REUSING RECYCLED AGGREGATES IN STRUCTURAL CONCRETE

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A thesis submitted to the Department of Civil Engineering in partial fulfillment for the degree of Bachelor of Science in Civil Engineering



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Section: 13B
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Dedicated

to

Our Honorable Teachers

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ABSTRACT:

The construction activities in Bangladesh generate a big amount of construction and demolition (C&D) materials each year. The disposal of waste has become a severe social and environmental problem in the territory. The possibility of recycling of waste from the construction industry is thus of increasing importance. In addition to the environmental benefits in reducing the demand on land for disposing the waste, the recycling C&D wastes can also help to conserve natural materials and to reduce the cast of waste treatment prior to disposal.

The aim of the thesis is to provide scientific bases for the possible use of recycled aggregates in structure concrete by conducting a comprehensive laboratory programmer to gain a better understanding of the mechanical, microstructure and durability properties of concrete produced with recycled aggregates.

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CHAPTER 1: INTRODUCTION

1.1 GENERAL ASPECTS

The utilization of many industrial by-products in the construction industry is now well-developed as it helps in improving the sustainability in two ways. First, reuse ofthe materials which otherwise will burden the environment and will be occupying scarce land resource. Second, it minimizes the degradation of land and the environment as a result of comparatively less digging. “Recycling” is an all-prevailing practice now as it conserves the planet’s resources.

Construction and demolition (C&D) wastes are normally composed of concrete rubble, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. Concrete rubble usually constitutes the largest proportion of C&D waste. It has been shown that crushed concrete rubble, after separation from other C&D waste and sieved, can be used as substitute for natural coarse aggregates in concrete or as a sub-base or a base layer in pavements. This type of recycled material is called recycled aggregate.

The reutilization and recycling of C&D waste is necessary, as it seems the only way to decrease it. Following the Second world war certain countries, for example Germany, were interested in the recycling of “dumping materials”. Other countries, namely the Netherlands, Denmark, Belgium, Spain and a few French regions, all of which have a lack of granulated materials followed Germany’s example in the interest shown in waste material recycling.

1.2 OBJECTIVES

The objectives of this thesis are:

- To develop a technique for utilizing higher percentage recycled aggregate in concrete. This includes fly ash replacement of cement, or additional fly ash to recycled aggregate concrete.
- To investigate the properties and durability of concrete made with recycled aggregates.
- To investigate the microstructure of recycled aggregate concretes.
- Based on the results of research findings, recommend a broader scope for the use of recycled aggregate in structural and non-structural concrete and define the design guideline for the use recycled aggregate in concrete.

1.3 ARRANGEMENT OF THE THESIS

This doctoral thesis deals with the use of recycled aggregate in concrete. A brief description of the different chapters is given below.

Chapter 1 is an introductory chapter that gives the reader the background to the topic, the objective and scope of the thesis.

Chapter 2 is aimed: (1) to provide readers with general information about the recycled aggregate properties and their constituents regarding environmental resistance as well as other properties; (2) summarizes related research work on recycled aggregate concrete conducted in recent years.

In chapter 3, the experimental methodology of this thesis is shown. This chapter will present the basic properties of recycled aggregate, concrete mix proportions and test methods.

In chapter 4, the experimental results on the fresh properties such as slump, slump loss, air content, bleeding and wet density of concrete made with different percentages recycled aggregate and different levels of fly ash are presented.

In chapter 5, the general conclusions obtained for experimental work are presented. The recommendations for design recycled aggregate structural concrete are carried out based on the research results in the aforesaid chapter and future research is proposed as a continuation of this work.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

With the ever-increasing world population there is a growing need for facilities, which in turn requires finite natural resource. For this reason, many industries, backed by government support and regulations, are now looking for ways of re-using materials in manufacture of new products. This process has been in operation for a number of years and the construction industry worldwide is no exception. In Europe and other developed countries, recycling of building materials started about the end of World War II when bricks and other materials that were recovered from the ruins of war were utilized for reconstruction of amenities (Olorunsogo, 1999, Poon et al 2001). However, recycling as a means of sustainable use of materials started in Asia until fairly recently.

For a variety of reasons, reuse of construction and demolition (C&D) waste by the construction industry is becoming increasingly important day by day. In addition to environmental protection, conservation of natural aggregate resources, shortage of waste disposal land, and increasing cost of waste treatment prior to disposal are the principal factors responsible for the growing interest in recycling C&D waste.

Among the inert C&D Waste, the concrete rubble has the largest proportion and hence its recycling is most important. Many laboratory and field studies have shown that the size fraction of the concrete rubble corresponding to coarse aggregate can be satisfactorily used as a substitute for natural aggregate and the recycled concrete

aggregate shows that the later would give at-least two third of the compressive strength and the elastic modulus of the natural aggregate.

On the other hand, there are some drawbacks in using recycled aggregates: for example, they have to be separated from other demolition debris before use, and special care is necessary to ensure they are not contaminated. Consequently a lot of potentially useful material is placed in landfills. However, many countries increasingly concern with environmental protection and sustainable development, are introducing legislation and policy measure to encourage the use of recycled aggregates. The incentive to the construction industry often comes in the form of higher landfill costs, and therefore more inspiration towards the production of recycled aggregates. This policy is particularly well established in the Netherlands and the Copenhagen district of Denmark; both of these areas now recycle over 80% of their demolition waste (Collins, 1997).

In recent years certain countries have considered the reutilization of construction and demolition waste as a new construction material as being one of the main objectives with respect to sustainable construction activities. This thesis focuses on recycling of C&D waste as an aggregate in structural concrete. From the mid 70s, many researchers have dedicated their work to describe the properties of these kinds of aggregates, the minimum requirements for their utilization in concrete and the properties of concrete made with recycled aggregates. However, minor attention has been paid to both reuse recycled aggregate in structural concrete and the durability of recycled aggregate concretes.

2.2 AGGREGATES OBTAINED FROM C&D WASTE

Recycled aggregates are produced from the re-processing of mineral waste materials, with the largest source being construction and demolition (C&D) waste. C&D waste are normally composed of concrete rubble, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. Concrete rubble usually constitutes the largest proportion of C&D waste. It has been shown that crushed concrete rubble, after separation from other C&D waste and sieved, can be used as a substitute for natural coarse aggregates in concrete or as a sub-base or a base layer in pavements.

2.3 PROPERTIES OF RECYCLED AGGREGATES OBTAINED FROM CRUSHED CONCRETE

Physical properties

Recycled aggregate looks like crushed stone (Figure 2-1). However, the physical properties of crushed concrete differ from those of conventional concrete. In general, crushed concrete particles are more angular have a rougher surface texture than those of natural aggregate. Roughly textured, angular, and elongated particles require more water to produce workable concrete than smooth, rounded compact aggregate.



Figure 2-1 Recycled aggregate

The lightweight and porous cement mortar attached to the recycled aggregates causes crushed concrete aggregates to have a lower specific gravity and higher water absorption than those of comparatively sized natural aggregates.

2.3.1 Density

In general, the saturated surface density (SSD) of recycled aggregates is lower than that of natural aggregates, due to the low density of the mortar that is adhered to the original aggregate. It depends on the following:

a) Strength of original concrete:

It concludes that with the same quantity of mortar, a recycled aggregatethat has been obtained from a concrete of higher strength will have a higher density.

b) Size of aggregate:

The saturated surface density (SSD) of the aggregates depends on their quality. The aggregates with a higher amount of adhered mortar will have a lower density.

According to Hansen (1985) the density changes with the size of the aggregate when concrete is ground with the same grinding machine employing the same amount of energy in the grinding process. Many studies report on intervals of densities (2290 to 2490 kg/m^3) depending on the size of the aggregates. The density (SSD) of recycled aggregate concrete reduces with smaller sizes of aggregates.

As mention previously the SSD density does not only depend on original concrete strength but also on the kind of crushing or grinding machine employed and the energy used.(Hansen et al 1983, Dhir et al 2004).

In order to calculate the density of the recycled aggregate the same standard as that of raw aggregates is used, namely the ASTM C-127 standard (Standard Test Method for Specific Gravity and Absorption of Coarse (or Fine) aggregate).In Hong Kong the BS 812: Part 2 is used. The aggregates must have density to 2000 kg/m^3.The same value is required by RILEM DIN 4226-100 and BS 8500-2:2002 for recycled aggregates which are derived from crushed concrete.

2.3.2 Water absorption

The water absorption capacity of the recycled aggregate in the mixture represents one of the main difference between the recycled and raw aggregates. It is reported to depend on:

a) Size of aggregate: The capacity of absorption of the aggregate increases with its smaller size increased.The smaller size aggregates having a greater water absorption capacity.

Poon et al (2002) found that the absorption capacity of recycled aggregate increased with a higher amount of adhered mortar. The high amount of adhered mortar in recycled aggregate also produced a decrease in density. In all case it was accepted that absorption capacity was not dependent on the strength of the original concrete.

b) Quantity of adhered mortar: There is a relationship between absorption and amount of adhered mortar. Ravindrarajah et al (2000) demonstrated with 15 samples, that the average value of water absorption in recycled aggregate was 6.35%, whereas in raw aggregate it was 0.90%. The absorption capacity of recycled aggregates depends on the quantity and quality of adhered mortar.

c) Density: There is dependence between density and absorption capacity. Recycled aggregates with adhered mortar have lower density and higher absorption capacity.

2.3.3 Strength of recycled aggregate

According to the Los Angeles Abrasion test recycled aggregates obtained by grinding 40 MPa strength of concrete have lower abrasion than aggregates obtained by 16 MPa strength concrete is shown in Table 2-1.

Table 2-1 Los Angeles Abrasion Loss percentage of recycled aggregates obtainedby grinding 40 MPa

	Recycled aggregates in abrasion according to several investigators					
	Hansen and Narud (1983)			**Hasaba (1981)**	**Japanese Investigator (1978)**	**Yoshikane (2000)**
Size Fraction	4-8 mm	8-16 mm	16-32 mm	5-25 mm	(*)	5-13 mm
Los Angeles Abrasion Loss Percentage	30.1	26.7	22.4	23.0	25.1-35.1	20.1

(*) For recycled aggregate, according to 15 different concretes crushed by different way.

The crushing machine and the power employed in the crushing used by each researcher are unknown, so it must be careful in comparing the results. Los Angeles abrasion is higher when the strength of original concrete is lower due to the lower strength of adhered mortar.

According to ASTM C-33 standard “Standard Specification for Concrete Aggregates”,

the aggregates will be valid to use in concrete production if the loss determined by the "Los Angeles Abrasion test" is less than 50%.

Chemical properties

One of the main issues surrounding the use of recycled concrete aggregate in concrete production is the potential for reaction between the recycled aggregates and alkaline water. Alkali-silica reaction results in volumetric expansion, in which there is a high probability of internal fracturing and premature deterioration of the concrete. Where alkali-silica reactivity is of concern, the potential for deterioration should be evaluated. Chloride ions from marine exposure can also be present in recycled aggregates. Because of the use of deicing salts as a mechanism to control development of ice on pavement, there is a strong possibility that chloride ions will be present in recycled concrete aggregate. The presence of chloride ions in Portland cement concrete can adversely impact the reinforcing steel within concrete. Reinforcing steel in the presence of chloride ions will react to form iron oxide or rust. If the formation of iron oxide persists, there is a high probability of delamination of the concrete structure.

2.3.4 Contaminants

The presence of contaminants in recycled aggregate influence the strength and durability of concrete made with these aggregates. Nowadays recommendations exist with respect to the limitation of the diverse components which can be presence in recycled aggregates.

For example, the compressive strength of concrete which employs 3% of plaster is 15% lower than that without plaster. If the cured concrete follows a humid route it obtains a reduction of 50%. Since the plaster is softer and weaker in water. Sulphate resistant

Portland cement should be used to produce concrete with contaminated recycled aggregate containing plaster or gypsum (Dhir et al 2004).

