of concrete since most aggregates are not affected by water and can restrain shrinkage during the hydration process.

Table 2.2: Shape of aggregates (Jackson, 1989)

Classification	Description
Rounded	Fully water –worn or completely shaped by attrition
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges
Angular	Possessing well-defined edges formed at the intersection of roughly planar faces
Flaky	Material of which the thickness is small relative to the other two dimensions
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions
Flaky and Elongated	Material having the length considerably larger than the width, and the width considerably larger than the thickness

Aggregates can be categorized into two groups, the fine aggregates and the coarse aggregates. The details of both aggregates will be discussed further on the following part. Besides, the shape and texture of aggregates will post an effect on the workability of fresh concrete. For good workability, ideal aggregate particle is one that is close to spherical in shape with a relatively smooth surface. Table 2.2 shows the particle shape classification of aggregates meanwhile Table 2.3 describes the surface texture classification of aggregates.

Table 2.3: Surface texture of aggregates (Jackson, 1989)

Surface Texture	Characteristics
Glassy	Conchoidal fracture
Smooth	Water-worn, or smooth due to fracture of laminated or fine-grained rock
Granular	Fracture showing more or less uniform rounded grains
Rough	Rough fracture of fine- or medium-grained rock containing no easily visible crystalline constituents
Crystalline	Containing easily visible crystalline constituents
Honeycombed	With visible pores and cavities

2.2.2.1 COARSE AGGREGATE

Aggregate can be classified into two main groups which are natural aggregate and manufactured aggregate. Gonilho Pereira et al. (2009) stated that natural coarse aggregates can be obtained from different type of rocks such as basalt, granite, calcareous and marble. Meanwhile, manufactured aggregate is artificial aggregate that is produced by wide variety of raw materials through industry procedure. The 70-80% of concrete volume is composed of aggregates where the coarse aggregate account for two out of three from the total volume of both aggregates.

According to Portland Cement Association (2015), coarse aggregates are any particle with size greater than 4.75mm sieve but generally in the range between 9.5 mm to 57.5 mm in diameter. The coarse aggregate is the major contributor for the concrete durability and play an important role in high strength concrete. From the research of Gonilho Pereira et al. (2009), it is proved that the compressive strength of basalt is the highest followed by granite.

2.2.2.2 FINE AGGREGATE

Fine aggregate is defined as any particle that can pass through the 4.75mm sieve, but retained on the 75 μm sieve (Subramani & Ravi, 2015). Example for fine aggregate is sands obtained from the land or the marine environment. The main function of fine aggregate is to fill the voids between the coarse aggregate. The fine aggregate should be round shaped for purpose of increased workability.

Same as coarse aggregate, fine aggregate such as sand can be categorized into natural sand and manufactured sand. Natural sand is formed from weathering and decomposition of all types of rock whereas manufactured sand is produced from crushing the stone, gravel or air cooled blast furnace slag. In concrete production, river sand is the most common material used as fine aggregate due to its high accessibility.

2.3 PREVIOUS RESEARCH OF COARSE AGGREGATE REPLACMENT

The continuously high demand from the construction industry on concrete production may eventually lead to the depletion of natural aggregate supply. Natural aggregate is a non-renewable resource that will deplete one day because it had been taken for granted. Therefore, it is crucial to have an alternative aggregate material as replacement to overcome the over-dependence on natural aggregate. The consumption of aggregate in the construction industry has been increasing over the years, in line with the robust development in the construction industry, and at the same time, impacts the environment as well.

According to Kalpavalli (2015), exhaustion of natural aggregate is escalating because of the increasing demand for concrete production. The replacement of natural aggregate with waste materials will effectively reduce the negative impact to the environment, because both the quarrying activity and waste production can be reduced. Therefore, manufactured aggregate from waste materials is of importance to replace the natural aggregate in concrete. This will not only help to preserve the non-renewable raw materials, but also plays a role in reducing and reusing the waste product. Based on previous researches, cockle shell, oil palm kernel shell and recycled concrete aggregate could be used to partially replace the natural aggregate in the concrete.

2.3.1 COCKLE SHELL AS PARTIAL COARSE AGGREGATE REPLACEMENT

Boey et al. (2011) mentioned that cockle shell is available in abundant and discarded as waste in larger quantity due to active cockle trade. According to Muthusamyet al. (2012), investigation and incorporation of waste cockle shell as partial coarse aggregate replacement in concrete production is needed to increase the usage of cockle shell. Therefore, researches to investigate the performance of concrete with waste cockle shell as partial coarse aggregate replacement in terms of compressive strength and workability is undertakened by many scientists, technologists, and engineers.

Addition of waste cockle shell as partial coarse aggregate replacement of 5% to 30% could reduce the concrete workability due to its shape and rougher texture. Meanwhile, the replacement of coarse aggregate by cockle shell exhibit highest value of compressive strength at the 20% replacement level compare to the other mixtures, including the conventional concrete. In short, certain percentage of cockle shell as partial coarse aggregate replacement can produce better strength of concrete than existing one and has high potential to be used as building material.

2.3.2 OIL PALM KERNEL SHELL AS PARTIAL COARSE AGGREGATE REPLACEMENT

Malaysia Palm Oil Board (2011) stated that an average 2.2 to 2.4 million tonnes of oil palm kernel shell is yield annually. This statistic indicated the high quantity of waste product OPKS is produced every year and been disposed in a landfill area. Therefore, many researchers had investigated the potential of OPKS to be utilized as construction materials in order to resolve landfill disposal issue. Due to the light and hard properties of OPKS, it can be utilized to replace natural coarse aggregate to produce lightweight concrete.

From the research by Alengaram et al. (2013), utilization of OPKS as lightweight aggregates (LWA) in concrete was investigated. The physical properties of

OPKS were discussed, as well as the mechanical properties and structural behavior of OPKS concrete. The test result proved that the OPKS can be categorized as lightweight aggregates due to the low specific gravity within the range of 1.17 – 1.62. In term of mechanical properties, Alengaram et al. (2013) mentioned that the modulus of rupture and splitting tensile test are closed to the conventional concrete. In term of structural behavior, the OPKS beam showed higher ductile behavior compared to the normal weight concrete (NWC) beam. In addition, the moment curvatures of OPKS beam exhibited similar trend as NWC beam.

According to Alengaram (2008), the structural behavior of reinforced oil palm kernel shell (OPKS) concrete beam in grade 30 concrete has been investigated. Results show that OPKS beam has higher moment capacity than NWC beam by 3%. The mode of failure for OPKS beam was ductile failure whereas the mode of failure for NWC beam was brittle failure. OPKS beam can be deflected to a higher constant load compared to NWC beam which show brittle failure without giving any pre-failure warning.

Mo et al.(2015) investigated the mechanical and structural properties of reinforced concrete beam between oil palm shell concrete (OPSC) and normal weight concrete (NWC) in similar compressive strength. The result reported that the splitting tensile strength of OPSC is slightly lower than that of NWC in the condition of similar compressive strength. Meanwhile, the modulus of elasticity for OPSC was only 24.5% of NWC.

According to Mo et al. (2015), both OPSC and NWC beams presented similar ultimate moment and also had similar flexural failure mode. The moment-deflection relationship of reinforced concrete beams prepared with OPSC and NWC are shown in Figure 2.1. It is very clear that the ascending part of moment-deflection curve for OPSC beam was less steep compared to that of NWC due to the lower modulus of elasticity of OPSC. In addition, the average primary crack spacing of the OPSC beam is smaller compared to the NWC beam. This phenomenon is attributed to the better bonding between OPSC and steel bar.

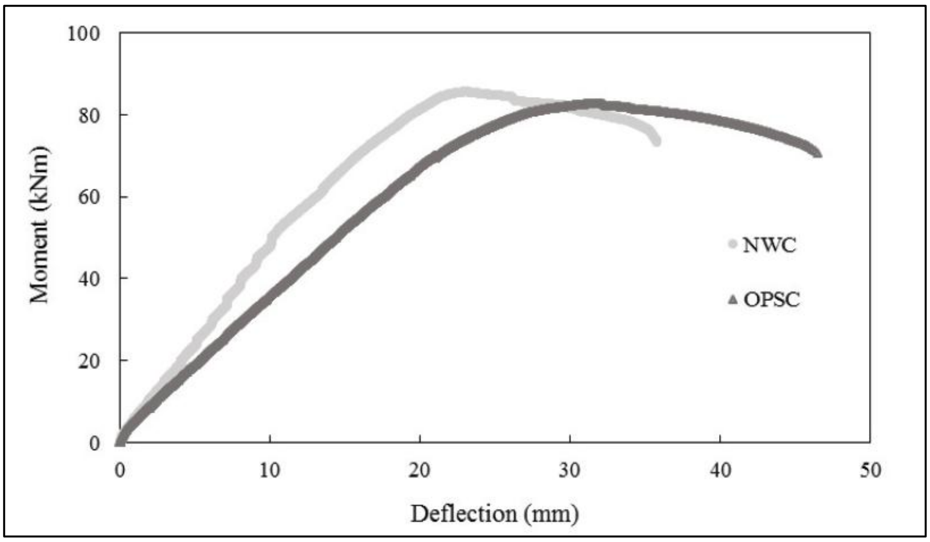


Figure 2.1: Moment-deflection relationship of reinforced concrete beams prepared with OPSC and NWC (Mo et al., 2015)

2.3.3 RECYCLED CONCRETE AGGREGATE AS PARTIAL COARSE AGGREGATE REPLACEMENT

The demolition of buildings and structures produces a lot of concrete aggregates, which can be recycled, but often they are dumped (Serreset al., 2015). Reutilization of these concrete aggregates in construction industry is necessary to develop a sustainable concrete to ensure the negative environmental impact can be reduced. Therefore, many research and development works have been taken over 30 years to investigate the use of RCA that influence the performance of concrete as construction materials (Silva et al., 2014).

Based on findings of Kalpavalli (2015), the recycled aggregates had low specific gravity and bulk density compared to the conventional aggregates and also had high water absorption due to present of attached mortar on the surface of recycled aggregates. Besides that, the result exhibited that the compressive strength of the recycled aggregate concrete was closed to target strength with the maximum 30% replacement level of natural aggregate by recycled aggregates. The flexural test presented decrease trend in flexural strength with increased percentage of recycled aggregate in concrete but still lies within the usable range.