2.4 PROPERTIES OF CONCRETE MADE WITH RECYCLED AGGREGATE

Recycled aggregate has been used as a replacement of the natural aggregate for a number of years. The potential benefits and drawbacks of recycled aggregate concrete, when compared with equivalent concrete using natural aggregate, have been quite extensively studied. The properties of concrete made with recycled aggregates differ from those of concrete with only natural aggregates due to the high water absorption and low density of recycled aggregates. However, the property variation within concrete with up to 20% by weight of recycled concrete aggregate or up to 10% by weight of recycled masonry aggregate are negligible (Ravindrarajah et al 1985, 1987, Hendriks et al, 1998, Dhir, etal 1999, Otsuki et al 2003, Poon et al 2004,). The absorption, aggregate crushing value and soundness are the prime factors which control the recycled aggregate properties.

2.4.1 Characteristics of fresh recycled aggregate concrete

Mixture design: The same principles used to design the concrete mixtures with conventional aggregates – sand, gravel, or crushed stone – should be followed when using recycled aggregates. Trial mixtures are required to determine proper proportions and to check new concrete's quality. In practice, slight modifications are required. Hansen concluded that for the DOE mix design, the following modifications would be necessary (O'Mahony 1990, Dhir et al 1999, 2004).

1. When designing a concrete mix using recycled aggregate of variable quality, a higher standard deviation should be employed in order to determine a target mean strength on the basis of a required characteristic strength
2. When the coarse recycled aggregate is used with natural sand, it may be assumed at the design stage that the free water/cement ratio required for a certain compressive strength will be the same for recycled aggregate concrete as for conventional concrete. If trial mixes show that the compressive strength is lower than required, an adjustment of the water/cement ratio should be made.
3. For a recycled aggregate mix to achieve the same slump, the free water content will need to be approximately 10 litres/m^3 higher than for conventional concrete.
4. If the free water content of a recycled aggregate concrete is increased, the cement content will also need to be higher to maintain the same water/cement ratio.
5. Trial mix should be made to obtain the required workability and the most suitable water/cement ratio.

Because of the high water absorption of recycled aggregate, some deviation in trial batch weights will likely be necessary. The concrete mix design engineer must be vigilant in determining the necessary quantity of mixing water when recycled aggregate are used, and especially when the mixture includes fine recycled aggregates.

Mixing water and workability Because of the relatively high absorption of recycled aggregates as compared to conventional aggregates, more mixing water and a higher starting slump may be necessary. This is particularly true for aggregates if they are dry before batching. Experience shows that recycled aggregates continue to absorb water after mixing in a batch plant. This can cause a loss of slump and workability after

mixing is completed. To offset this recycled aggregate – like structural lightweight aggregate con be pre-wetted in stockpiles with a sprinkling system.

According to Mukai (1979), Buck (1973), Frondisou-Yannas (1977), Malhotra (1978), Hansen et al (1983), Ravindrarajah et al (1985), and Poon et al (2003), concrete made with recycled coarse aggregates and natural sand needs 5% more water than conventional concrete in order to obtain the same workability. If the sand is also recycled, 15% more water is necessary to obtain the same workability.

Water-cement ratio at the initial design stage, it may be assume that the water-cement ratio for required compressive strength will be the same for recycled concrete as it would be for conventional concrete, provided the recycled concrete contains coarse aggregate and natural sand. A water-cement ratio adjustment will have to be made if a trial mix design shows that compressive strength is lower than initially assumed. Tavakoli et al (1996) demonstrated that concrete made with 100% of recycled aggregate with lower w/c ratio than conventional concrete can have a large compressive strength. When the w/c ratio is the same the compressive strength of concrete made with 100% recycled aggregate is lower.

Cement content: The calculated cement content for recycled aggregate concrete will be somew hat higher than the cement content for comparable conventional concrete because of the higher free water requirements of recycled concrete mixtures. At least 5% extra cement would be required in mixtures using the coarse recycled aggregate and virgin fine; at least 15% extra would be needed if both coarse and fine recycled aggregates were used. In any case, compressive strength may be increased by using

higher cement content and /or replacing some of the recycled aggregate with conventional aggregate. (Environmental Council of Concrete Organization 2003).

Density and air content: New concrete will have a lower density because of the large amount of old mortar and cement paste adhering to recycled aggregates. The density of new concrete may be from 5-15% lower than that of control concretes made with conventional aggregate. The natural air content of recycled aggregate concrete may be a little higher than that of corresponding concretes made with conventional aggregates.

Fine-coarse aggregate ratio: For economy and cohesion of fresh concrete, a number of researchers have found that the optimum ratio of fine to coarse aggregates is about the same for recycled aggregate concretes as for conventional concrete. Still other researchers have concluded that crushed concrete fines should be used in producing new concrete because of problems in accurately determining their water absorption, free water content, and saturated surface dry density. While some concrete specifies agree, other have found it beneficial to use 10% to 30% recycled fine as a weight percentage of total fine aggregate in the mixture.(Willam, 1999). This is not to imply that 100% recycled fines cannot be used successfully in concrete.

2.4.2 Characteristics of hardened recycled aggregate concrete

Before reviewing the influences that recycled aggregates may have on the characteristics of hardened concrete, it would be appropriate to mention as a general principle that up to 30% of the conventional aggregate in concrete may be replaced by recycled aggregate without significantly affecting the mechanical properties of the new concrete. Not only compressive strength, but also tensile, shear, fatigue, bond, and

variability of strength are important mechanical properties of any hardened concrete, including recycled aggregate concrete.

Compressive strength

The compressive strength of recycled aggregate concrete can be equal to or higher than that of the original concrete if the recycled aggregate concrete is made with the same ora lower water-cement ratio than the original concrete. More commonly, concrete will be 5% to 10% lower than that of a corresponding concrete made with conventional aggregates. Some minor strength loss will likely occur when crushed concrete fines are substituted for natural sand, because sand particles have greater strength. Many researchers have presented conclusions regarding the variation of the compressivestrength of concrete made with 100% of recycled aggregates with respect to conventional concrete. According to some researchers the value has a decrease of 20% (Tam et al 2005), decrease from 14 to 32% (BCSJ, 2002), decrease of 10%.

The compressive strength of the conventional concrete and concrete made with different percentage of recycled aggregates and water-cement ratio can be seen in Table 2-2 of Hansen (1992).

Table 2-2: Compressive strength of original concrete and recycled aggregate concrete for various w/c and coarse/fine aggregate ratio (Hasen, 1992)

W/C	Concrete compressive strength, lb per sq in			
	Natural coarse and fine aggregate (original concrete)	Recycled coarse aggregate and 100% natural sand	Recycled coarse aggregate, 50% recycled fine aggregate, and 50%natural sand	Recycled coarse aggregate and 100% recycled fine aggregate
0.45	5440	5370	4930	4350
0.55	4190	4130	3630	3120
0.68	3190	3050	2540	1890

Development of compressive strength of the concrete

The tests conducted by Rohi et al (1998) concluded that the compressive strength of concrete made with 100% recycled aggregate increases by 2% from 7 to 28 days with respect to the 16% increase in conventional concrete. This could be due to either the water absorption capacity of the recycled aggregates or to be the bad adherence of the aggregate with the cement paste.

Tensile and flexural strength

Concrete's tensile and flexural strengths are important when designing structures and pavements. Won (1999) found that for the same water-cement ratio, the replacement virgin fine with crushed concrete fine does not change the tensile strength. When using recycled coarse aggregate, the flexural strength may be slightly lower than a similar mixture using conventional aggregates. On the other hand, using crushed concrete fines may reduce flexural strength by 10% to 20% (Topcu et al 2003).

Ravindrarajah et al (1985) demonstrated that there are no great differences in tensile strength of coarse recycled aggregate and natural sand concrete with respect to conventional concrete. However, if fine recycled aggregate replaces the natural sand in the concrete using coarse recycled aggregates then the tensile strength reduce by 20% with respect to conventional concrete.

Tam et al (1985) presented that there was no great difference between the flexural strength of concrete made with recycled coarse aggregate and natural sand or conventional concrete. Their conclusions can be seen in Table 2-3.

Table 2-3: Percentage of strength reduction according to recycled aggregate used (Tam et al, 1985)

	Reduction of tensile strength	Reduction of tension strength	Reduction of shear strength
Concrete with coarse recycled aggregate and natural sand	6%	0%	26%
Concrete with coarse and fine recycled aggregate	10%	7%	32%

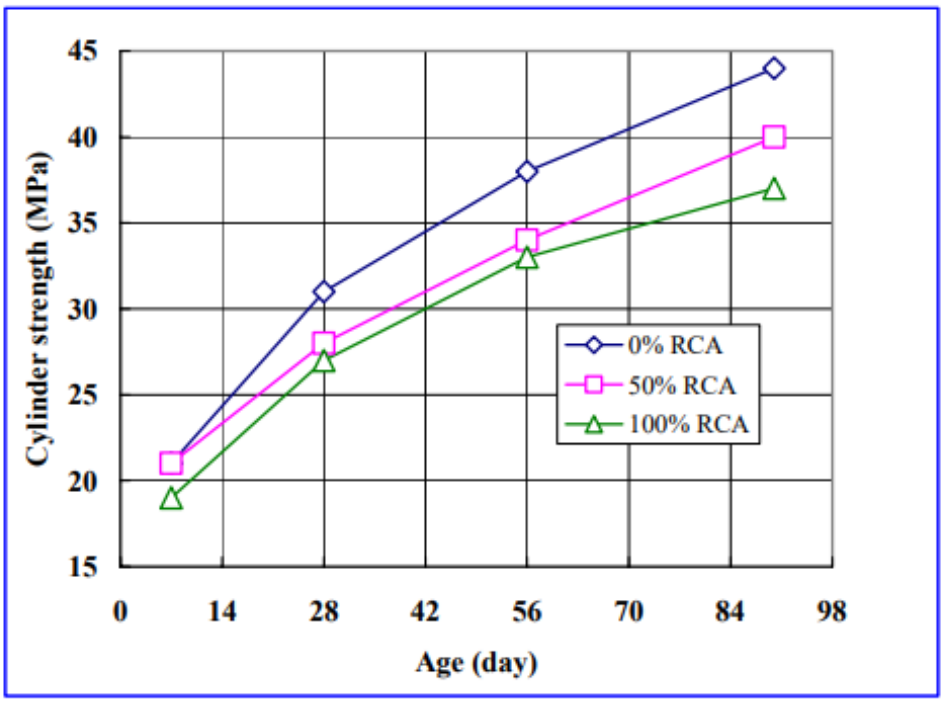


Figure 2-2: Compressive strength over time of concrete of different quantities of recycled aggregate. Ravindrarajah (2000)

Grübl (1997, 1998) expressed the split cylinder tensile strength as a percentage of the compressive strength. Fig. 2-5 shows the variation in concrete with different compositions. The figures under each vertical bar represent the percentages of natural aggregates, concrete chips and brick chips respectively. It may be noted that the split cylinder tensile strength of the reference concrete is 8% of the compressive strength while there is considerable scatter in concrete of different composition, ranging between 4% and 8%. Di Niro et al (1998) investigated the tensile strength of the concrete with

varying content of recycled concrete coarse aggregate. Their results are shown as Table 2-4:

Table 2-4: Tensile Strength of Concretes with different Recycled Aggregate Content (Di Niro et al, 1998)

% OF Recycled Aggregates	28 day Compressive Strength (MPa)	28 day Tensile Strength (MPa)	% of tensile strength ofConcrete with All natural Aggregate	Ratio of Tensile strength and Compressive Strength
100 (Presoaked)	32.1	2.67	68.1	0.083
100	36.3	2.71	69.1	0.074
70	36.6	2.86	73.0	0.078
50	38.0	2.67	68.1	0.072
30	43.0	3.79	96.7	0.088
0	44.95	3.92	100	0.087

Shear, bond, and fatigue strength.

Barra et al (1998) found that when new concrete was made with recycled aggregates from aged concrete pavements, fatigue characteristics of the new concrete were the same as for concrete made with virgin aggregates. Miyazawa et al (2000) discovered that the bond strength between reinforced steel and recycled aggregate concrete was same as that of conventional concrete under both static and fatigue loading when recycled coarse aggregate and natural sand were used. Shear strength appears to follow a similar pattern. Good flexural fatigue strength in recycled aggregate concrete can be attributed to a superior bond between cement mortar and paste in new concrete and recycled aggregate particles.