Arezoumandi et al. (2015) investigated the flexural strength of reinforced concrete beams between 100% of recycled concrete aggregate (RCA) and conventional concrete (CC) under four-point loading method. In term of cracking progression, the result indicated that both of RCA and CC beam exhibited similar behaviour exclude the crack spacing of RCA beams was closed compared to those of CC beams. In term of load-deflection behaviour, the RCA beams presented higher deflection compared to the CC beams due to the lower stiffness presence in RCA beam. However, the result stated the flexural behaviour of RCA beams was comparable and superior at both service and ultimate states. In short, the RCA can be used and instead of the non-renewable natural coarse aggregate to develop an environmentally friendly concrete.

2.4 CERAMIC WASTE

Ceramic waste can be classified into two sources. The first source of ceramic waste is the ceramic industry. Yap & Foong (2013) had mentioned that about 15 to 30 % of daily production goes to waste ceramic industry. The second source of ceramic waste is correlated with construction and demolition activity. In the composition of construction and demolition waste, it is more than half corresponds to ceramic materials which had contributed highest percentages of all materials (Juan et al., 2011).

2.4.1 CLASSIFICATION OF CERAMIC WASTES

Ceramic wastes can be divided into two separate categories, differentiated by their source of raw materials. The structural ceramic factories which use red paste to manufacture products such as bricks, blocks and roof tiles will tend to produce fired wastes that fall into the first category. On the other hand, fired wastes of the second category came from the production of stoneware ceramic such as wall, floor tiles and sanitary ware, which uses white paste. The usage of white paste is more popular than red paste, and hence, contributes to the higher volume of ceramic waste. The fired ceramic wastes were classified according to the type and production process, as shown in Figure 2.2.

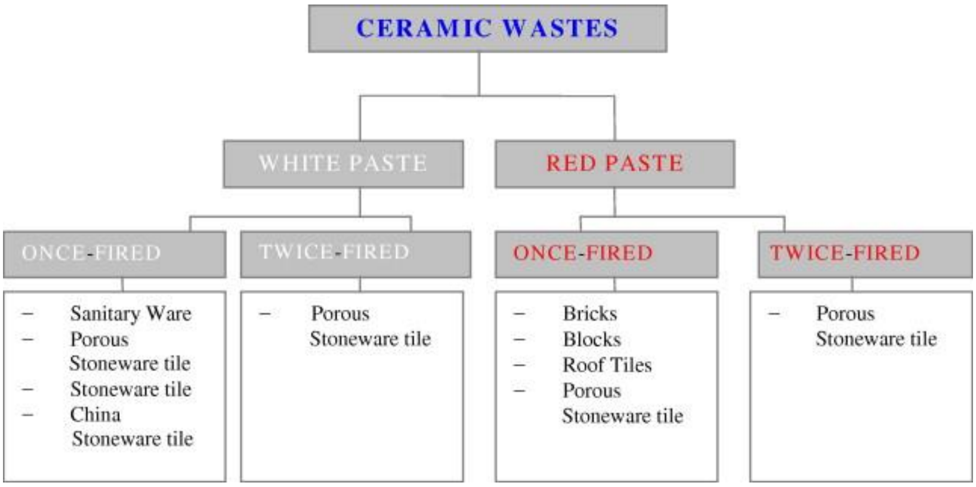


Figure 2.2: Classification of ceramic waste by type and production process (Pacheco-Torgal & Jalali, 2010)

2.4.2 CHEMICAL COMPOSITION

Two of the utmost important oxides present in the ceramic pastes are alumina and silica. It is undeniable that fired ceramic products possess chemical composition that is quite similar with one of raw substance used to manufacture ceramic products. As these materials are heated, it will alter only the mineralogical constitution. Different types of clay used may cause the difference of proportion of the silica and alumina. The red paste display high quantity of iron oxide which is mainly accountable for the red colour of the products. Ceramic aggregate was produced with crushed the ceramic wastes. Table 2.4 presented the chemical composition of ceramic paste.

Table 2.4: Chemical composition of ceramic pastes (Pacheco-Torgal & Jalali, 2010)

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2
Red paste twice-fired ceramic	51.7	18.2	6.1	6.1	2.4	0.2	4.6	0.8
White paste once-fired ceramic	58.0	18.0	1.0	8.3	0.6	0.2	1.2	0.8
White paste twice-fired ceramic	59.8	18.6	1.7	5.5	3.5	1.6	2.5	0.4
Red paste for stoneware tile	29.1	20.3	7.7	1.2	1.1	0.4	4.2	0.9
White paste for stoneware tile	65.0	21.3	1.3	0.2	0.3	2.5	3.7	0.2
White paste for sanitary ware	65.8	22.2	0.6	0.1	0.1	1.0	3.5	0.3

2.4.3 RESEARCH DEVELOPMENT

Sekar et al. (2011) studied strength characteristics of concrete made with waste materials as coarse aggregate. Waste materials such as broken glass pieces ceramic insulator and ceramic tile waste are 100 % used to replace the natural coarse aggregate in concrete. As a result, ceramic tile aggregate concrete exhibited similar strength in compression, flexure and split tensile as conventional concrete. The strength results of concrete with different waste materials as coarse aggregate are shown in Table 2.5.

Table 2.5: Comparison of strength results (Sekar et al., 2011)

Mix	Average Compressive Strength (MPa)		Average Splitting Tensile Strength (MPa)		Average Flexural Strength (MPa)	
	7 days	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**
A	6.81	21.26	0.86	3.24	10.37	17.13
B	5.67	17.86	0.85	2.89	9.78	16.90
C	4.76	15.66	0.79	2.94	8.70	13.95
D	7.18	20.23	0.92	2.95	9.91	18.02

A – Controlled specimen
B – Ceramic insulator scraps
C – Crushed glass
D – Ceramic tile waste

According to Senthamarai & Devadas Manoharan (2005), the mechanical properties of ceramic waste coarse aggregate concrete were determined. As the lower water absorption of ceramic waste coarse aggregate, the fresh ceramic waste coarse aggregate was more workable than conventional concrete. The results indicated that the compressive strength of ceramic waste coarse aggregate concrete is not much different from conventional concrete. Besides that, the splitting tensile strength of ceramic waste coarse aggregate concrete was less than conventional concrete whereas the flexural strength between both concretes was almost same.

Ch et al., (2015) studied that the suitability of waste ceramic tiles as partial replacement of fine and coarse aggregates in the concrete. To investigate the combined behaviour and performance of ceramic materials in concrete, different percentages of fine and coarse aggregates replaced were included in the study (Table 2.6). Based on the workability test, maximum slump is achieved when the fine aggregate was 20 % replaced by tiles powder. The result indicated that increase in workability of concrete with increased of tile powder. Besides that, it is also showed that slightly increase in workability when coarse aggregate was replaced by crushed tiles.

In addition, Ch et al. (2015) also mentioned that the quality of all concrete mixer was excellent based on ultrasonic pulse velocity test. According to compressive strength test at 28 days, the maximum compressive strength is achieved when the 20% of fine aggregate was replaced by tiles powder. The result also presented that the compressive strength of concrete is increased up to 10 % of replacement level but then decreased at 20 % of replacement level when ceramic tiles was replaced in coarse aggregate only. The results of compressive strength and slump value with different percentage of fine and coarse aggregates replaced are shown as Table 2.6.

Table 2.6: Results of compressive strength and slump value with different percentage of fine and coarse aggregates replaced (Ch et al., 2015)

Mix	Fine Aggregate (%)		Coarse Aggregate (%)		Average Compressive Strength (MPa)		Slump (mm)
	Sand	Tiles Powder	Coarse Aggregate	Crushed Tiles	7 days	28 days	
A0	100	0	100	0	32.73	34.30	40
A1	100	0	90	10	34.36	36.69	45
A2	100	0	80	20	30.41	32.97	45
A3	90	10	100	0	26.97	34.30	120
A4	80	20	100	0	28.09	36.69	130
A5	90	10	90	10	26.72	38.72	65
A6	90	10	80	20	26.07	35.56	55
A7	80	20	90	10	35.19	39.16	80
A8	80	20	80	20	31.23	35.46	75

According to Tavakoli et al. (2013), waste ceramic tile was used to partial replace coarse aggregate in concrete with 10 %, 20 %, 30 % and 40% replacement by weight of coarse aggregate. The result reported that the highest compressive strength achieved as 10 % of coarse aggregate was replaced by ceramic tile which had increased about 5 % compared to conventional concrete. However, it is slightly decreased in compression strength due to increase of flaky ceramic tile aggregate. The unit weight of concrete was decreased as the amount of ceramic tile aggregate was increased. In short, the researcher concluded that the optimum percentage of replacement ceramic tile as coarse aggregate was ranged from 10 to 20 %.

2.5 STRENGTH OF CONCRETE

Performance of concrete could be evaluated from mechanical properties or structural behaviour to identify suitability of waste product as partial coarse aggregate replacement materials. Furthermore, strength of concrete is the ability of concrete to resist the stress produced by an external force without failure. There are various tests such as compressive and flexural test could be carried out to determine the performance and strength of concrete.

2.5.1 COMPRESSIVE STRENGTH

Compressive strength is the most important mechanical property of concrete. It is measured on the capacity of a structure to sustain the compressive load without fracture. It is usually used to determine the overall quality of concrete as it is most convenient to measure (Li, 2004). The compressive strength of a concrete is depending on the mix design and curing conditions (Alengaram et al., 2013).

Compressive strength test is carried out to determine the ultimate load that can withstand by concrete without failure. Compressive tests on the specimens should be conducted immediately after removal from curing process. Cube and cylinder are the common types of specimens used to compression test. The compressive strength is expressed as ultimate compressive load per cross-sectional area, normally in pascals (Pa) or pounds in square inch (psi).

In addition, compressive strength of concrete can be affected by many parameters such as the quality of raw materials, water/cement ratio, coarse and fine aggregates ratio, temperature, relative humidity, compaction of concrete, age of concrete and curing of concrete. These parameters are important in the development of compressive strength to produce a good quality concrete.

2.5.2 FLEXURAL BEHAVIOUR

Flexural test is carried out to determine the flexural behaviour of a beam. The flexural behaviour is happened at the middle of the beam due to the load is imposed directly at the centre area. The deflection of the beam could be measured with linear variable displacement transducer (LVDT) and mode of failure also can be observed from the beam (Alengaram et al., 2008).

Two methods for flexural test for beam are three point loading and four point loading. The three point loading has smaller stress concentration and mostly concentrated under the centre of the loading point whereas the four point loading has larger stress concentration and spread over a larger region. Both methods of loading test are not much different from each others.

According to Arezoumandi et al. (2015), flexural behaviour of a beam can be studied in term of flexural loading capacity, deflection, ductility and failure mode. Other than that, the pattern of cracks also can be observed with the flexural test. The arrangement of longitudinal and shear reinforcement steel is one of important factor affected the failure mode of a beam.

2.6 CONCLUSION

From the previous literature, many researchers had investigated the potential of ceramic waste as partial coarse aggregate replacement material in concrete. However, the replacement porcelain granite tile waste as coarse aggregate with size of pallet form had not been studied yet. Besides that, there is no much research on reinforced structural member with porcelain granite tile waste coarse aggregate. Hence, it is important to identify the suitability of this type aggregate in structural concrete.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discussed the method for preparation and the test to be performed to examine the suitability of replacement ceramic waste as coarse aggregate in the concrete. It also summarized the research methodology of the study. The detail of the materials used for concrete cube and reinforced concrete beam will be presented in this chapter. Besides that, the method of the experimental works and test were discussed through this chapter.

The main purpose of the research was to collect the data through the concrete density, compressive and flexural strength test and all the data was analysed to achieve the research objectives. The flow chart of the research was summarized the research of the study show as Figure 3.1.

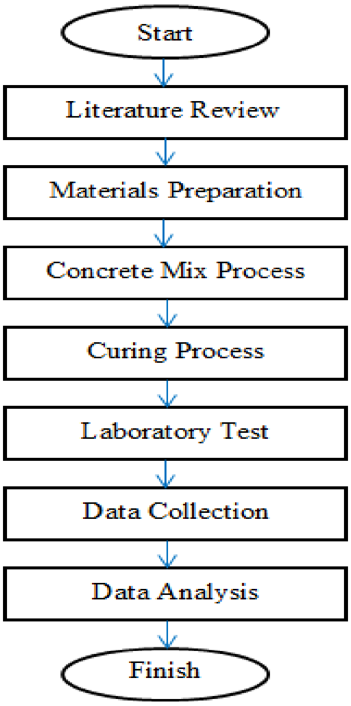


Figure 3.1: Flow chart of research

3.2 MATERIALS

The materials used in this study were cement, coarse aggregate, ceramic waste coarse aggregate, fine aggregate, water and reinforcement bar. The porcelain granite tile waste (PGTW) was replaced as coarse aggregate in the percentages. All the types of material were clearly presented and prepared carefully to ensure quality of the concrete. The description of each material was discussed on the following part.

3.2.1 CEMENT

Cement is known as binding material used in production of concrete. It is often called hydraulic cement and mixed with water and aggregates to form concrete. There are lots of cement types such as Ordinary Portland cement, sulphate resisting cement, rapid hardening cement and so on. The cement that selected to be used in this research was Portland Composite Cement as shown in Figure 3.2. This cement is the most common cement used in Malaysia for general concrete construction works. For the precaution, the cement was needed to be arranged and kept at dry place to prevent it to become hardened.

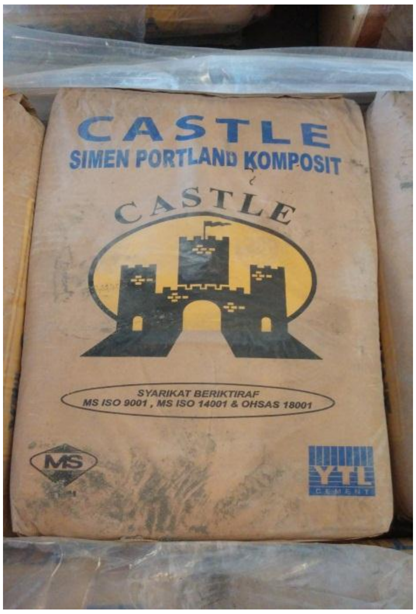


Figure 3.2: Portland Composite Cement

3.2.2 COARSE AGGREGATE

There were two types of coarse aggregate used in this research which were natural aggregate and ceramic waste aggregate. The natural coarse aggregate used was granite in this study and it was shown in Figure 3.3. Granite is a natural resource that cannot be replaced once it used. The maximum size of granite aggregate used was 20 mm.

The ceramic waste used was homogenous porcelain granite tile and it was collected from the construction waste at UMP. Homogenous porcelain granite tile was used to improve the precious due to different porcelain granite tiles has different characteristics. The collected Porcelain Granite Tile Waste (PGTW) was broken into pieces with requires size by hammer. The size of ceramic waste coarse aggregate was fixed at 5- 20 mm. The PGTW as coarse aggregate was 0%, 10%, 20% and 30% in concrete mixing by weight. The PGTW used was shown in Figure 3.4.

All the coarse aggregate used throughout this experimental works was air dried to obtain saturated surface dry condition. Then, the coarse aggregate was sieved to obtain the proper size needed for concrete mixing and remove other impurities.

Figure 3.3: Natural granite

Figure 3.4: Porcelain Granite Tile Waste (PGTW)

3.2.3 FINE AGGREGATE

Fine aggregate used in this research was river sand. The function of fine aggregate is used to fill the void between coarse aggregate and denser the concrete. The aggregate pass through sieve 4.75 mm is considered as fine aggregate according to

ASTM. The fine aggregate was sieved to obtain the required size for concrete mixing and kept at air dry condition before mixing process. The fine aggregate was needed fully dry before used in mixing due to wet sand may disturb the moisture content of concrete mix. Figure 3.5 illustrated the river sand used in this study.

Figure 3.5: River sand

3.2.4 WATER

Water used in this research was tap water. Water is needed for hydration process with cement and contributes to workability. In concrete mix, the water used should not be contaminated and it should be at neutral state where the pH level is not more and less than 7. Tap water supplied at laboratory was used for concrete works and curing process due to fulfil the requirement state and easy to obtain.

3.2.5 REINFORCEMENT BAR

The reinforcement bar used in this research was high yield steel. The function of reinforcement bar is increased the strength of concrete due to concrete is poor on tensile strength. The diameter of reinforcement steel bar used was 12 mm arranged longitudinally at the bottom of beam whereas the diameter of link bar used was 6 mm arranged vertically with spacing 250 mm. The concrete cover for reinforced concrete beam was fixed at 20 mm. The reinforcement bar was cut into the 1700 mm long by steel cutter and then bends the end of steel bar with plier. The arrangement of reinforcement bar was show in Figure 3.6.

Figure 3.6: Arrangement of reinforcement bar

3.3 CONCRETE MIX DESIGN

Concrete mix design is the method used to determine the proportions concrete mix constituents in order to achieve desired strength. There are numerous methods available for concrete mix designs for concrete such as IS method, ACI method, DOE method and so on. Department of Environment method (DOE) was selected to be used in this research because it is an effective and substantial method in concrete mix design.

The ingredients of the concrete which are cement, fine aggregate, coarse aggregate, ceramic waste coarse aggregate and water to be included in the concrete mix design. In this research, it was to design concrete mix to strength of 25 N/mm^2 at 28 days. Natural coarse aggregate was replaced partially with PGTW.

Four different percentages of replacement of coarse aggregate was determined by weight method. In other words, four different mix types were prepared for the test which were 0%, 10%, 20% and 30% of PGTW and named as P0, P1, P2 and P3 respectively. The mix design was calculated based on the six cubes and one beam for each mix types. The mix design also included 15% wastage. The data for the mix proportion was tabulated in Table 3.1.

Table 3.1: Mix proportion table

Mix Type	Cement (kg)	Water (kg)	w/c ratio	Fine Aggregate (kg)	Granite Aggregate (kg)	PGTW (kg)
P0	30.75	16.88	0.65	60.38	70.88	-
P1	30.75	16.88	0.65	60.38	63.79	7.09
P2	30.75	16.88	0.65	60.38	56.70	14.18
P3	30.75	16.88	0.65	60.38	49.62	21.26

3.4 PREPARATION OF SPECIMENS

The cube and beam specimens were prepared in this study. Four different proportions of concrete included control were needed to be prepared in this study. For cube, three specimens were prepared for each proportion. Besides that, four specimens of reinforced concrete beam were prepared in this study. The cube specimens were casted in the cube mould with size of 150 mm x 150mm x 150 mm. Meanwhile, the beam specimens casted in the beam mould with size of 150 mm x 200 mm x 1500 mm.

The moulds were cleaned properly and a layer of grease oil was applied on the inner surface of moulds to facilities the removal process. The materials of concrete were prepared and weighted according to the concrete mix design. All the materials were then poured into concrete mixer for mixing process due to concrete mixer ensures the mixture was mixed evenly. After completed mixing process, the fresh concrete was poured into the mould. The concrete surface was finished with trowel to provide smooth surface. Next, the specimens was left and kept at laboratory for 24 hours of casting. After removal the specimens from the moulds, the cube specimens were cured immediately with different method.

3.5 CURING

Curing is the important step in controlling of moisture content and temperature in concrete for a specific time. In addition, curing is essential for cement hydration to prevent loss of moisture during the early hardening process. The properties of hardened concrete are influenced by curing. Proper curing is needed to ensure the strength of concrete. In this study, cube specimens were cured into the water curing tank as shown in Figure 3.7 whereas the beam specimens were cured by cover the top surface with wet sacks as shown in Figure 3.8. All the specimens were cured for 28 days and it was sufficient period for the curing process.

Figure 3.7: Water curing tank

Figure 3.8: Curing with wet sacks

3.6 CONCRETE DENSITY TEST

Concrete density test was carried out to determine the density of hardened concrete. The density of hardened concrete was measured according to ASTM C 642. This test method can be used to determine conformance with the specification for concrete. The concrete density test was performed by simple dimensional check and weighting method. The conventional concrete and PGTW concrete was tested for determination of density in hardened concrete specimens. The formula for the density of concrete was expressed as in Eq. (3.1):

$$D = \frac{M_c - M_m}{V_c} \tag{3.1}$$

Where

D = Density of the concrete (kg/m^3)

M_c = Mass of the concrete measure (kg)

M_m = Mass of the empty concrete measure (kg)

V_c = Volume of the measure (m^3)

3.7 COMPRESSIVE STRENGTH TEST

Compressive strength test was carried out to determine the compressive strength of hardened concrete specimen. The test was conducted by complies with the standard of ASTM C 39. The test was conducted immediately after removal the cube specimens from the curing tank. It was tested for the measurement of concrete strength at the design age of 7 and 28 days. The compressive strength test was conducted by using compressive testing machine as shown in Figure 3.9.