Modulus of elasticity

It found that the use of both coarse and fine recycled aggregates significantly reduced the modulus of elasticity of new concrete (see Table 2-5). The recycled aggregates from

15% to 40% can be explained by the "mortar effect.' Mortar has a lower modulus than virgin coarse aggregate, and since recycled aggregate concrete has higher volumetric proportion of mortar than conventional concrete, a lower modulus of elasticity should be expected.

Table 2-5: Elastic modulus of concretes with different recycled aggregate content (Won, 1999)

Natural Aggregate (%)	Recycled Aggregate (%)	28 day Compressive Strength (MPa)	28 days Elastic Modulus (GPa)	Relative E-value
100	0	37	27.7	1.00
75	25	40	29.4	1.06
50	50	34	26.1	0.94
25	75	40	26.6	0.96
0	100	38	18.0	0.65

Drying shrinkage and creep

The drying shrinkage and creep of recycled aggregate concrete is higher by 40% to 80% than those of a corresponding conventional concrete. This is due to the large amount of old mortar and cement paste attached to recycled aggregates. Reinforced concrete elements constructed of recycled aggregate concrete appear to be no more prone to shrinkage cracking than conventional concrete because high shrinkage and creep tend to cancel each other out, comparatively lower values of drying shrinkage are reported for new concretes using coarse recycled aggregate and natural sand; comparatively higher value exist when both fine and coarse aggregate are recycled.

Siebel and Kerkhoff (2002) found that the finer fractions of the recycled material absorb more water because the cement paste adhering to the natural stone aggregate becomes relatively smaller as the grain size of the recycled aggregate increases. Because of this, the more fine recycled aggregate the concrete contains, the higher is the shrinkage value.

2.4.3 Durability of recycled aggregate concrete

Durability is the capacity of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service. Some of the factors important to the durability of recycled aggregate concrete are permeability, carbonation, freeze-thaw resistance, and sulphate resistance.

2.4.4 Permeability and water absorption

Permeability of the concrete is one of the basic properties that can cause durability problem in the concrete. Abou-Zeid et al. (2005) reported that recycled aggregate concrete exhibited higher water permeability and lower resistance to chloride ion penetration compared to conventional concrete. Salem et al (2003) showed that recycled aggregate concrete hada lower resistance to freezing and thawing compared to natural concrete. Otsuki et al (2003) reported that the carbonation resistance of recycled aggregate concrete wasinferior compared to that of natural aggregate concrete.

Permeability appears to be somewhat higher for recycled aggregate concrete when compared to conventional concrete at the same water-cement ratio. This may increase the risk of corrosion of reinforcing steel in recycled aggregate concrete, but any risk can be offset by using a lower water-cement ratio, adequate curing, and admixture-such as fly ash, ground slag, or silica fume.

2.5 SUMMARY

- The recycled aggregate obtained from crushed concrete consists of adhered mortar and original aggregates. The quantity of adhered mortar in recycled aggregates is higher in small size aggregates. Due to the adhered mortar in original aggregates mechanical and physical properties of recycled aggregates are worse than those of raw aggregates.

- The water absorption capacity of recycled aggregates has to be taken into account using recycled aggregate in new concrete production. The coarse recycled aggregates used in concrete manufacture should be kept in humid conditions; this will ensure not only concrete workability but also the effective water-cement ratio.

- There is not a significant change in the properties of concrete made with 20% - 30% of coarse recycled aggregates with respect to that of conventional concrete.

- For concrete made with 100% of recycled aggregates, the effective water-cement ratio must be lower than that of conventional concrete in order to obtain the same compressive strength.

- The compressive strength of recycled aggregates concrete depends on the strength of the original concrete. The adhered mortar of recycled aggregates can be the weakest point in the concrete. Concrete made with 50 and 100% of recycled aggregate , the strength have a lower increase in compressive strength from 7 to 28

days than that conventional concrete using only virgin aggregates.

- The variation coefficient of recycled aggregate concrete is higher than conventional concrete.

- The tension and flexural strength of concrete made with recycled aggregates and natural sand is similar to conventional concrete. However, if recycled aggregates are saturated at concrete production, the tension strength of recycled aggregate concrete decreases.

- The modulus of elasticity of recycled aggregate concrete is always lower than that of conventional concrete.

- The bond, shear, and fatigue strength of concrete made with recycled aggregates are the same as for concrete made with virgin aggregates.

- The drying shrinkage and creep of recycled aggregate concrete is higher than that of corresponding conventional concrete.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

In this chapter, the materials properties, mix proportions and test methods used in this study are presented. ASTM Type I cement and a low-calcium fly ash equivalent to ASTM Class F was used in this study. Crushed granite and river sand were used as natural aggregates.

In total, six series of concrete mixtures were prepared with different water-to-cement ratios and cement contents. Series I and II aimed to study the influence of using fly ash as a cement replacement with steam curing regimes on the properties of normal strength (35 MPa) recycled aggregate concrete. The concrete mixtures in Series I and II were prepared with cement contents of 410 and 400 kg/m^3 and water-to-cement ratios of 0.55 and 0.45 respectively, and fly ash was used as 0.25 and 35% by weight replacements of cement. Series III and IV aimed to study the influence of using fly ash as an additional mineral admixture with steam curing regimes on the properties of normal strength recycled aggregate concrete. The concrete mixtures in these series were prepared with a recycled aggregate concrete. The concrete mixtures in these series were prepared with a cement content of 410 kg/m^3 and water-to cement ratios of 0.55 and 0.50 respectively, and fly ash was employed as 0, 25 and 35% by weight addition of cement. Series V and, VI was similar to Series III and IV but the design strength was 60 MPa. The concrete, mixtures in Series V and VI were prepared with a cement content of 400 kg/m^3 and water-to-cement ratios of 0.45 and 0.40 respectively. In all the concrete

mix series, recycled aggregate was used as 0, 20, 50, and 100% by weight replacements of thenatural coarse aggregate.

3.2 MATERIALS

3.2.1 Cement and fly ash

The Portland cement used was "Shah" cement equivalent to ASTM Type I, from Shah Cement Industries Limited. The fly ash used was a low-calcium fly ash equivalent to ASTM Class F. The chemical compositions and physical properties of the cement and fly ash are given in Table 3-1 and Table 3-2.

Table 3-1 - Chemical compositions of cement and fly ash

Materials	Composition (%)						
	LOI	**SiO_2**	**Fe_2O_3**	**Al_2O_3**	**CaO**	**MgO**	**SO_3**
Cement	2.97	19.61	3.32	7.33	63.15	2.54	2.13
Fly ash	3.90	56.79	5.31	28.21	<3	5.21	0.68

Table 3-2 - Physical properties of cement and fly ash

Properties	Materials	
	Cement	**Fly ash**
Density (g/cm^3)	3.16	2.31
Specific surface area (cm^2/g)	3519.5	3960

3.2.2 Aggregates

Natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. In this study, crushed granite was used as the natural aggregate and recycled aggregate sourced from a recycling facility was used. The nominal sizes of the natural and recycled coarse aggregates were 20 and 10mm and their particle size distributions conformed to the requirements of BS 882 (1985). The physical and mechanical

properties of the coarse aggregate are shown in Table 3-3. The porosity of the aggregates was determined using mercury intrusion porosimetry (MIP). River sand was used as the fine aggregate in the concrete mixtures. On average, the particle density was between 2300 and 2600 kg/m3, water absorption was between 3-7%, and 10% fines value was generally greater than 100 KN.

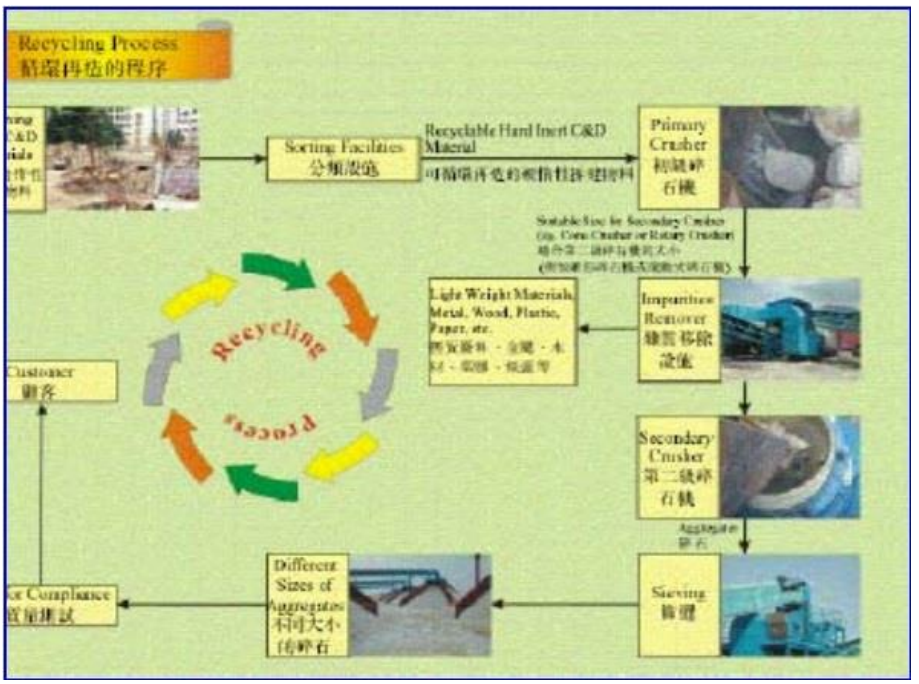
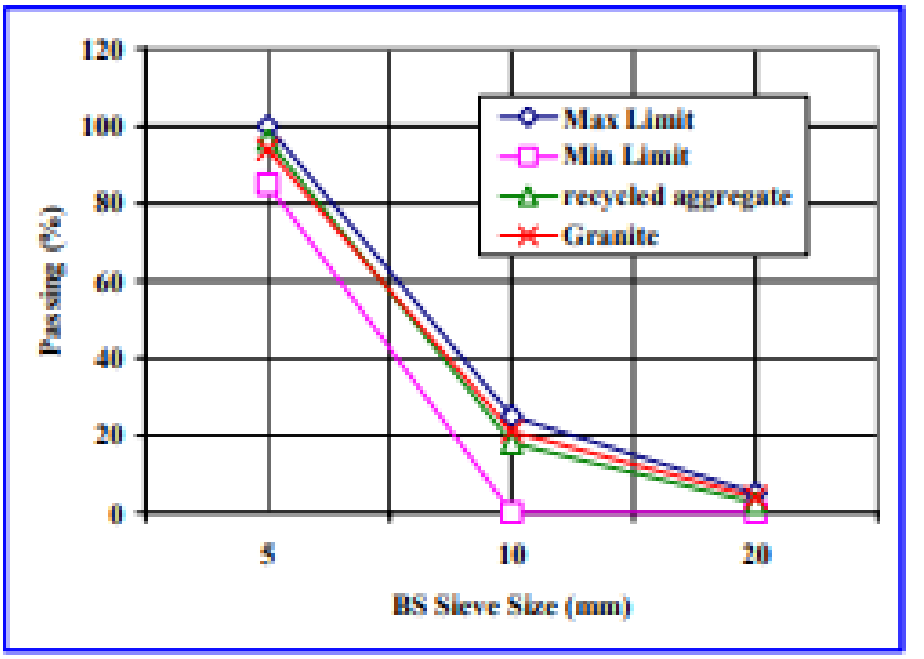


Figure 3-1 The recycling process (From fact sheet of Civil Engineering Department)