The concrete specimen was subjected to the compression load at the specified rate. The specimen was tested to its failure and the maximum load that can be achieved. The ultimate compressive strength can be calculated by dividing the maximum load carried by the specimen during the test by the cross-sectional area. The formula of the compressive strength was expressed in Eq.(3.2):

$$f_c = \frac{P}{A} \tag{3.2}$$

Where

f_c = Compressive strength of concrete specimen (N/mm^2 or MPa)

P = Maximum load carried by the specimen during test (N)

A = Average cross-sectional area of the specimen (mm^2)

Figure 3.9: Compressive testing machine

3.8 FLEXURAL TEST

Flexural test was carried out to determine the flexural behaviour of reinforced concrete beam specimen. The test was conducted immediately after removal the beam specimens from the curing. All the specimens were white washed in order to facilities the crack marking. The machine used was Magnus Frame Machine and it was tested under four point loading method. The beam specimens were subjected to two-point loads under a load control mode.

The linear variable displacement transducer (LVDT) was used for the measurement of the deflection at the mid-span. The LVDT was connected to the data logger so that the reading at every time interval was captured by the computer until the failure of beam was happened. The patterns of the crack were observed and the crack width was measured by the callipers. Besides that, the mode of failure of beam specimens could be determined by crack patterns. Figure 3.10 shows the experimental setup for beam specimens.

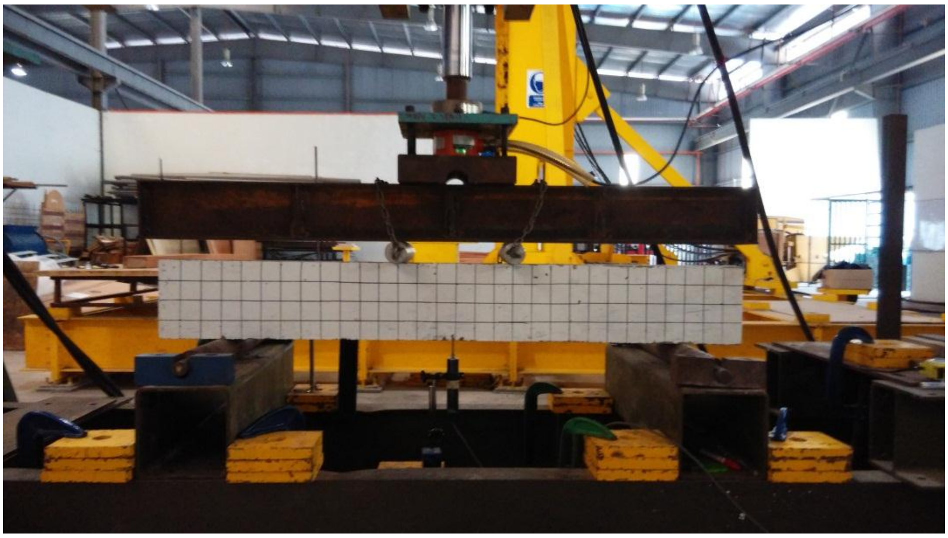


Figure 3.10: Experimental setup for beam specimens

3.9 CONCLUSION

This chapter presented the sequence of the experimental works which were involved the materials preparation, preparation of test specimens, curing process, concrete density test, compressive strength test and flexural test. All the experimental data was collected and analysed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter presented the results obtained from the experimental testing and discussions of test in previous chapter which examine the performance of porcelain granite tile waste (PGTW) in concrete composition. The results of the test included the compressive strength, concrete density and beam strength of the specimen. The results and discussions focused on the beam strength such as load-deflection behaviour and mode of failure. All the results of the test were discussed in this chapter and all the data was illustrated in table and graph for better understanding of the test results.

4.2 CONCRETE DENSITY TEST

The density test was carried out to determine the density of the hardened concrete. The 150 mm x 150 mm x 150 mm cube specimens were tested for the 28 days concrete density. The average results were obtained by test with three specimens for each percentage of PGTW content. The results for concrete density were listed in Table 4.1.

From the Table 4.1, the result shows that the concrete density was decreased as the percentage of PGTW content increased. The concrete densities of 10%, 20% and 30% PGTW was marginally decreased by 1.3%, 2.0% and 2.9% respectively as compared to density of control concrete. The result indicated that the concrete density was almost constantly decreased by 1% for each 10% of PGTW content increased.

Table 4.1: Results of concrete density

Percentage of PGTW Content	**Weight (kg)**	**Concrete Density (kg/m^3)**
0%	7.766	2301.0
10%	7.667	2271.7
20%	7.611	2255.1
30%	7.540	2234.1

On the other hand, decreased in concrete density was due to the unit weight of PGTW as coarse aggregate was lesser than granite stone. The densities of various percentage of PGTW content within the range of 2200-2600 kg/m^3, regarded as density of normal weight concrete (Neville, 2011).

4.3 COMPRESSIVE STRENGTH TEST

The compressive strength test is important to determine the strength of the hardened concrete. The cube specimens were cured and tested at the ages of 7 and 28 days for the compressive strength. The average results were acquired by test with three specimens for each age of curing. The results for compressive strength of the PGTW concrete cube were shown in Table 4.2 and the graph for compressive strength against curing ages was presented in Figure 4.1.

Table 4.2: Results of the compressive strength

Percentage of PGTW Content	**Compressive strength (MPa)**	
	7 Days	**28 Days**
0%	18.40	26.74
10%	20.36	29.20
20%	22.87	31.65
30%	18.08	25.45

The compressive strength of concrete specimens was increased with age of curing. At the 7th day, the compressive strength of P2 concrete was attained 20.36 MPa, which was the highest among of the others. The result shows that the early strength of the P2 concrete which was 24.3% higher than P0. At the 28th day, the compressive strength of P2 was attained 31.65 MPa, which was also the highest among of the others. The result presents that strength of P2 concrete at 28 days was 18.4% higher than P0.

The early strength of the all specimens achieved approximately 70% of 28th day strength. The compressive strength of P0, P1, P2 and P3 concretes was increased from 7th day to 28th day by 45.3%., 43.4%, 38.4% and 40.76% respectively. Besides that, compressive strength of P1 and P2 concretes was drastically increased by 9.2% and 18.4% respectively, as compared to P0. For P3 concrete, the compressive strength was slightly decreased by 4.8% as compared to P0.

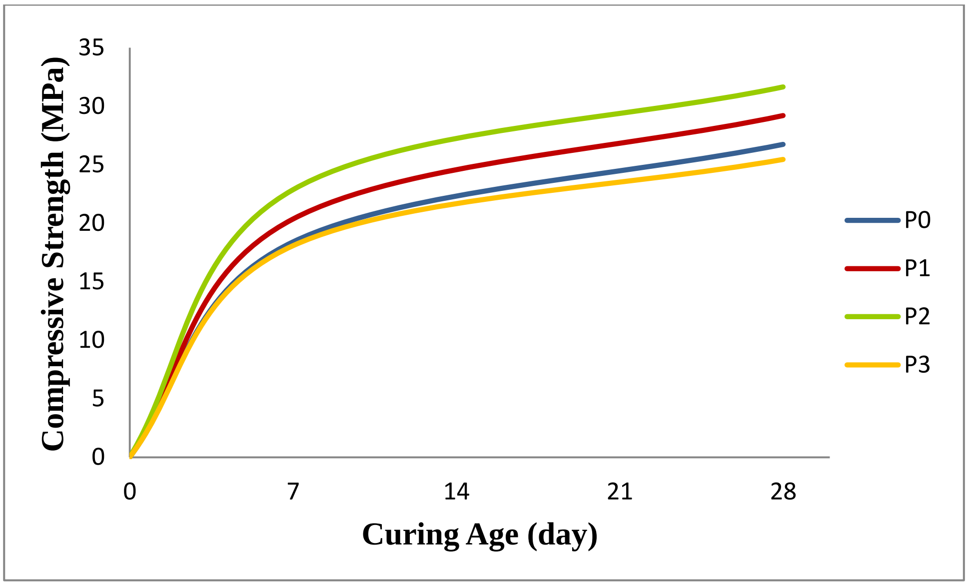


Figure 4.1: Graph of compressive strength against curing age

Tavakoli et al. (2013) stated that substitute the ceramic wastage as partial coarse aggregate in concrete produced no remarkable negative effect in concrete quality. The author also mentioned that the best case for replacement was amount of 10 to 20%. On the contrary, reduction of strength was due to larger amount using of tiles increased the percent of flaky aggregates. As a result of smooth surface of aggregate, lack of engagement between concrete and aggregate also caused decrease of strength.

In compressive strength result, all the concrete was passed the design grade of 25 MPa. On the other hand, the result shows that the compressive strength of PGTW concrete was increased at 10% and 20% but decreased at 30%. The highest compressive strength at 28 days was occurred at P2 concrete. Therefore, it can be concluded that the optimum percentage of PGTW replacement in concrete was 20%.

4.4 LOAD AND DEFLECTION THEORY

Theoretical load and deflection are calculated based on ACI 318-05 and EC 2. The theoretical data was used to compare the result between the experimental and theoretical. In addition, the theoretical data is important to predict the outcome of experimental works.

4.4.1 Load Theory (Based on ACI 318-05)

Nominal moment capacity, $M_n = A_s f_{yk}(d - \frac{B_1 c}{2})$

$$B_1 c = \frac{A_s f_{yk}}{0.85 f_{ck} b}$$

Where M_n = moment capacity of the rectangular beam (kNm)

A_s = cross section of steel reinforcement (mm^2)

f_{yk} = yield of steel reinforcement (kN/m^2)

d = distance from compression to the centroid of tension steel

f_{ck} = compressive strength of concrete beam (kN/m^2)

b = width of beam (m)

$$M_n = 226\ x\ 500\ x\ (168 - \frac{\left(\frac{226 \text{ x } 500}{0.85 \text{ x } 25 \text{ x } 150}\right)}{2})$$

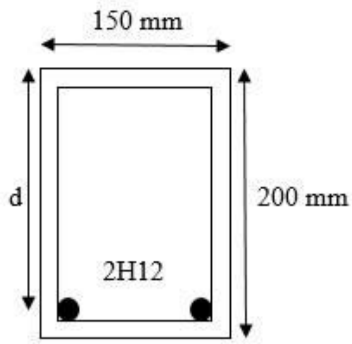
= 16.98 kNm

Maximum shear force, P/2 = 37.73 kN

P = 75.47 kN

4.4.2 Load Theory (Based on EC 2)

Length of beam, L	= 1500 mm
Effective width of section, b	= 150 mm
Depth of section, h	= 200 mm
Nominal cover, c	= 20 mm
Concrete strength, f_{ck}	= 20 N/mm^2
Shear link strength, f_{yk}	= 250 N/mm^2
Diameter of reinforcement, ∅ bar	= 12 mm
Diameter of shear link, ∅ link	= 6 mm
Reinforcement strength, f_{yk}	= 500 N/mm^2



Design:

Effective depth, d = h – c – 0.5 (∅ bar) – ∅ link

= 200 – 20 – (12/2) – 6

= 168 mm

F_{cc} = F_{st}

$0.454f_{ck}bx$ = $0.87f_{yk}A_s$

x $= \frac{0.87f_{yk}A_s}{0.454f_{ck}b}$

$= \frac{0.87(500)(226)}{0.454(20)(150)}$

= 57.74 mm

Level arm, z = d – 0.4x

= 168 – 0.4(57.74)

= 144.90 mm

Ultimate moment, M $= 0.87f_{yk}A_sz$

$= 0.87 \text{ x } 500 \text{ x } 226 \text{ x } 144.90$

$= 14.25$ kNm

Maximum shear force, $P/2 = 31.67$ kN

$P = 63.34$ kN

4.4.3 Deflection Theory (Based on ACI 318-05)

For the deflection, calculation was based on Eq.(4.1), (4.2) and (4.3) referring ACI 318-05. The load from 5 to 90 kN were calculated. The calculation below refered to the first load of 5 kN and then it was continuous calculated until 90 kN load specified as show in Table 4.3.

The moment of inertia is a property of shape and used to estimate the resistance of a beam to bending and deflection. The deflection of a beam not only depend the load but also depend on the geometry of the cross section. The critical moment of inertial was used to ensure the larger deflection was predicted in theoretical.

The product EI is known as beam stiffness and used to measure the beam resists the deflection under the bending moment. In addition, the different EI was used to estimate the minimum and maximum deflection.

Based on ACI 318-05, the moments of inertia were calculated as follow:

$$I_{cr} = \frac{bc^3}{3} + [(d - c)^2 \text{ x } (n \text{ x } A_s)] \tag{4.1}$$

$$= \frac{150(61.45)^3}{3} + [(168 - 61.45)^2 \text{ x } (11.76 \text{ x } 226)]$$

$$= 4.2\text{x}10^7 \text{ mm}^4$$

where $n = \frac{\text{E steel}}{\text{E concrete}}$ (4.2)

$= \frac{200}{17}$ (based on ASTM A-36)

= 11.76

(b/2) c^2 + 226nc – 226nd = 0

(150/2) c^2 + 226(11.76) c – 226(11.76)(168) = 0

c = 61.45 mm

For P = 5 kN,

$$\delta \text{ min} = \frac{PL^3}{48EI}\left[\left[\frac{3a}{L} - 4\left(\frac{a}{L}\right)^3\right] + \left[\frac{3b}{L} - 4\left(\frac{b}{L}\right)^3\right]\right] \tag{4.3}$$

$$= \frac{(5\ x\ 10^3)x\ 1200^3}{48(200\ x\ 10^3)(4.2\ x\ 10^7)}\left[\left[\frac{3(450)}{1200} - 4\left(\frac{450}{1200}\right)^3\right] + \left[\frac{3(750)}{1200} - 4\left(\frac{750}{1200}\right)^3\right]\right]$$

= 0.0388 mm

For P = 5 kN,

$$\delta \text{ max} = \frac{PL^3}{48EI}\left[\left[\frac{3a}{L} - 4\left(\frac{a}{L}\right)^3\right] + \left[\frac{3b}{L} - 4\left(\frac{b}{L}\right)^3\right]\right]$$

$$= \frac{(5\ x\ 10^3)x\ 1200^3}{48(11.76\ x\ 10^3)(4.2\ x\ 10^7)}\left[\left[\frac{3(450)}{1200} - 4\left(\frac{450}{1200}\right)^3\right] + \left[\frac{3(750)}{1200} - 4\left(\frac{750}{1200}\right)^3\right]\right]$$

= 0.6605 mm

Table 4.3: Theoretical deflection data

Load, P (kN)	Deflection, δ (mm)	
	Minimum	Maximum
0	0	0
5	0.0388	0.6605
10	0.0777	1.3211
15	0.1165	1.9816
20	0.1554	2.6421
25	0.1942	3.3027
30	0.2330	3.9632
35	0.2719	4.6237
40	0.3107	5.2843
45	0.3496	5.9448
50	0.3884	6.6053
55	0.4272	7.2659
60	0.4661	7.9264
65	0.5049	8.5869
70	0.5438	9.2474
75	0.5826	9.9080
80	0.6214	10.5685
85	0.6603	11.2290
90	0.6991	11.8896

4.5 FLEXURAL TEST

The beam specimens were cured and tested at the age of 28 days for the flexural test. The beams were tested under four point loading test. The purpose of the testing was to examine the ultimate load, deflection, first crack and mode of failure for all beams. All the data was collected from the flexural test by using Magnus Frame. The raw data for all the beams was shown in Appendix B to E.

4.5.1 Load-deflection Behaviour

All the beams were reinforced included control beam. The results of PGTW beams were compared with the control beam in order to determine the behaviour of beams in term of load carrying capacity and deflection. The experimental data was plotted based on the Appendix B to E. The results of load-deflection curves for all beams between theoretical and experimental were presented in the Figure 4.2.

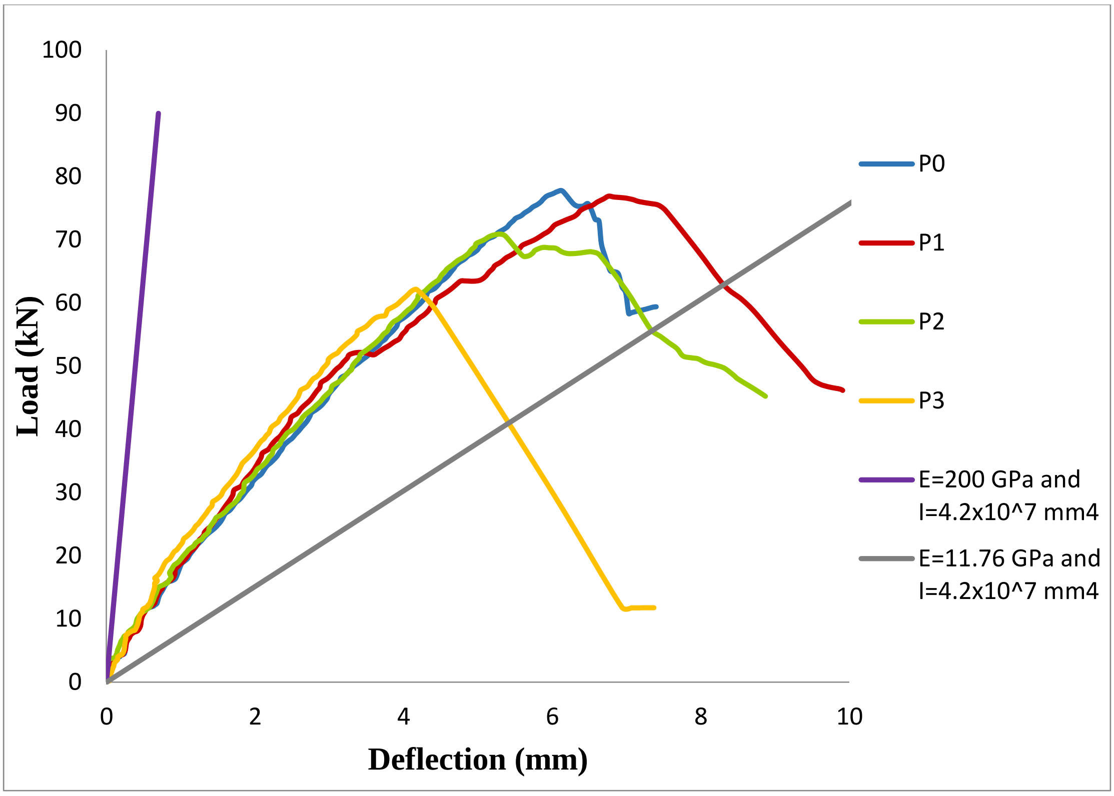


Figure 4.2: Load-deflection curve for all beams between theoretical and experimental

From the Figure 4.2, the load was continuously increased with deflection until reached the ultimate load. Before first crack occurred, all the beams exhibited nearly linear load-deflection behaviour. A significant change in the deflection was displayed for all the beams when the first crack observed. After reached the ultimate load, the beams also presented a significant increase in deflection. The load was then decreased as the deflection increased rapidly.

Kamal et al. (2015) stated that the behaviour of all beams was gone through three stages. The first stage was elastic behaviour, in which the relationship of load-deflection was linear as load proportioned to the deflection, and ended with first crack noticed. The crack propagation stage was the second stage, in which the load-deflection relationship was non-linear. The failure stage was the third stage.

The ultimate load of P0 beam was 77.70 kN, which was the highest among the beams. The results show that the control beam was better in load carrying capacity as compared to other beams. The ultimate loads for P1, P2 and P3 beams were lower than P0 beam, which were 76.90 kN, 70.89kN and 62.10 kN respectively. Furthermore, the ultimate load of P1 beam was marginally decreased by 1.0% as compared to P0 beam. The ultimate load of P2 and P3 beams were decreased drastically by 8.8% and 20.1% respectively as compared to P0 beam.

Based on the Figure 4.2, all the PGTW beams behaved same load-deflection curve with control beam. Other than that, the load-deflection for all beams was within the range of theoretical as expected. At the load of 50 kN, the deflection of P0, P1, P2 and P3 beams were about 3.38 mm, 3.15 mm, 3.31 mm and 2.95 mm respectively whereas the theoretical deflection was between 0.39 mm and 6.51 mm.

Table 4.4: Results of load-deflection

Specimen	Load (kN)	Deflection (mm)	Remarks
P0	19.55	1.09	First crack observed
	77.70	6.14	Ultimate load
P1	19.24	1.04	First crack observed
	76.90	6.76	Ultimate load
P2	18.77	0.94	First crack observed
	70.89	5.30	Ultimate load
P3	17.99	0.75	First crack observed
	62.10	4.18	Ultimate load

Table 4.4 shows that the load-deflection data for all beams. The load was recorded when first crack was observed. The beam was considered as failures when a larger number of cracks were occurred at ultimate load. The first crack of P0, P1, P2 and P3 beams was observed when the load at 19.55 kN, 19.24 kN, 18.77 kN and 17.99 kN respectively. The results indicated that the first crack of P1, P2 and P3 beams was happened faster than P0 beam.