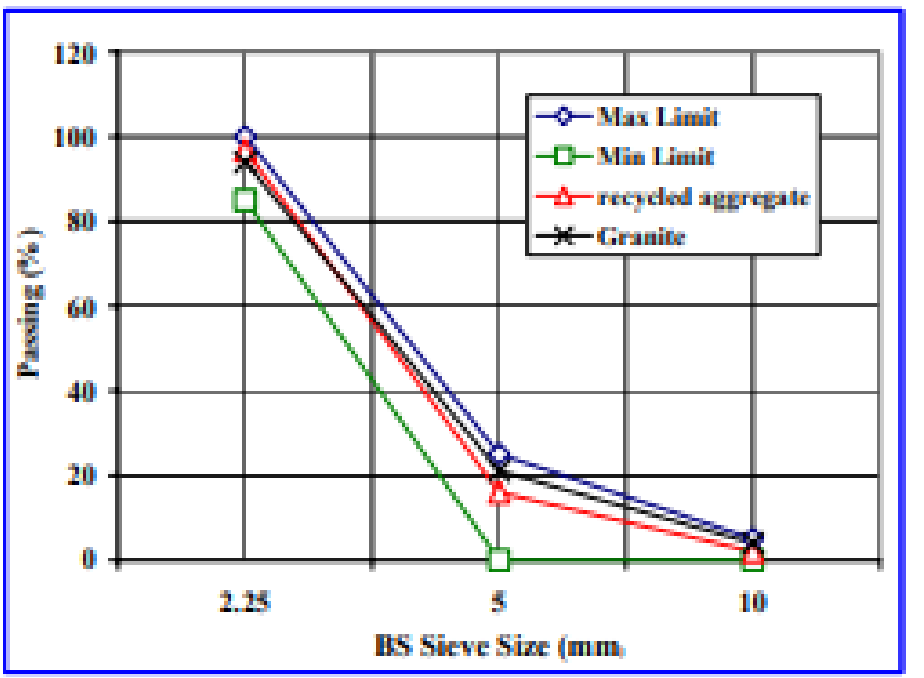
Grading and composition of natural and recycled aggregates

1) Aggregate grading

The natural and recycled aggregates had similar size fractions, 5/10 mm, 10/20 mm and 20/37.5 mm. The fractional size of the river sand employed in all the concrete mixes was 0/5 mm. All the aggregate particle size distributions were in accordance with BS 882. Figure 3-2 shows that the recycled coarse aggregates and natural coarse crushed granite were within the limits required by the standard. According to BS 882-103 the sand grading was within the grading limits, as shown in Figure 3-3.



(a)



(b)

Figure 3-2 Particle size distribution of coarse aggregate according to BS 882. (a) 20 mm; (b) 10 mm

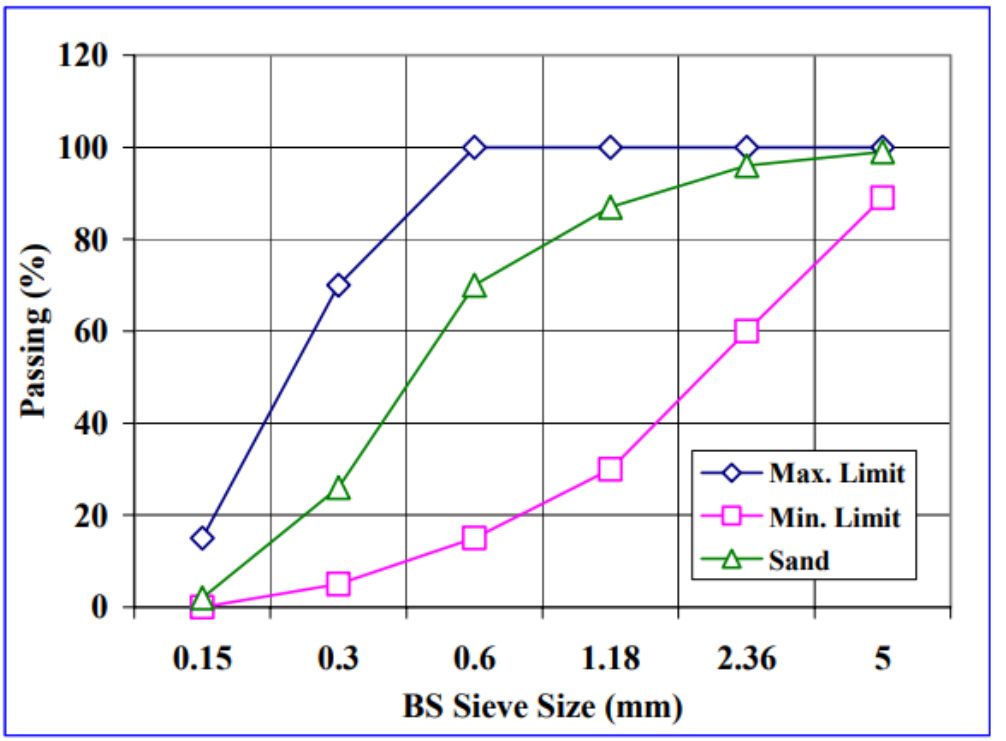
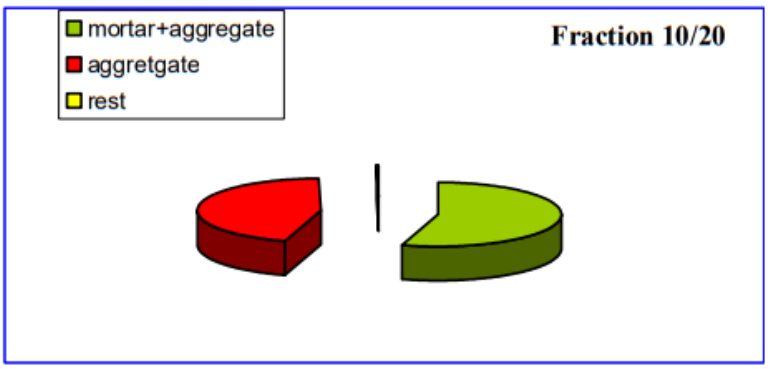


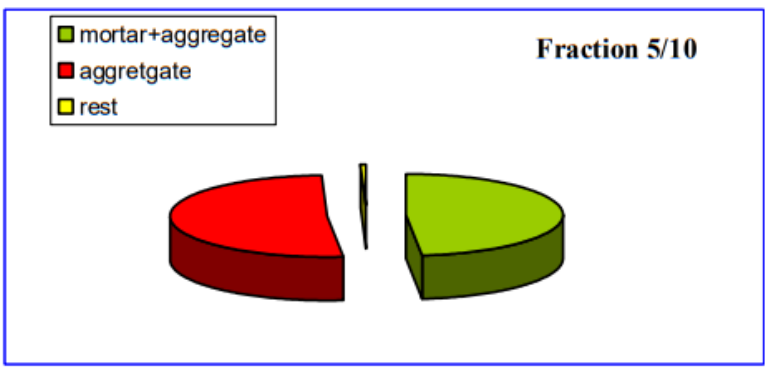
Figure 3-3 Sand grading according to BS 882

2) Recycled aggregates composition

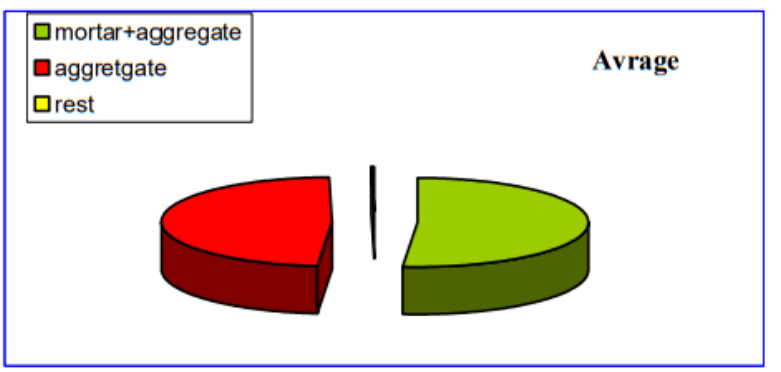
A representative sample was taken to determine the composition of recycled aggregates. According to normative DIN 4226 – 100, a mass of 25 kg of each fraction of aggregates was taken. Two materials dominated the composition of recycled aggregates as shown in Figure 3-4. Figure 3-4 is divided into 3 graphics; (a) and (b) represented the different fractions by mass and (c) is the average composition calculated from the relative percentages of the different fractions in the aggregates.



(a)



(b)



(c)

Figure 3-4 Recycled aggregate composition.

The most important difference between two fractions shown on (a) and (b) is that when the aggregate was finer, the percentage of impure materials was higher. In all the fractions, the quantity of aggregates and aggregates with adhered old mortar was higher than 99%, although the clean aggregates without mortar was higher when the aggregate was smaller. Similarly the quantity of aggregates with adhered old mortar was smaller.

3.2.3 Super plasticizer

For the concrete mixtures in Series III, IV, V and VI, a sulfonated naphthalene formaldehyde condensate (Darex Super 20) obtained from Ducon Concrete Admixtures in Bangladesh was used. This super plasticizer was available as a dark-brown 40-42% solids aqueous solution with a density of 1210 kg/m^3.

3.3 Concrete mixtures

3.3.1 Mix proportions

A total of six series of concrete mixtures was prepared in the laboratory. The concrete mixtures in Series I, III and IV were prepared with a OPC content of 410 kg/m^3 and water-to-cement (W/C) ratio of 0.55, 0.55, and 0.50 respectively. The concrete mixtures in Series II, V and VI were prepared with a cement content of 400 kg/m^3 and W/C ratio of 0.45, 0.45, and 0.40 respectively. In this study, recycled aggregate was used as 0, 20, 50 and 100% by weight replacements of the natural coarse aggregate. In Series I and II, fly ash was used as 0, 25 and 35% by weight replacements of cement. However, in Series III, fly ash was used as 0, 25 and 35% on addition to cement, and in series IV, V, and VI fly ash was used as 0, and 25% on addition to cement by weight. The mix notations of concrete mixture in six series are shown in Table 3-3. The absolute volume method was adopted to design the mix proportions of the concrete mixtures in Series I -VI as shown in Table 3-4 – Table 3-8, respectively. In the concrete mixtures, the 10 and 20 mm coarse aggregates were used in a ratio of 1:2.

3.3.2. Specimens casting and curing

All mixing was conducted in a pan mixer of 0.11 m^3 capacity under laboratory condition. The cement, sand and coarse aggregates were placed and dry-mixed for about 2 min before water was added. After 3 min of mixing followed when water was added. For each concrete mixture, 100 mm cubes, 70 x 70 x 285 mm prisms, and 100ϕ x 200 mm cylinders were cast. The cubes and prisms were used to determine the compressive strength and drying shrinkage respectively. The 100ϕ x 200 mm cylinders were used to evaluate the tensile splitting strength, static modulus of elasticity and resistance to chloride-ion penetration of concrete. 100x100x500 mm beams were used to determine flexural strength and fracture energy of the concrete. Additionally, creep test was performed for the concrete mixtures in Series I (W/B=0.55) using the 150ϕ x 300 mm cylinders.

In this study, normal water curing and initial steam curing were used. For the water cured specimens, the specimens were cured in air for a period of 24 hours before they were demoded. After demolding, three cubes and three cylinders were immediately tested for the 1-day compressive and splitting tensile strengths, and the rest of the specimens were cured in a water tank at 27 ± 1ºC until other test ages were reached. For steam curing, the concrete specimens immediately after casting (without demolding) were initially cured in a steam bath at 65^{o}C for 8 hours. The steam curing cycle is shown in Figure 3-5. After the steam curing stage, the specimens were demolded and three cubes and three cylinders were tested for the 1-day compressive and splitting tensile strengths. The rest of the specimens were further cured in a water tank at 27 ± 1ºC until other test ages were reached.

Table 3-3 Mix notation of concrete mixture

Fly ash (%)	Recycled aggregate (%)	Notation					
		Series I	Series II	Series III	Series IV	Series V	Series VI
		Water-to-cement ratio (W/C)					
		0.55	0.45	0.55	0.50	0.45	0.40
0	0	R0	R0	R0	R0	R0	R0
	20	R20	R20	R20	R20	R20	R20
	50	R50	R50	R50	R50	R50	R50
	100	R100	R100	R100	R100	R100	R100
25	0	*r-R0F25	r-R0F25	*a-R0F25	a-R0F25	a-R0F25	a-R0F25
	20	r-R20F25	r-R20F25	a-R20F25	a-R20F25	a-R20F25	a-R20F25
	50	r-R50F25	r-R50F25	a-R50F25	a-R50F25	a-R50F25	a-R50F25
	100	r-R100F25	r-R100F25	a-R100F25	a-R100F25	a-R100F25	a-R100F25
35	0	r-R0F25	r-R0F25	a-R0F35	-	-	-
	20	r-R20F25	r-R20F25	a-R20F35	-	-	-
	50	r-R50F25	r-R50F25	a-R50F35	-	-	-
	100	r-R100F25	r-R100F25	a-R100F35	-	-	-

* a: fly ash was added as x% by weight of cement; r: fly ash was used as x% by weight replacement of cement.