The ultimate load of P1, P2 and P3 beams was decreased by 1.0%, 8.8% and 20.1% respectively, as compared to P0 beams. The result was not presented that the P2 and P3 beams were weaker in load carrying capacity because both beams were virtually approached with the theoretical value as expected. The result of ultimate load from experimental and theoretical was listed in Table 4.5.

Table 4.5: Result of ultimate load from experimental and theoretical

Specimen	Load (kN)	EC2 (kN)	ACI 318 (kN)
P0	77.70	63.34	75.47
P1	76.90		
P2	70.89		
P3	62.10		

According to the result obtained, all the beams experience relatively small deflection prior to failure. The deflection for all the beams was less than 7 mm at the ultimate load. Based on the cracks observed, the results indicated that all the beams behaved same pattern of crack due to the arrangement of the reinforcement was same for all beams.

On the other hand, the result shows that the ultimate load of PGTW beam decreased at 10%, 20% and 30%. The ultimate load of P1 beam was not much difference with P0 beam. In conclusion, the replacement of PGTW in concrete beam was not significantly contributed to load carrying capacity. However, all the beams had same load-deflection behaviour with control beam.

4.5.2 Modes of failure

The flexural failure mode was observed for all beams. The yielding of tensile steel was took place and then followed by concrete crushing in compression. Due to all the beams were designed as under-reinforced, thus the failure was started by yielding of the tension steel before the concrete fail in compression as expected.

Figure 4.3 presented the failure mode of control beam. The formations of crack were recorded with mark on the each beam. The first crack was always happened close to the mid-span of the beam. Besides that, the number of crack for all beams was about 10 to 13 whereas the crack width of beams was ranged between 0.15 mm and 5 mm.

For all the beams, failure was started with flexural crack and then extended to the neutral axis. After reached the neutral axis, the crack was started to incline to form compression failure zone. The beam was failed in brittle manner as the no prolonged deflection happened at the ultimate load. The failure finally was ends with flexural shear crack. In short, overall results indicated that all the beams failed in flexure shear and the failure zone was almost same for all beams.

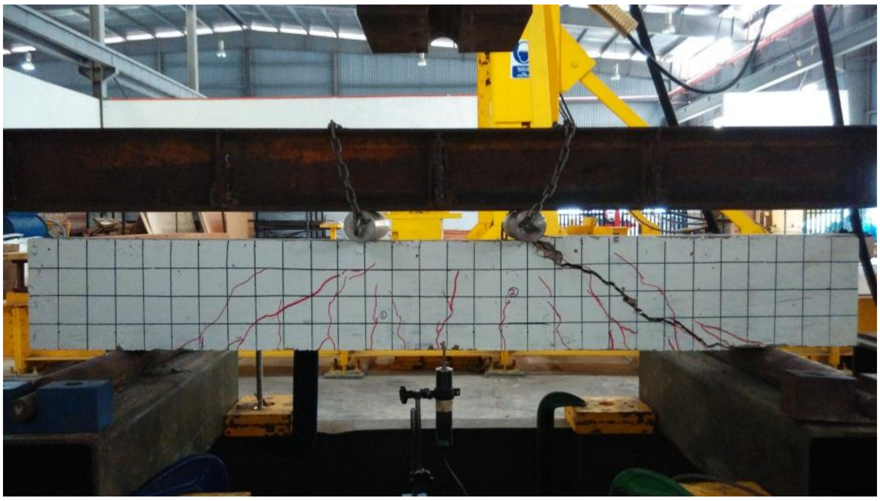


Figure 4.3: Failure mode of control beam

4.6 CONCLUSION

This chapter discussed about the experiment result and discussion of this study. The compressive strength results indicated that 10% and 20% of PGTW was increased. All the PGTW reinforced concrete beams had showed similar flexural behaviour as control reinforced concrete beam. Besides that, the comparison between theoretical and experimental data for reinforced concrete beams also analysed in this study. The conclusion of the study and recommendation for future research were presented on the next chapter.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter presented the conclusion of the research based on the objectives listed in this study. The objectives of the research were to determine the compressive strength of PGTW as coarse aggregate in concrete and to study the flexural behaviour of reinforced concrete beam with replaced aggregate. The outcomes of the experimental test were able to determine the suitability of PGTW as partial replacement in structural concrete. Other than that, some recommendations were suggested for future research.

5.2 CONCLUSIONS

Based on the results and discussion obtained in the previous chapter, several conclusions can be drawn for this research. First, the density of PGTW concrete was slightly low as compared to the conventional concrete. Hence, the use of PGTW was reduced the weight of concrete. However, the PGTW concrete was not defined as lightweight concrete due to it within the range of 2200-2600 kg/m^3, regarded as density of normal weight concrete.

For compressive strength, all types mixes were within the requirement of normal concrete which were achieved the characteristic strength of 25 MPa at 28 days. The highest compressive strength at 28 days was occurred at P2 concrete, which was 18.4% higher than control concrete. Thus, optimum compressive strength was obtained at P2. Tavakoli et al. (2013) had mentioned that the maximum compressive strength obtained by 10% to 20% of replacement with ceramic waste as coarse aggregate.

For flexural behaviour, all reinforced concrete beams with PGTW had showed same flexural behaviour with conventional reinforced concrete beam. The ultimate load of PGTW beams was decreased at all type mixes as compared to conventional beam. The ultimate load of P1 beam was marginally decreased by 1.0% as compared to P0 beam. However, the P1 beam was the only one that displayed nearly same load carrying capacity and deflection as conventional beam.

Apart from that, the load-deflection curves of PGTW beams were still fall within the range of theoretical although the PGTW beams were not significantly contributed to the load carrying capacity. Besides that, all the beams failed in the flexure mode and the number of crack for all beams was about 10 to 13 only.

In short, the objectives of this research were achieved. The optimum percentage for replacement of coarse aggregate with PGTW was 10% based on the overall result obtained on this study. Therefore, this research has proved that Porcelain Granite Tile Waste (PGTW) can be partially replaced the coarse aggregate in the reinforced concrete beam.

5.3 RECOMMENDATIONS

The performance of reinforced concrete member that conducted in this research cannot be expected to represent all performance of PGTW in reinforced concrete. Therefore, further study should be conducted with large number of reinforced concrete members for analysis of real performance. The recommendations for future study were as following:

i. It is recommended that further studies by change in shape and size of PGTW aggregate to reduce the effect of flaky shapes, smooth surface and create the stronger bonding between concrete and aggregate.
ii. The flexural behaviour of partial replacement of both coarse and fine aggregates with PGTW in reinforced concrete beams is recommended for further studies.

iii. Improvement of performance for reinforced concrete beam also suggested for the further studies by adding mineral admixture such as fly ash and silica fume to produce higher performance in reinforced concrete beam.

iv. The load-strain behaviour of reinforcement steel is recommended for further studies to better understanding on the flexural behaviour of reinforced concrete beam.

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APPENDIX A

CONCRETE MIX DESIGN

Universiti Malaysia PAHANG CONC	MAKMAL KONKRIT / TABLE 1 : CONCRETE MIX DESIGN FORM	
		Document No : CONC/2011/015
		Issue No : 1
		Revision No : 0
		Effective Date : 10 Oktober 2011
		Page No : 1 of 1

Stage		Item	Reference or Calculation	Value
1	1.1	Characteristic Strength	Specified	25 N/mm2 at 28 days; Proportion defective 5 %
	1.2	Standard Deviation (σ)	Table 1.1	8 N/mm2 or no data ____ N/mm2
	1.3	Margin (k x σ)	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm2
	1.4	Target mean strength	C2	____ (Characteristic strength) + ____ (Margin) = 38 N/mm2
	1.5	Cement type	Specified	OPC / SRPC / RHPC
	1.6	Aggregate type : Coarse	Specified	Crushed / Uncrushed
		Aggregate type : Fine	Specified	Crushed / Uncrushed
	1.7	Free-water/cement ration	Table 1.3 Figure 2	0.57
	1.8	Maximum free-water/cement ratio	Table 1.4	0.55 use the lower value ____
2	2.1	Slump	Specified	60 - 180 mm
		Vebe Time	Specified	0 - 3 s
	2.2	Maximum aggregate size	Specified	10mm / 20mm / 40mm
	2.3	Free - water content	Table 2.1	225 kg/m3
3	3.1	Cement Content	C3	225 (Free water content) / 0.55 (Free-water/cement ratio) = 410 kg/m3
	3.2	Maximum cement content	Specified	____ kg/m3
	3.3	Minimum cement content	Specified	Use 3.1 if < 3.2; Use 3.3 if > 3.1
	3.4	Modified free - water / cement ratio		____
4	4.1	Relative density of aggregate (SSD)		2.7 known / assumed
	4.2	Concrete density	Figure 3	2380 kg/m3
	4.3	Total Aggregate Content	C4	2380 (Concrete Density) - 410 (Maximum Cement Content) - 225 (Free water Content) = 1745 kg/m3
5	5.1	Grading of fine aggregate (BS 822)	Percentage passing 600μm sieve	40 %
	5.2	Proportion of fine aggregate	Figure 4	46 %
	5.3	Fine aggregate content	C5	1745 (Total aggregate content) x 0.46 (Proportion of fine aggregate) = 803 kg/m3
	5.4	Coarse aggregate content	C5	1745 (Total aggregate content) - 803 (Fine aggregate content) = 942 kg/m3

Quantities	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg) (10mm / 20mm / 40mm)
per m3 (to nearest 5kg)	410	225	805	945
per trial mix of 0.075 m3 6 cubes (150 mm x 150 mm x 150 mm)	30.75	16.88	60.38	70.88

1 N/mm2 = 1MN/m2 = 1 Mpa beam (150 mm x 200 mm x 1500 mm)
OPC = Ordinary Portland Cement
SRPC = Sulphate-resisting Portland Cement wastage - 15%.
RHPC = Rapid-hardening Portland Cement
Relative density = specified density = ratio between weight of sampel to weight of water
SSD = based on a saturated surface-dry basis