3.4. TEST METHODS

In this study, the fresh properties and hardened properties was determined. The test properties and ages of concrete mixture in different series are shown in Table 3-9.

Table 3-4 - Proportioning of the concrete mixtures Series I

Notation	Fly ash (%)	Recycled aggregate (%)	Constituents (kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	225	410	642	1048	0
R20	0	20	225	410	642	840	204
R50	0	50	225	410	642	524	506
R100	0	100	225	410	642	0	1017
r-R0 F25	25	0	225	410	611	1048	0
r-R20F25	25	20	225	410	611	840	204
r-R50F25	25	50	225	410	611	524	506
r-R100F25	25	100	225	410	611	0	1017
r-R0F35	35	0	225	410	598	1048	0
r-R20F35	35	20	225	410	598	840	204
r-R50F35	35	50	225	410	598	524	506
r-R100F35	35	100	225	410	598	0	1017

Table 3-5 - Proportioning of the concrete mixtures in Series II

Notation	Fly ash (%)	Recycled aggregate (%)	Constituents (kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	180	400	708	1108	0
R20	0	20	180	400	708	886	215
R50	0	50	180	400	708	554	538
R100	0	100	180	400	708	0	1075
r-R0 F25	25	0	180	400	688	1108	0
r-R20F25	25	20	180	400	688	886	215
r-R50F25	25	50	180	400	688	554	538
r-R100F25	25	100	180	400	688	0	1075
r-R0F35	35	0	180	400	668	1108	0
r-R20F35	35	20	180	400	668	886	215
r-R50F35	35	50	180	400	668	554	538
r-R100F35	35	100	180	400	668	0	1075

3.4.1 Determination of slump loss of fresh concrete

The slump of the fresh concrete prepared was measured using the standard slump test apparatus. When a fresh concrete mixture was first prepared, about 20 L (3 times the quantity required for the slump test) of the fresh concrete was taken aside on a steel plate. The first (initial) slump was measured. Afterward, slump values were regularly measured at intervals of 15 min. The concrete mixtures were covered by plastic films between the test intervals. The total testing period lasted for 165-210 min. The room

temperature during the test was 21 ± 2 °C.

Table 3-6 - Proportioning of the concrete mixtures in Series III

Notation	Fly ash (%)	Recycled aggregate (%)	Constituents (kg/m^3)					
			Water	Total cementitious material	Sand	Granite	Recycled aggregate	SP (l/m^3)
R0	0	0	225	410	642	1048	0	-
R20	0	20	225	410	642	840	204	-
R50	0	50	225	410	642	524	506	-
R100	0	100	225	410	642	0	1017	-
a-R0 F25	25	0	225	512.5	582	992	0	-
a-R20F25	25	20	225	512.5	582	794	193	-
a-R50F25	25	50	225	512.5	582	496	482	-
a-R100F25	25	100	225	512.5	582	0	963	-
a-R0F35	35	0	225	553.5	598	1048	0	2.8
a-R20F35	35	20	225	553.5	598	840	204	2.8
a-R50F35	35	50	225	553.5	598	524	506	2.8
a-R100F35	35	100	225	553.5	598	0	1017	2.8

Table 3-7 - Proportioning of the concrete mixtures in Series IV

Notation	Fly ash (%)	Recycled aggregate (%)	Constituents (kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	205	410	662	1081	0
R20	0	20	205	410	662	865	210
R50	0	50	205	410	662	541	525
R100	0	100	205	410	662	0	1049
a-R0 F25	25	0	205	512.5	618	1009	0
a-R20F25	25	20	205	512.5	618	802	196
a-R50F25	25	50	205	512.5	618	505	489
a-R100F25	25	100	205	512.5	618	0	979

Table 3-8 - Proportioning of the concrete mixtures in Series V

Notation	Fly ash (%)	Recycled aggregate(%)	Constituents (kg/m^3)				
			Water	Total cementitiousmaterial	Sand	Granite	Recycled aggregate
R0	0	0	180	400	708	1108	0
R20	0	20	180	400	708	886	215
R50	0	50	180	400	708	554	538
R100	0	100	180	400	708	0	1075
a-R0 F25	25	0	180	500	665	1040	0
a-R20F25	25	20	180	500	665	802	202
a-R50F25	25	50	180	500	665	520	504
a-R100F25	25	100	180	500	665	0	1009

Table 3-9 Test schedules

Properties	Test ages	Series
Compressive and splitting tensile strength	1, 4, 7, 28 and 90 days	I, II, III, IV, V and VI
Flexural strength	28 and 90 days	I and II
Elastic modulus	28 and 90 days	I, II, III, IV, V and VI
Strain-strain curve	28 days	I and II
Fracture energy	28 and 90 days	I and II
Drying shrinkage	1, 4, 7, 14,28,56,90 and 112 days	I, II, III, IV, V and VI
Creep	1, 4, 7, 14,28,56,90 and 120 days	I
Chloride-ion penetration	28 and 90 days	I, II, III, IV, V and VI



Figure 3-5 “Croker” concrete mixer

3.4.2 Air content test

The air content of the fresh content was determined according to BS EN 12350-7:2000 - pressure methods (Figure 3-6).



Figure 3-6 Pressure gauge for air content test

3.4.3 Bleeding test

ASTM C232 standard test method (ASTM Standard (1992)) was used to measure the bleeding of the concrete mixture. The fresh concrete was filled into a container in two layers and vibrated for 10 seconds for each layer on a vibrating table. The container had the diameters of 290 mm and 285 mm at the top and the bottom respectively, and a height of 285mm. The container was then placed on a level platform free from vibration and covered with a lip to prevent the evaporation of water. A pipette was used to draw off the bleed water at 10 minutes intervals during the first 70 minutes and at 30 minutes intervals thereafter until cessation of bleeding.

The ASTM standard (ASTM Standard (1992)) specified that the bleeding test has to be conducted immediately after mixing. In this study, tests started at 30, 60, 120 minutes after mixing were also conducted. For these additional tests, the concrete in the mixer was remixed and was then filled in to the container. The procedures described above were followed to measure the amount of bleed water. The effect of the starting time of bleeding tests were investigated as in practice the casting of concrete is likely any time between 0 and 2 hours after mixing (Wainwright, et al 2000).

All the tests were conducted in the laboratory environment at the room temperature of about 20 to 24 ^{o}C.

The method used to determine the bleeding of the concrete was in accordance with ASTM C232-99. (Figure 3-7) The test samples were fresh concrete weighing 20 ± 0.5 kg. The vibrating cycle used was: Power on for 3 s, and Power off 30 s.

Bleeding water per unit area of surface was calculated as follows:

$$V=V_1/A \quad (3\text{-}1)$$

Where:

V_1 = volume of bleeding water measured during the selected time interval, mL, and

A = area of exposed concrete, cm^2.

The accumulated bleeding water, expressed as a percentage of the net mixing water contained within the test specimen was calculated as follows:

$$C = (w/W) \times S \quad (3\text{-}2)$$

$$Bleeding, \% = (D/C) \times 100 \quad (3\text{-}3)$$

Where:

C = mass of the water in the test specimen, g,

W = total mass of the batch, kg,

w = net mixing water (the total amount of water minus the water absorbed by the aggregates), kg,

S = mass of the sample, g, and

D = mass of the bleeding water, g, or total volume withdrawn from the test specimen in cubic centimeters multiplied by $1 g/cm^3$.



Figure 3-7 Bleeding container, cover and vibrating platform

3.4.4 Compression and tensile splitting strength test

The compressive and splitting tensile strengths of concrete were determined using a Denison compression machine with a loading capacity of 3000 kN. (Figure 3-8). The loading rates applied in the compressive and splitting tensile tests were 200 kN/min and 57 kN/min, respectively. The compressive and splitting tensile strengths were measured at the ages of 1, 4, 7, 28 and 90 days.



Figure 3-8 "Denison" compression machine

3.4.5 Static modulus of elasticity

The static modulus of elasticity of concrete was determined in accordance with ASTM C 469-65. In this thesis, this test was carried out on the concrete specimens at the ages of 28 and 90 days.

3.4.6 Drying shrinkage test

A modified British Method (BS1881, part 5: 1970) was used for the test. After removing the concrete prisms from the curing tank at 27±2 °C, the initial length of each specimen was measured (Figure 3-9). The specimens were then stored in an environmental chamber with a temperature of 55ºC and a relative humidity of 95 % until the next measurements at 1, 4, 7, 28, 56, 90 and 112 days. Before each measurement was taken on the scheduled day, the specimens were first removed from the environmental chamber and conveyed to a second cooling chamber for about 4 hours at a controlled temperature of 25ºC and a relative humidity of 75 %. The length

of each specimen was then measured within 15 minutes before delivering the specimens back to the environmental chamber for the subsequence drying process. The procedure of drying, cooling and measuring continued until the final length measurement at 112 day was recorded.



Figure 3-9 Drying shrinkage test

3.4.7 Creep test

Creep strain was measured according to ASTM C 512 (2002) when the specimens were cured for 28 days. The creep test was carried out at a temperature of 23± 2 ºC and was lasted for 120 days. The specimens were initially loaded to 35% of the 28-day axial compressive strength of the concrete. Simultaneously, the drying shrinkage of the same concrete mixture was measured. The actual creep strain of the concrete was calculated by subtracting the drying shrinkage values from the total time dependent deformation of the corresponding concrete mixture under load.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

The objectives of this chapter are to present and discussed the test results of the fresh properties of recycled aggregate concrete and the concrete made with class-F fly ash in Series I and Series II. These properties include slump, slump lose, air content, fresh density and bleeding. The influences of recycled aggregate on the slump, air content and bleeding are discussed. The effect of delaying the starting time of bleeding tests and the used of fly ash on the bleeding of concrete, compressive strength, tensile splitting strength, static modulus of elasticity, drying shrinkage, creep on the recycled aggregate concrete were presented and discussed.