APPENDIX B

DATA FOR P0 BEAM

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	2.66	0.07	17.57	0.97
0.01	0	2.75	0.08	18.72	1.01
0.01	0	2.97	0.09	19.15	1.05
0.03	0	3.25	0.10	19.55	1.09
0.03	0	3.54	0.12	20.16	1.12
0.06	0	3.67	0.13	20.77	1.16
0.06	0	3.78	0.14	21.23	1.19
0.05	0	3.87	0.15	21.83	1.23
0.08	0	3.94	0.16	22.41	1.28
0.08	0	4.03	0.18	22.97	1.32
0.08	0	4.20	0.19	23.44	1.36
0.08	0	4.33	0.21	23.91	1.41
0.11	0	4.50	0.24	24.39	1.46
0.11	0	4.92	0.25	24.89	1.50
0.11	0	6.17	0.26	25.45	1.54
0.14	0	7.03	0.29	26.06	1.57
0.16	0	7.51	0.30	26.69	1.60
0.15	0	7.78	0.33	27.20	1.66
0.17	0	7.94	0.35	27.77	1.70
0.20	0	8.06	0.38	28.42	1.74
0.24	0	8.19	0.40	28.90	1.79
0.28	0	8.34	0.41	29.43	1.83
0.35	0	9.00	0.42	30.06	1.87
0.38	0	10.31	0.46	30.62	1.91
0.41	0	11.03	0.50	31.12	1.95
0.44	0.01	11.43	0.53	31.73	1.97
0.46	0.02	11.70	0.56	32.36	2.02
0.52	0.02	11.86	0.59	32.89	2.08
0.57	0.02	12.03	0.63	33.56	2.12
0.68	0.02	12.20	0.65	34.23	2.16
0.86	0.03	12.50	0.68	34.72	2.21
0.99	0.03	13.66	0.71	35.29	2.26
1.12	0.03	14.66	0.76	35.82	2.30
1.31	0.03	15.33	0.79	36.39	2.33
1.54	0.03	15.75	0.82	36.83	2.36
1.76	0.03	15.82	0.83	37.50	2.39
2.17	0.03	15.95	0.85	38.15	2.45
2.35	0.04	16.10	0.89	38.60	2.50
2.50	0.05	16.43	0.93	39.17	2.54

APPENDIX B

DATA FOR P0 BEAM continued

Load (kN)	Deflection (mm)
39.78	2.59
40.37	2.63
40.87	2.67
41.48	2.71
42.13	2.74
42.62	2.76
43.18	2.83
43.75	2.89
44.27	2.93
44.87	2.97
45.50	2.99
46.12	3.03
46.52	3.06
47.09	3.10
47.72	3.14
48.21	3.16
48.69	3.23
49.37	3.28
49.99	3.33
50.41	3.38
50.89	3.43
51.24	3.47
51.69	3.52
52.11	3.54
52.65	3.59
53.26	3.66
53.82	3.70
54.25	3.75
54.84	3.79
55.39	3.84
55.91	3.88
56.38	3.91
57.05	3.93

Load (kN)	Deflection (mm)
57.63	4.00
58.08	4.05
58.61	4.10
59.12	4.15
59.66	4.20
60.12	4.24
60.69	4.28
61.26	4.31
61.78	4.33
62.24	4.41
62.79	4.46
63.37	4.50
63.78	4.55
64.33	4.60
64.95	4.64
65.51	4.68
65.89	4.70
66.41	4.75
66.93	4.82
67.47	4.87
67.83	4.93
68.35	4.99
68.85	5.02
69.35	5.07
69.72	5.09
70.16	5.14
70.57	5.22
71.12	5.27
71.53	5.33
71.97	5.39
72.52	5.43
73.04	5.48
73.41	5.51

Load (kN)	Deflection (mm)
73.79	5.58
74.27	5.63
74.70	5.69
75.19	5.74
75.57	5.80
76.02	5.85
76.43	5.88
76.93	5.93
77.29	6.01
77.62	6.07
77.70	6.14
75.55	6.30
75.32	6.41
75.73	6.48
74.69	6.53
73.21	6.58
72.97	6.63
69.54	6.66
67.81	6.70
65.12	6.78
64.97	6.83
64.61	6.89
62.55	6.94
61.59	6.99
58.33	7.03
58.44	7.06
58.66	7.13
58.83	7.19
58.99	7.25
59.15	7.30
59.35	7.36
59.40	7.40

APPENDIX C

DATA FOR P1 BEAM

Load (kN)	Deflection (mm)
0	0
0.08	0
0.12	0
0.14	0
0.18	0
0.21	0
0.23	0
0.23	0
0.27	0
0.28	0
0.30	0
0.31	0
0.39	0
0.40	0
0.41	0
0.49	0
0.51	0
0.57	0.01
0.71	0.01
0.76	0.02
0.93	0.02
1.02	0.03
1.21	0.03
1.40	0.04
1.72	0.04
2.11	0.05
2.29	0.05
2.56	0.06
2.77	0.07
2.91	0.08
3.16	0.09
3.40	0.10
3.53	0.11
3.69	0.12
3.77	0.13
3.83	0.13
3.87	0.14
4.01	0.14
4.10	0.14

Load (kN)	Deflection (mm)
4.15	0.14
4.16	0.17
4.26	0.19
4.39	0.22
4.70	0.23
4.92	0.25
5.45	0.26
6.22	0.27
6.72	0.29
7.05	0.31
7.36	0.32
7.64	0.34
7.81	0.36
7.92	0.37
8.01	0.40
8.14	0.42
8.45	0.44
8.99	0.46
9.89	0.47
10.60	0.49
10.98	0.51
11.41	0.53
11.59	0.53
11.79	0.55
11.94	0.59
12.16	0.62
12.54	0.65
12.87	0.66
13.80	0.69
14.45	0.72
14.84	0.75
15.37	0.77
15.64	0.80
15.80	0.82
16.03	0.85
16.16	0.87
16.55	0.90
17.05	0.92
17.91	0.93

Load (kN)	Deflection (mm)
18.54	0.98
18.98	1.02
19.24	1.04
19.65	1.07
20.13	1.10
20.66	1.13
20.96	1.16
21.42	1.20
21.97	1.23
22.54	1.25
22.86	1.28
23.31	1.31
23.73	1.32
24.24	1.36
24.73	1.41
25.27	1.44
25.90	1.48
26.61	1.53
27.34	1.57
28.17	1.62
28.79	1.66
29.61	1.70
30.43	1.72
31.01	1.81
31.79	1.85
32.48	1.90
33.24	1.96
34.11	2.01
34.73	2.04
35.54	2.08
36.26	2.10
36.85	2.18
37.69	2.23
38.34	2.28
38.95	2.34
39.79	2.39
40.37	2.43
41.16	2.47
41.96	2.49

APPENDIX C

DATA FOR P1 BEAM continued

Load (kN)	Deflection (mm)
42.54	2.57
43.30	2.62
43.96	2.68
44.61	2.74
45.39	2.79
46.05	2.83
46.62	2.87
47.41	2.89
48.03	2.97
48.71	3.03
49.49	3.09
50.07	3.15
50.65	3.19
51.25	3.24
51.82	3.27
52.16	3.37
52.12	3.48
51.79	3.59
52.14	3.65
52.70	3.72
53.24	3.80
53.82	3.87
54.30	3.94
55.02	3.98
55.63	4.03
56.17	4.06
56.87	4.15
57.59	4.21
58.08	4.27

Load (kN)	Deflection (mm)
58.74	4.33
59.42	4.37
59.97	4.42
60.64	4.44
61.33	4.53
61.79	4.59
62.42	4.66
63.04	4.72
63.48	4.77
63.49	4.83
63.44	4.94
63.61	5.03
64.16	5.10
64.88	5.15
65.43	5.20
65.92	5.23
66.48	5.31
67.15	5.38
67.53	5.44
68.07	5.51
68.62	5.56
69.14	5.60
69.47	5.66
69.92	5.75
70.39	5.82
70.92	5.89
71.33	5.95
71.79	5.99
72.38	6.04

Load (kN)	Deflection (mm)
72.91	6.14
73.26	6.21
73.64	6.29
74.07	6.34
74.62	6.38
75.09	6.45
75.45	6.54
75.99	6.61
76.45	6.69
76.90	6.76
76.75	6.84
76.63	6.97
76.38	7.08
76.04	7.17
75.76	7.31
75.48	7.43
74.59	7.53
68.41	7.95
62.85	8.31
60.59	8.55
58.39	8.74
53.86	9.06
49.94	9.36
47.93	9.50
47.13	9.61
46.73	9.72
46.52	9.81
46.36	9.88
46.17	9.91

APPENDIX D

DATA FOR P2 BEAM

Load (kN)	Deflection (mm)
0	0
0.58	0
0.76	0
0.69	0
0.72	0
0.88	0
1.11	0
1.56	0
1.94	0
2.25	0
2.35	0
2.58	0
2.78	0
3.03	0
3.17	0
3.29	0
3.38	0.01
3.42	0.02
3.50	0.03
3.63	0.04
3.69	0.05
3.79	0.07
3.79	0.08
3.85	0.10
4.05	0.12
4.33	0.13
4.55	0.14
5.10	0.15
5.92	0.18
6.29	0.19
6.55	0.20
6.86	0.22
7.09	0.23
7.29	0.24
7.43	0.26
7.54	0.28
7.65	0.29
7.74	0.29
7.88	0.29

Load (kN)	Deflection (mm)
8.13	0.31
8.58	0.36
9.06	0.39
9.92	0.41
10.32	0.43
10.64	0.45
10.97	0.47
11.13	0.49
11.30	0.52
11.44	0.53
11.62	0.55
11.74	0.57
12.04	0.59
12.49	0.61
12.97	0.63
13.62	0.65
14.13	0.67
14.47	0.68
15.00	0.70
15.22	0.73
15.40	0.77
15.61	0.80
15.70	0.82
16.10	0.84
16.62	0.87
17.28	0.85
17.92	0.88
18.51	0.91
18.77	0.94
19.04	0.97
19.47	1.00
19.91	1.03
20.34	1.06
20.59	1.08
21.02	1.11
21.52	1.17
22.00	1.20
22.36	1.24
22.62	1.28

Load (kN)	Deflection (mm)
23.09	1.31
23.49	1.35
23.97	1.38
24.31	1.38
24.85	1.41
25.50	1.45
26.07	1.48
26.43	1.54
27.00	1.60
27.56	1.64
28.07	1.69
28.45	1.73
29.02	1.77
29.68	1.80
30.22	1.84
30.85	1.85
31.56	1.86
32.15	1.93
32.90	1.99
33.67	2.03
34.19	2.09
34.87	2.15
35.60	2.19
36.13	2.23
36.85	2.25
37.63	2.33
38.12	2.35
38.77	2.39
39.48	2.44
39.97	2.51
40.60	2.56
41.30	2.61
41.90	2.64
42.49	2.69
43.21	2.77
43.78	2.82
44.41	2.88
45.14	2.93
45.68	2.98