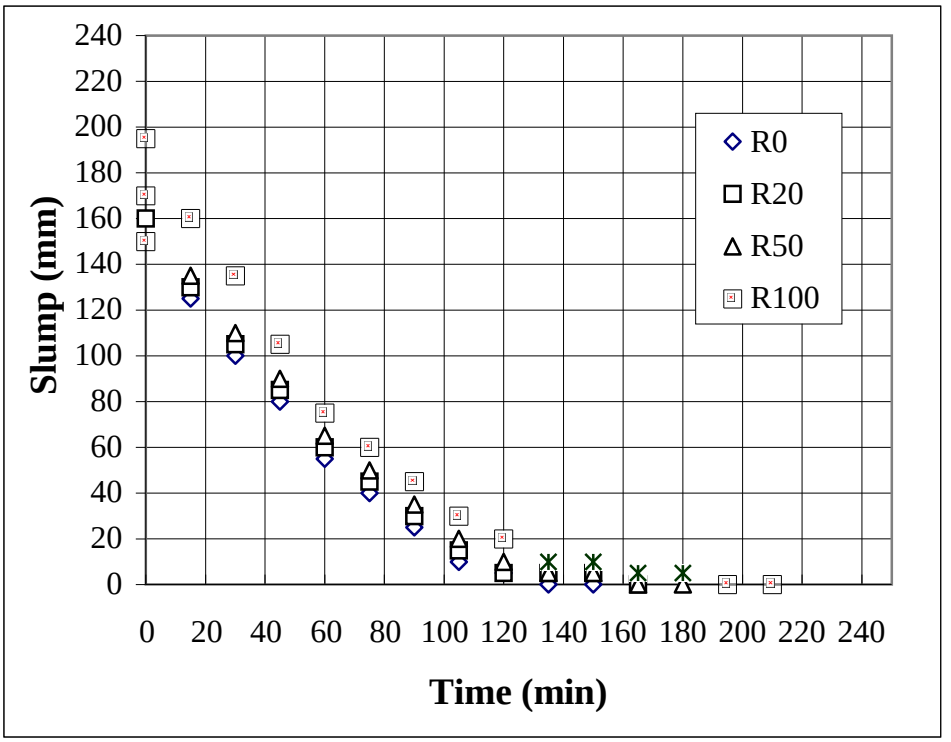
4.2 TEST RESULTS AND DISCUSSION

4.2.1 Initial slump and slump loss

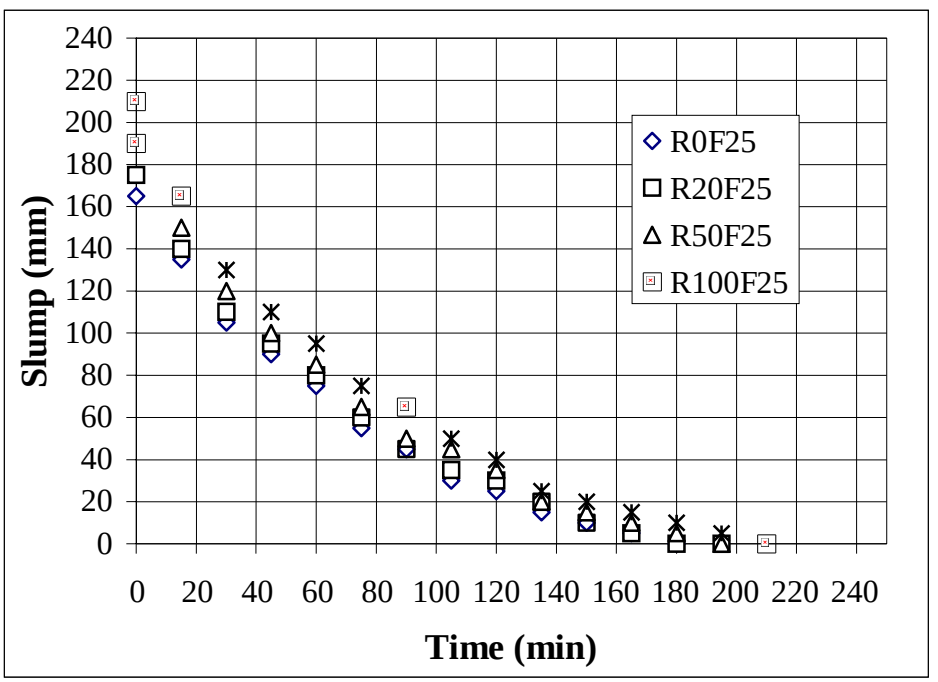
Figure 4-1(a) and Figure 4-2(a) show the changes of concrete slump with time for Series I and II mixes without fly ash, where the slump values are averages of two measurements. It can be seen from Figure 4-1 (a) that the initial slump of concretes increased with an increase in the percentage of recycled aggregate. The mix prepared with 100% recycled aggregate showed the greatest slump of 195 mm. This was due to the higher initial free water content in the concrete mixture. This higher initial free water content for concrete prepared with recycled aggregates was due to the higher

water absorption of the recycled aggregate which was used at the air dried condition with moisture content of the aggregates at mixing much lower than the water absorption. Additional amounts of water were added to maintain the mix proportions as given in Tables 3 - 4. The moisture states of the aggregates affected the change of slump of the fresh concretes. The initial slump of concrete was strongly dependent on the initial free water content of the concrete mixes (Poon, et al 2004). It is also shown in Figure 4-1(a) that the rate of slump loss was quicker within the first hour after mixing, but was slower afterward. The mix without recycled aggregate took about 130 minutes to decrease to the zero slump, while the mix with 100% recycled coarse aggregates took over 3 hours to reach this.

Figure 4-2 (a) shows that the initial slump value of concretes in series II increased with an increase in the percentage of recycled aggregate. This was due to although in series II concrete mixture, the water-to-cement ratio was decreased to level of 0.45, the recycled aggregate was used in the air-dry (AD) state with moisture content of 2.12% and 1.86% for 20 mm and 10 mm recycled aggregates, respectively. In order to reach the SSD state, the higher initial free water was added and in each mixture. It can also be seen from Figure 4-2 (a) that the rate of slump loss was quicker within the first 75 minutes after mixing, but was slower afterward. The mix with 100% recycled aggregates took about 165 minutes to decrease to the zero slump. This time was smaller than that mixes with conventional aggregate or 20%, and 50% recycled aggregates. So the effect of W/C ratio on the rate of slump loss was significant.

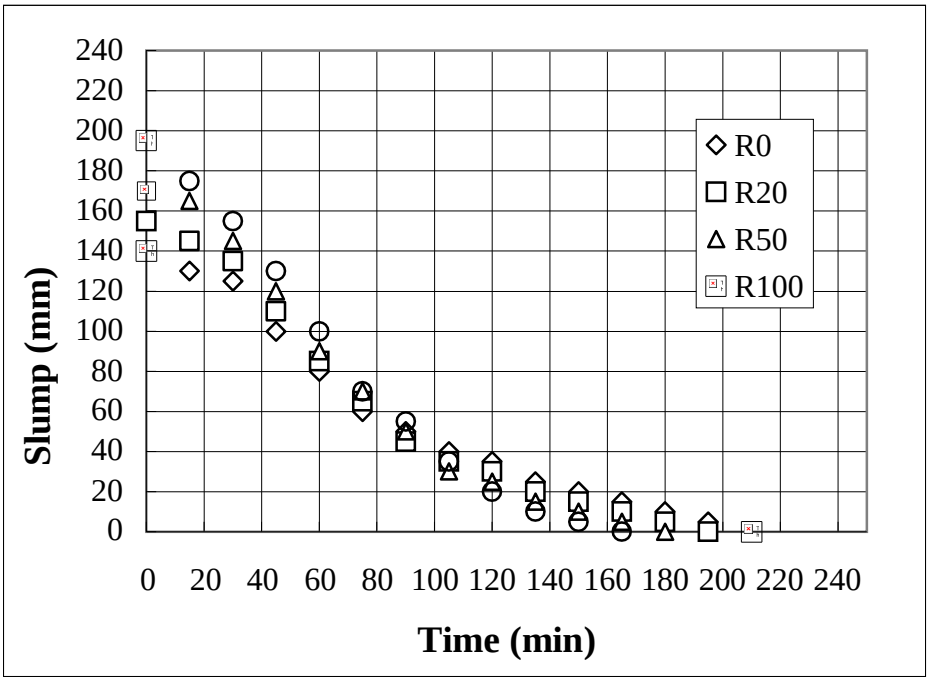


(a)

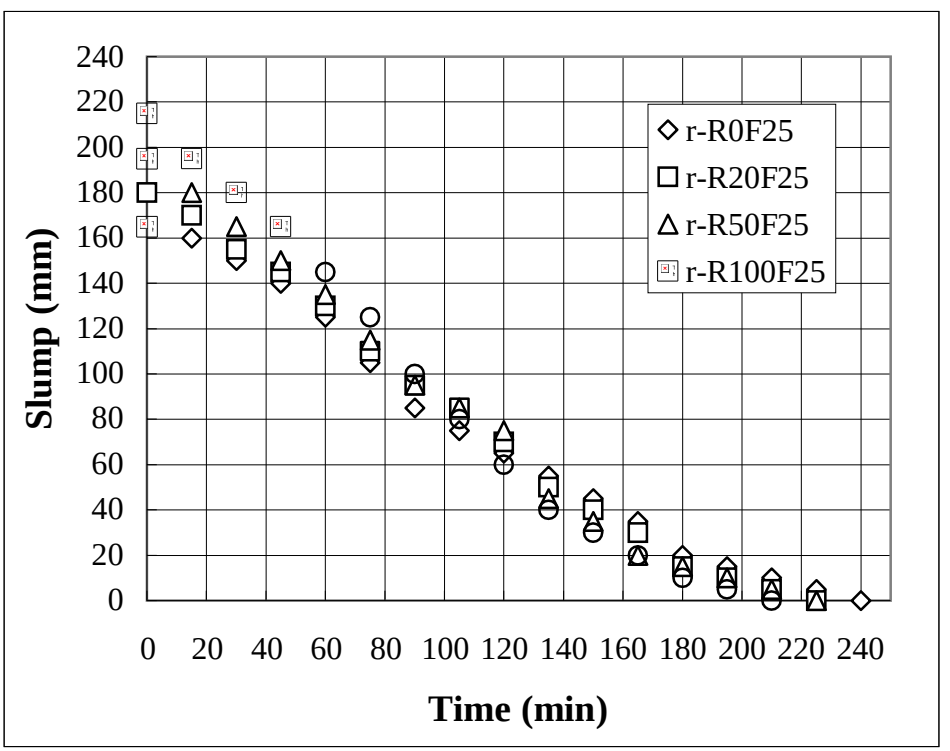


(b)

Figure 4-1 Changes of slump of concrete mixes in series I (a) without fly ash and (b) with 25% fly ash



(a)



(b)

Figure 4-2 Changes of slump of concrete mixes in series II (a) without fly ash and (b) with 25% fly ash

4.2.2 Bleeding of concrete

The results of the bleeding tests are summarized in Table 4-1 and Table 4-2 for concrete mixes in series I and series II, respectively. The bleeding rate is defined as the volume of water in ml collected per cm^2 per second during the first 60 min of the test. The bleeding capacity is defined as the total volume of bleeding water collected during the entire course of the test, expressed as the fraction of the initial volume of the concrete. The cumulative bleeding curves are shown in Figs 4-3 for Series I, Figs 4-4 for Series II mixes, respectively, where the accumulated volume of bleeding water is plotted against time (minutes after mixing).

The use of recycled aggregates that was over-wetted should be avoided to reduce the bleeding which has negative effects on the properties of hardened concrete. The results of the present study for concrete mixture in Series I as shown in Tables 4-1 indicatedthat the use of recycled aggregates, even at an air-dried state, resulted in higher bleedingrates and bleeding capacities. The use of 100% recycled aggregates increased the bleeding rate and bleeding capacity by 25.5% and 22.3% respectively. Delaying the starting time of bleeding tests resulted in significant reductions in both the bleeding rate and bleeding capacity for all the concrete mixes, when compared with the corresponding mixes with the same percentages of recycled aggregates.

It is clear from Table 4-1 that the replacement of cement by 25% fly ash reduced the bleeding rate and bleeding capacity for all the mixes when the bleeding tests were conducted immediately after mixing. For the mix with 100% recycled coarse aggregates, the fly ash reduced the bleeding rate and bleeding capacity by 9% and 13% respectively, when compared with the mix without fly ash. Further reductions in the bleeding rate and

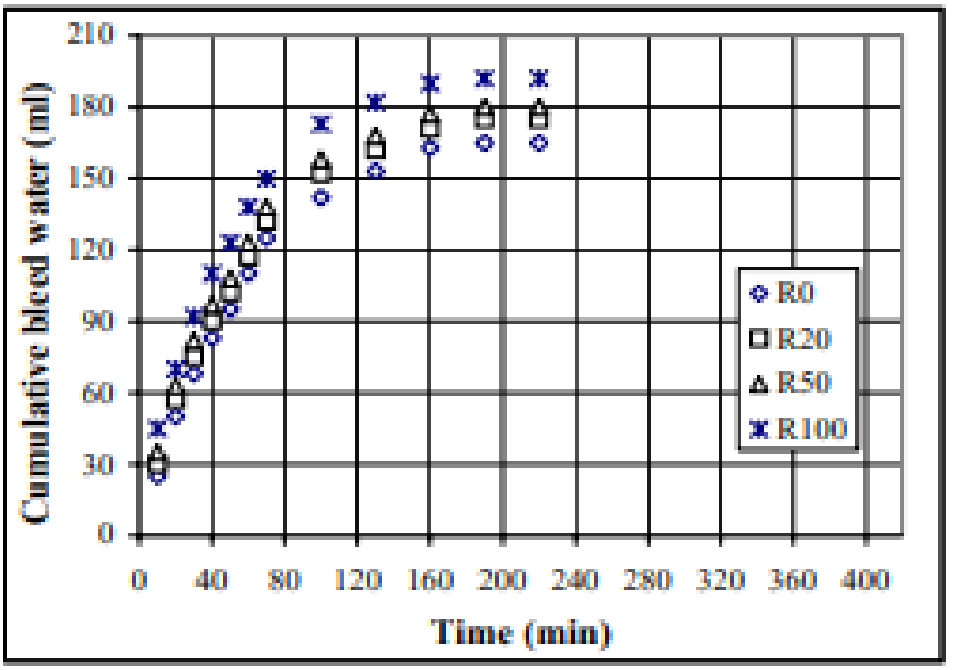
bleeding capacity were observed when the starting time of bleeding tests was delayed.

Table 4-1 Results of bleeding tests of Series I concrete mixes

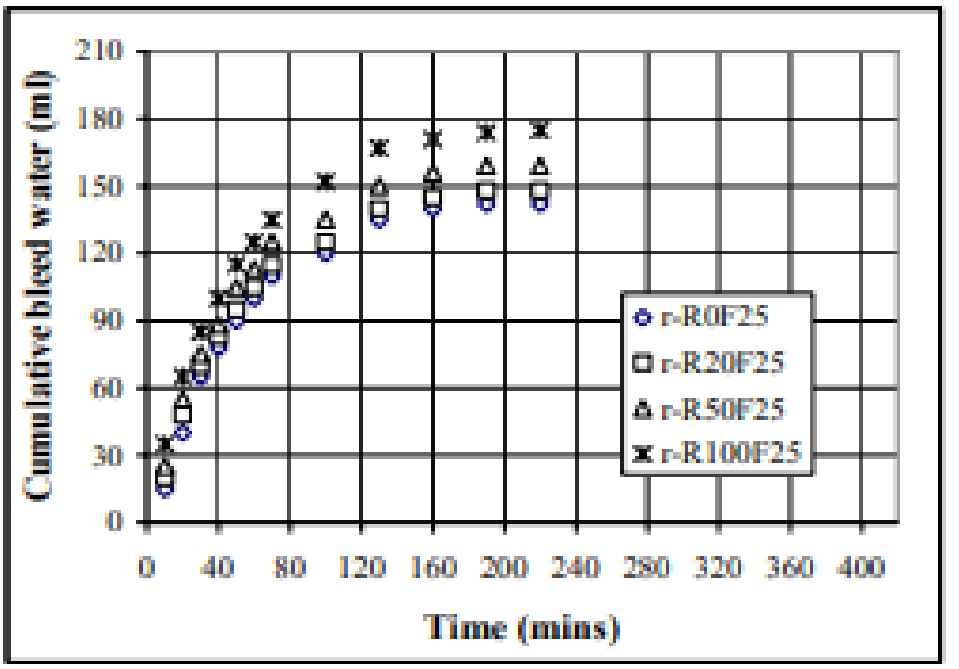
Mix	Test started immediately after mixing		Test started at 30 minutes after mixing		Test started at 60 minutes after mixing		Test started at 120 minutes after mixing	
	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s
R0	18.8	47.9	13.2	19.6	8.3	12.2	5.2	9.6
R20	19.9	50.9	14.2	20.5	8.7	13.1	5.4	10.0
R50	21.2	53.6	15.2	20.9	9.1	13.5	5.6	10.4
R100	23.0	60.1	17.1	22.2	9.9	14.4	6.1	10.5
r-R0F25	16.2	43.5	9.6	17.4	7.3	10.9	4.6	6.5
r-R20F25	16.9	45.7	10.4	18.3	7.6	11.3	4.8	6.7
r-R50F25	18.1	49.2	10.8	20.5	8.1	12.2	5.0	7.1
r-R100F25	20.0	54.5	12.0	22.7	8.8	13.9	5.4	7.8

Table 4-2 Results of bleeding tests of Series II concrete mixes

Mix	Test started immediately after mixing		Test started at 30 minutes after mixing		Test started at 60 minutes after mixing		Test started at 120 minutes after mixing	
	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s	Bleeding capacity 10^{-3} ml/ml	Bleeding rate 10^{-6} ml/cm^2/s
R0	14.6	34.9	9.7	19.6	6.2	12.2	4.1	9.6
R20	15.4	37.5	10.3	20.5	6.6	13.1	4.6	10.0
R50	16.6	41.0	10.8	20.9	7.3	13.5	5.0	10.4
R100	17.7	44.9	12.0	22.2	7.9	14.4	5.6	10.5
r-R0F25	11.8	30.5	8.0	13.1	5.1	7.8	3.6	5.7
r-R20F25	12.8	32.7	8.5	14.4	5.7	9.2	4.0	6.1
r-R50F25	13.7	34.9	9.2	16.1	6.2	10.5	4.4	6.5
r-R100F25	15.0	37.1	10.3	17.4	6.8	11.3	4.9	7.4

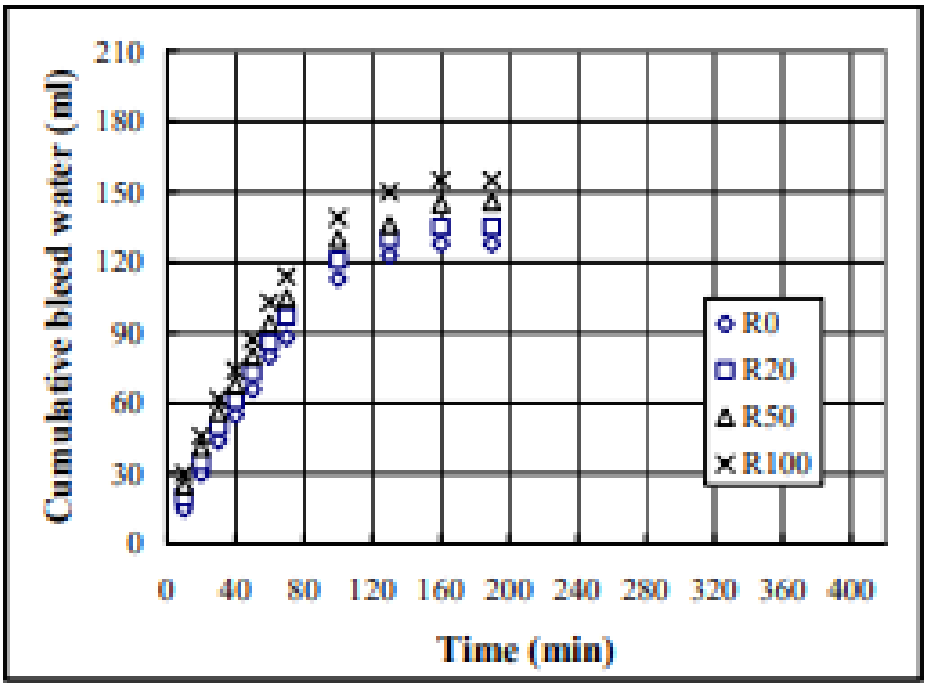


(a)

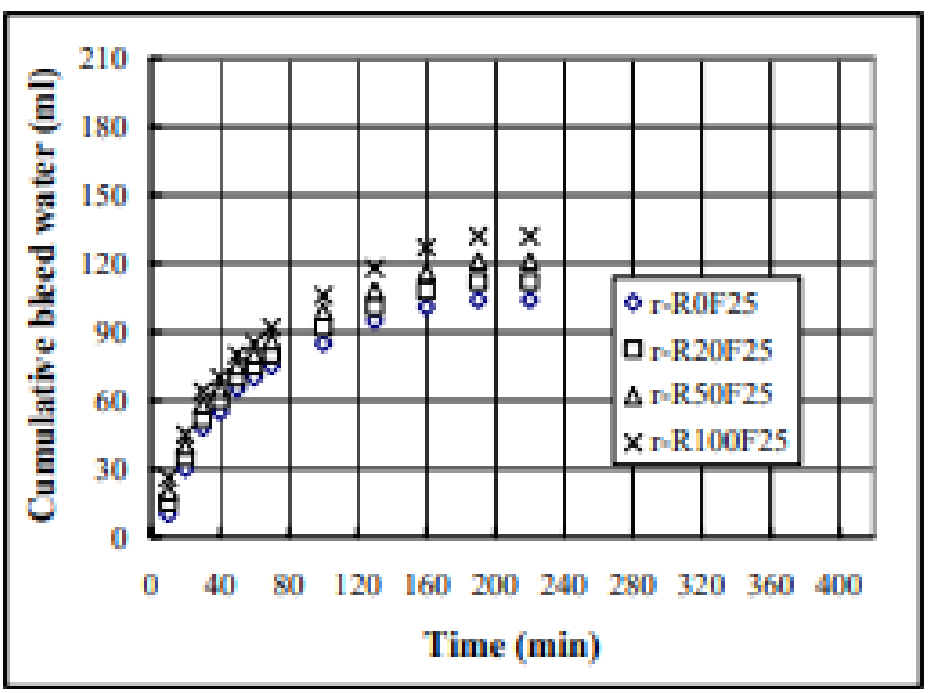


(b)

Figure 4-3 Cumulative bleeding curves of Series I mix, Tests started immediately after mixing (a) without fly ash and (b) with 25% fly ash



(a)



(b)

Figure 4-4 Cumulative bleeding curves of Series II mix, Tests started immediately after mixing (a) without fly ash and (b) with 25% fly ash

4.2.3 Air content and fresh density

The air content and fresh density of recycled aggregates concrete in both series I and II are shown in Table 4-3. Each presented value is the average of two measurements. It can be seen from Table 4-3 that the air content of the concrete in both series was increased with an increase in the recycled aggregate content. Fresh concretes made with 100% of recycled aggregates have higher and more varied natural air contents than conventional fresh concrete. This is consistent with the results of Hansen (1985) that the natural air content of recycled aggregate concrete may be slightly higher than that of control concretes made with conventional concrete.

It can be obtained from Table 4-3 that the fresh density of the concrete in both series is decreased within increase in the recycled aggregate and fly ash contents. This is due to the density of recycled aggregate and fly ash is lower than that of the conventional aggregate and cement. Furthermore, a decrease in the W/C ratio from 0.55 to 0.45 increased the fresh density of concrete.

Table 4-3 Fresh density and air content of concrete in Series I and II

Notation	Recycled aggregate (%)	Fly ash (%)	Series I		Series II	
			Air content (%)	Density (kg/m^3)	Air content (%)	Density (kg/m^3)
R0	0	0	1.8	2315	2.2.	2365
R20	20	0	2.0	2298	2.4	2342
R50	50	0	2.1	2274	2.7	2321
R100	100	0	2.3	2265	3.1	2304
r-R0F25	0	25	1.5	2309	2.0	2347
r-R20F25	20	25	1.7	2286	2.2	2324
r-R50F25	50	25	1.8	2259	2.5	2301
r-R100F25	100	25	2.0	2247	2.8	2286
r-R0F35	0	35	1.4	2296	1.8	2326
r-R20F35	20	35	1.5	2274	2.0	2305
r-R50F35	50	35	1.7	2259	2.2	2297
r-R100F35	100	35	1.9	2241	2.5	2275

4.2.4 Compressive and tensile splitting strengths

The compressive strength results are presented in Table 4-4 and Table 4-5 for the concrete mixtures in Series I and II, respectively. Each presented value is the average of three measurements. It is can be seen from Table 4-4 and Table 4-5 that the 28-day compressive strength of the concrete mixtures decreased with an increase in the recycled aggregate content. Furthermore, the use of fly ash as a partial replacement of cement also caused a reduction in the compressive strength. A closer observation for the strength development between the 28 and 90 days shows that the concrete mixtures prepared with fly ash had a greater gain in strength between 28 and 90 days. In Series I, the concrete mixtures prepared with 0, 25 and 35 % fly ash had an average of 8.2, 26.8 and 23.3 % increase in the compressive strength from 28 to 90 days, respectively. On the other hand, the concrete mixtures prepared with 0, 25 and 35 % fly ash in Series II had an average of 14.1, 32.7 and 24.0 % increase in the compressive strength from 28 to 90 days respectively. The higher increase in strength for the concrete mixtures prepared with fly ash was attributed to the pozzolanic effects of fly ash at late ages. Furthermore, the compressive strength increased with a decrease in the W/B ratio.