APPENDIX D

DATA FOR P2 BEAM continued

Load (kN)	Deflection (mm)
46.20	3.02
46.89	3.04
47.55	3.13
48.05	3.18
48.85	3.24
49.48	3.30
50.03	3.31
50.67	3.35
51.28	3.40
51.88	3.42
52.54	3.50
53.19	3.57
53.67	3.62
54.35	3.68
55.07	3.73
55.55	3.78
56.26	3.81
56.98	3.86
57.49	3.93
58.11	3.99
58.80	4.05
59.36	4.11
59.99	4.15
60.70	4.19
61.23	4.20

Load (kN)	Deflection (mm)
61.82	4.28
62.49	4.34
63.09	4.40
63.68	4.47
64.42	4.51
65.03	4.56
65.45	4.59
66.06	4.66
66.73	4.73
67.19	4.80
67.81	4.87
68.42	4.91
68.93	4.96
69.43	4.98
69.97	5.08
70.48	5.15
70.77	5.22
70.89	5.30
70.59	5.37
67.49	5.60
67.46	5.68
67.91	5.74
68.33	5.77
68.78	5.87
68.73	5.96

Load (kN)	Deflection (mm)
68.65	6.05
68.09	6.13
67.82	6.21
67.83	6.31
67.95	6.40
68.08	6.48
68.07	6.54
67.57	6.64
61.60	7.02
55.92	7.32
54.69	7.46
53.72	7.57
52.78	7.68
51.62	7.76
51.33	7.87
51.18	7.96
50.70	8.04
50.45	8.10
50.17	8.20
49.67	8.32
48.60	8.44
47.98	8.50
46.69	8.68
45.79	8.80
45.24	8.87

APPENDIX E

DATA FOR P3 BEAM

Load (kN)	Deflection (mm)
0	0
0.01	0
0.01	0
0.02	0
0.02	0
0.03	0
0.03	0
0.03	0
0.04	0
0.05	0
0.05	0
0.06	0
0.08	0
0.14	0.01
0.15	0.01
0.19	0.03
0.19	0.03
0.23	0.04
0.21	0.04
0.26	0.04
0.34	0.04
0.35	0.04
0.38	0.04
0.39	0.04
0.45	0.03
0.46	0.03
0.48	0.03
0.50	0.04
0.54	0.04
0.63	0.04
0.65	0.04
0.78	0.05
0.99	0.05
1.22	0.06
1.34	0.06
1.66	0.07
2.01	0.08
2.34	0.09
2.62	0.10

Load (kN)	Deflection (mm)
2.85	0.10
3.07	0.11
3.35	0.13
3.57	0.15
3.77	0.15
3.87	0.15
3.96	0.15
4.04	0.16
4.18	0.17
4.28	0.19
4.32	0.19
4.42	0.21
4.83	0.23
5.34	0.24
6.33	0.25
6.90	0.26
7.37	0.26
7.73	0.29
7.93	0.32
8.12	0.35
8.21	0.38
8.38	0.39
8.85	0.41
9.57	0.43
10.54	0.45
11.05	0.48
11.54	0.49
11.76	0.52
11.97	0.55
12.19	0.56
12.43	0.58
13.05	0.60
13.92	0.62
14.65	0.64
15.26	0.65
15.69	0.65
15.91	0.68
16.19	0.68
16.46	0.65

Load (kN)	Deflection (mm)
17.02	0.70
17.99	0.75
18.72	0.78
19.19	0.81
19.54	0.85
20.04	0.88
20.61	0.91
20.98	0.95
21.46	0.98
22.06	1.02
22.68	1.04
23.05	1.08
23.60	1.13
24.13	1.17
24.68	1.20
25.12	1.24
25.76	1.28
26.37	1.32
26.84	1.35
27.37	1.38
27.92	1.42
28.54	1.43
28.92	1.48
29.54	1.54
30.23	1.57
30.71	1.60
31.22	1.64
31.76	1.68
32.39	1.72
32.84	1.75
33.48	1.78
34.19	1.81
34.65	1.83
35.23	1.88
35.81	1.93
36.34	1.97
36.78	2.00
37.46	2.04
38.10	2.08

APPENDIX E

DATA FOR P3 BEAM continued

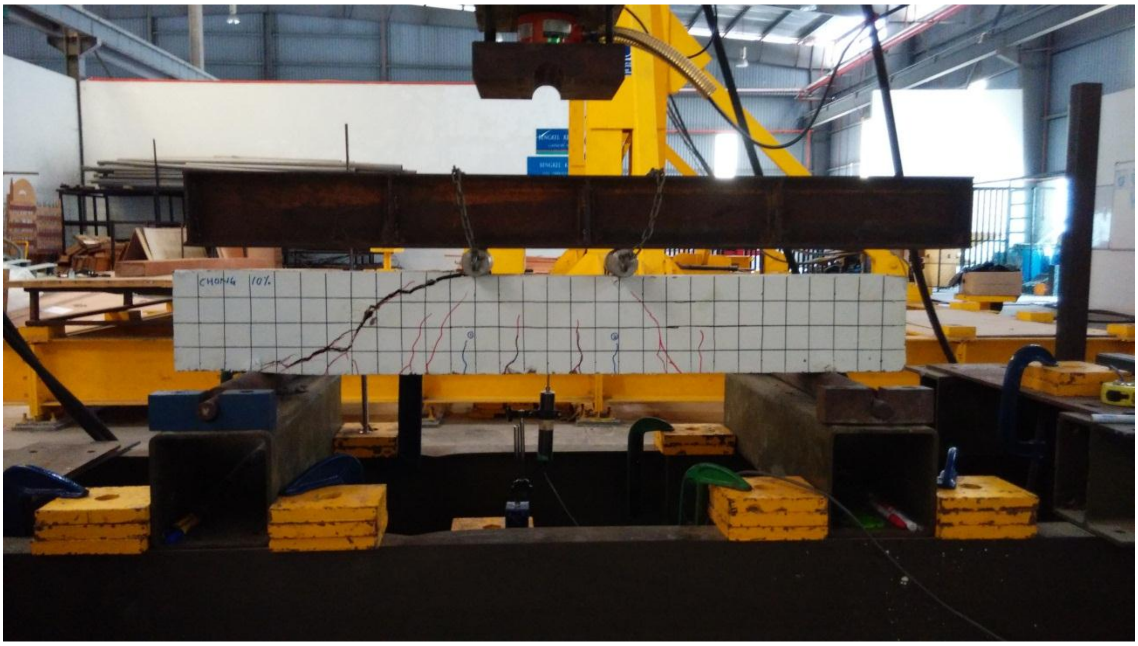
Load (kN)	Deflection (mm)
38.51	2.12
39.01	2.15
39.50	2.19
40.14	2.21
40.55	2.24
41.16	2.31
41.82	2.34
42.31	2.38
42.84	2.43
43.43	2.47
44.06	2.51
44.49	2.54
45.18	2.58
45.79	2.60
46.25	2.62
46.75	2.70
47.36	2.74
47.98	2.78
48.34	2.83
48.96	2.88

Load (kN)	Deflection (mm)
49.60	2.91
50.10	2.95
50.57	2.98
51.13	2.99
51.71	3.05
52.10	3.11
52.67	3.15
53.21	3.20
53.72	3.25
54.06	3.29
54.49	3.33
55.00	3.37
55.52	3.38
55.90	3.44
56.33	3.50
56.92	3.55
57.47	3.60
57.79	3.65
57.91	3.70
58.00	3.75

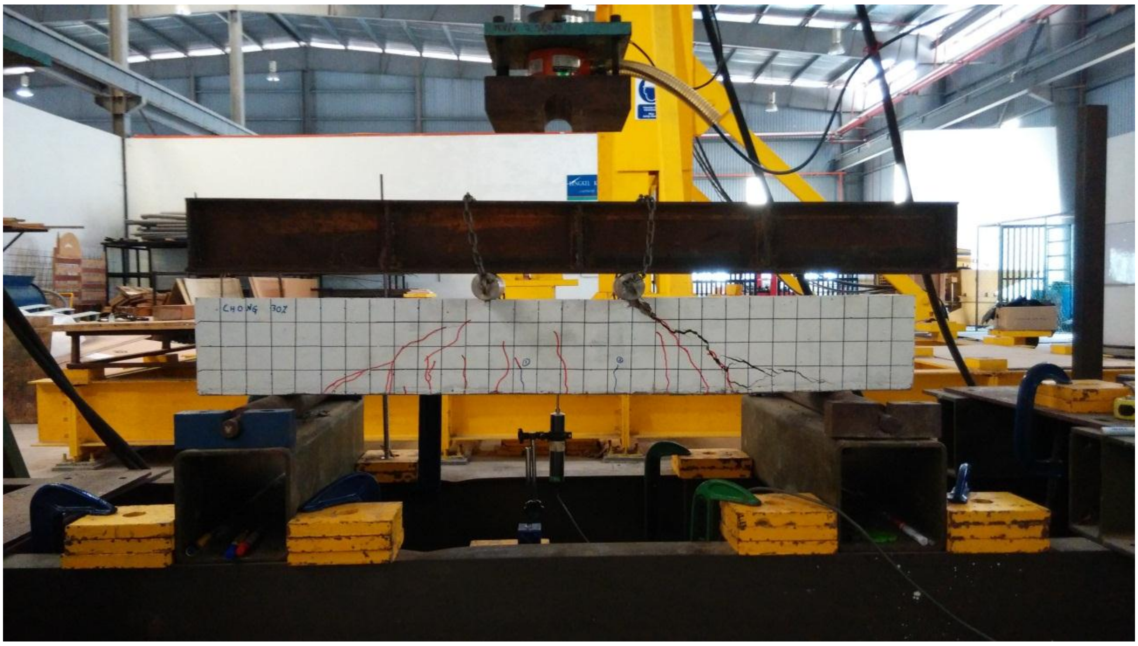
Load (kN)	Deflection (mm)
58.47	3.77
58.93	3.79
59.46	3.87
59.84	3.92
60.30	3.96
60.81	4.01
61.34	4.06
61.71	4.09
62.04	4.13
62.10	4.18
58.61	4.45
31.04	5.95
11.84	6.94
11.77	7.07
11.76	7.15
11.78	7.23
11.78	7.29
11.78	7.37

APPENDIX F

PHOTO FOR FAILURE MODE OF BEAMS



Failure mode for P1 beam



Failure mode for P2 beam

APPENDIX F

PHOTO FOR FAILURE MODE OF BEAMS continued

Failure mode for P3 beam

APPENDIX G

PHOTO OF EXPERIMENTAL WORKS

APPENDIX G

PHOTO OF EXPERIMENTAL WORKS continued