Table 4-4 - Compressive strength of the concrete mixtures in Series I

Notation	Fly ash (%)	Recycled aggregate (%)	Compressive strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	12.8	23.3	30.2	48.6	52.7
R20	0	20	11.9	22.4	29.1	45.3	50.8
R50	0	50	11.6	21.8	27.6	42.5	49.5
R100	0	100	10.2	18.6	24.4	38.1	45.5
r-R0 F25	25	0	12.1	22.8	28.6	43.6	57.9
r-R20 F25	25	20	11.5	24.3	32.8	42.8	57.3
r-R50 F25	25	50	11.1	22.9	30.4	41.7	53.4
r-R100F25	25	100	9.4	19.1	25.1	36.8	50.1
r-R0 F35	35	0	7.7	16.6	22.5	40.7	47.8
r-R20 F35	35	20	6.6	16.4	20.9	41.0	46.6
r-R50 F35	35	50	5.9	15.2	20.4	37.1	43.2
r-R100F35	35	100	4.8	14.6	19.4	25.2	37.4

Table 4-5 - Compressive strength of the concrete mixtures in Series II

Notation	Fly ash (%)	Recycled aggregate (%)	Compressive strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	25.8	45.8	53.8	66.8	72.3
R20	0	20	23.6	43.2	51.2	62.4	68.0
R50	0	50	21.1	40.3	44.8	55.8	61.5
R100	0	100	15.5	26.8	36.2	42.0	50.2
r-R0 F25	25	0	17.6	32.6	39.9	54.4	69.0
r-R20 F25	25	20	13.2	28.9	34.1	49.7	68.7
r-R50 F25	25	50	11.6	25.7	31.3	44.3	65.2
r-R100F25	25	100	11.1	21.4	28.6	39.5	52.3
r-R0 F35	35	0	12.8	25.6	30.6	45.9	56.6
r-R20 F35	35	20	11.6	23.6	28.5	43.6	55.8
r-R50 F35	35	50	10.9	21.2	26.3	40.4	52.3
r-R100F35	35	100	9.9	20.5	25.3	38.3	50.9

The compressive strength results of the concrete mixture in Series III, IV and V are presented in Table 4-6, Table 4-7 and Table 4-8, respectively. Each presented values is the average of three measurements. It can be seen from Table 4-6, Table 4-7 and Table 4-8 that at the all test age the compressive strength of recycled aggregate concrete in Series III, IV and V was decreased with an increase in the recycled

aggregate content. At 28 days, the compressive strength of the concrete with 100% recycled aggregate and no fly ash were decreased by 21.6%, 19.8%, 22.0% and 19.1% compared with those corresponding conventional aggregate concrete mixtures in Series III, IV and V, respectively. This is due to the recycled aggregates have a mount of the attached mortar and cement paste and a higher water absorption compared to the natural aggregates.

Table 4-6 – compressive strength of the concrete mixtures Series III

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.55	12.8	23.3	30.2	48.6	52.7
R20	0	20	0.55	11.9	22.4	29.1	45.3	50.8
R50	0	50	0.55	11.6	21.8	27.6	42.5	49.5
R100	0	100	0.55	10.2	18.6	24.4	38.1	45.5
a-R0 F25	25	0	0.44	15.6	30.4	38.8	52.9	68.8
a-R20F25	25	20	0.44	14.8	29.5	37.9	50.1	65.9
a-R50F25	25	50	0.44	14.1	28.4	37.0	48.1	63.7
a-R100F25	25	100	0.44	16.3	29.0	36.3	45.3	65.4
a-R0F35	35	0	0.41	25.8	42.4	50.6	68.9	75.8
a-R20F35	35	20	0.41	24.7	40.1	46.2	63.0	76.2
a-R50F35	35	50	0.41	22.4	38.4	44.5	56.5	73.5
a-R100F35	35	100	0.41	18.6	32.3	39.0	54.5	69.0

Table 4-7 – Compressive strength of the concrete mixtures in Series IV

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.50	20.5	36.2	42.8	54.1	57.6
R20	0	20	0.50	18.5	35.5	39.2	51.7	55.8
R50	0	50	0.50	16.7	31.1	38.4	47.1	53.6
R100	0	100	0.50	13.9	23.1	31.8	43.4	50.7
a-R0 F25	25	0	0.40	22.5	37.6	43.0	57.6	72.8
a-R20F25	25	20	0.40	21.0	35.4	42.2	55.8	71.4
a-R50F25	25	50	0.40	20.0	34.7	41.9	52.5	71.0
a-R100F25	25	100	0.40	16.5	33.5	39.5	51.2	71.5

Table 4-8 – Compressive strength of the concrete mixtures in Series V

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.45	25.8	45.8	53.7	66.8	72.3
R20	0	20	0.45	23.6	43.2	51.2	62.4	68.0
R50	0	50	0.45	21.1	40.3	49.8	56.8	61.5
R100	0	100	0.45	15.5	26.8	36.2	52.1	57.2
a-R0 F25	25	0	0.36	24.7	45.5	53.5	70.1	85.2
a-R20F25	25	20	0.36	24.1	45.1	52.0	67.3	80.2
a-R50F25	25	50	0.36	23.2	44.9	49.7	63.4	74.4
a-R100F25	25	100	0.36	21.5	42.8	47.1	61.1	70.9

Splitting tensile strength

The results of the tensile splitting strength of concrete in Series I and II are presented in Table 4-9 and Table 4-10 respectively. Each presented value is the average of three measurements. The results showed that the tensile splitting strength of the concrete mixtures in Series I and II decreased as the recycled aggregate content increased. At the same recycled aggregate replacement level, the use of fly ash as a partial replacement of cement reduced the tensile splitting strength of the concrete. Furthermore, the splitting tensile strength increased with a decrease in the W/B ratio.

Table 4-9 - Splitting tensile strength of the concrete mixtures in Series I

Notation	Fly ash (%)	Recycled Aggregate (%)	Splitting tensile strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	1.30	2.32	2.62	3.32	3.68
R20	0	20	1.27	2.30	2.53	3.21	3.66
R50	0	50	1.25	2.28	2.51	3.16	3.48
R100	0	100	1.21	2.20	2.38	3.06	3.23
r-R0 F25	25	0	1.14	1.99	2.40	3.28	3.42
r-R20 F25	25	20	1.01	1.88	2.28	3.13	3.28
r-R50 F25	25	50	1.00	1.82	2.23	3.09	3.22
r-R100F25	25	100	0.75	1.75	2.15	2.26	2.79
r-R0 F35	35	0	0.67	1.53	1.85	2.90	3.11
r-R20 F35	35	20	0.63	1.43	1.70	2.76	3.08
r-R50 F35	35	50	0.52	1.34	1.66	2.58	2.85
r-R100F35	35	100	0.49	1.27	1.61	2.56	2.72

Table 4-10 - Splitting tensile strengths of concrete mixtures in Series II

Notation	Flyash (%)	Recycled aggregate (%)	Splitting tensile strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	2.15	2.89	2.92	3.43	3.81
R20	0	20	1.91	2.28	2.85	3.16	3.62
R50	0	50	1.64	2.19	2.66	2.97	3.17
R100	0	100	1.41	2.15	2.59	2.84	3.02
r-R0 F25	25	0	1.40	2.06	2.39	3.42	3.50
r-R20 F25	25	20	1.08	1.69	2.05	3.14	3.21
r-R50 F25	25	50	1.03	1.84	2.13	3.10	3.16
r-R100F25	25	100	0.99	1.75	2.04	2.85	2.99
r-R0 F35	35	0	0.95	1.33	1.48	2.30	3.15
r-R20 F35	35	20	0.84	1.29	1.41	2.21	3.02
r-R50 F35	35	50	0.82	1.49	1.35	2.19	2.98
r-R100F35	35	100	0.79	0.98	1.48	2.19	2.99

The splitting tensile strength of concrete mixtures in Series III, IV and V made with and without fly ash were measured at the ages of 1, 4, 7, 28 and 90 days. The results are given in Table 4-11, Table 4-12 and Table 4-13, respectively. Each presented value is the average of three measurements. It can be seen from Table 4-11, Table 4-12 and Table 4-13 that at the all test age the splitting tensile strength of recycled aggregate concrete in Series III, IV and V was decreased with an increase in the recycled aggregate content. At 28 days, the splitting tensile strength of the concrete with 100% recycled aggregate and without fly ash decreased by 8.5%, 8.8% and 11.7% compared with those corresponding conventional aggregate concrete in Series III, IV and V, respectively.

Table 4-11 – Splitting tensile strength of the concrete mixtures in Series III

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Splitting tensile strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.55	1.30	2.32	2.62	3.32	3.68
R20	0	20	0.55	1.27	2.30	2.53	3.21	3.56
R50	0	50	0.55	1.25	2.28	2.51	3.16	3.43
R100	0	100	0.55	1.21	2.20	2.38	3.06	3.25
a-R0 F25	25	0	0.44	1.72	2.36	3.04	3.60	3.77
a-R20F25	25	20	0.44	1.53	2.21	2.74	3.48	3.56
a-R50F25	25	50	0.44	1.46	2.15	2.51	3.26	3.41
a-R100F25	25	100	0.44	1.33	2.02	2.29	3.14	3.35
a-R0F35	35	0	0.41	2.03	3.04	3.11	3.78	4.74
a-R20F35	35	20	0.41	1.91	2.72	2.91	3.66	3.74
a-R50F35	35	50	0.41	1.46	2.42	2.48	3.57	3.65
a-R100F35	35	100	0.41	1.52	1.97	2.41	3.24	3.51

Table 4-12 – Splitting tensile strength of the concrete mixtures in Series IV

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Splitting tensile strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.50	1.81	2.57	2.70	3.47	3.79
R20	0	20	0.50	1.37	2.21	2.56	3.39	3.64
R50	0	50	0.50	1.51	2.24	2.46	3.28	3.58
R100	0	100	0.50	1.24	1.78	2.35	3.19	3.41
a-R0 F25	25	0	0.40	1.73	2.71	2.80	3.58	3.91
a-R20F25	25	20	0.40	1.60	2.67	2.74	3.49	3.84
a-R50F25	25	50	0.40	1.23	2.05	2.62	3.35	3.75
a-R100F25	25	100	0.40	1.20	2.38	2.40	3.29	3.63

Table 4-13 – Splitting tensile strength of the concrete mixtures in Series V

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Splitting tensile strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.45	2.15	2.89	2.92	3.73	3.84
R20	0	20	0.45	1.91	2.28	2.85	3.56	3.72
R50	0	50	0.45	1.64	2.19	2.66	3.37	3.67
R100	0	100	0.45	1.41	2.15	2.59	3.34	3.49
a-R0 F25	25	0	0.36	2.22	2.62	3.31	3.98	4.34
a-R20F25	25	20	0.36	2.19	2.43	2.86	3.72	4.01
a-R50F25	25	50	0.36	2.06	2.38	2.54	3.58	3.83
a-R100F25	25	100	0.36	1.75	2.32	2.77	3.47	3.77

4.2.5 Static modulus of elasticity

The static modulus of elasticity values of the concrete mixtures in Series I and II are presented in Figure 4-5 and Figure 4-6 respectively. Each presented value is the average of two measurements. For the concrete mixtures in Series I and II, at the same fly ash content, the static modulus of elasticity values of concrete decreased as the recycled aggregate content increased. The 28-day static modulus of elasticity of concrete prepared with 100% recycled aggregate and no fly ash in Series I and II was about 40 and 28 % lower than that of the natural aggregate concrete in Series I and II respectively.

In other words, the predicted deformation of a structural concrete member prepared with recycled aggregate would be smaller than the actual value.

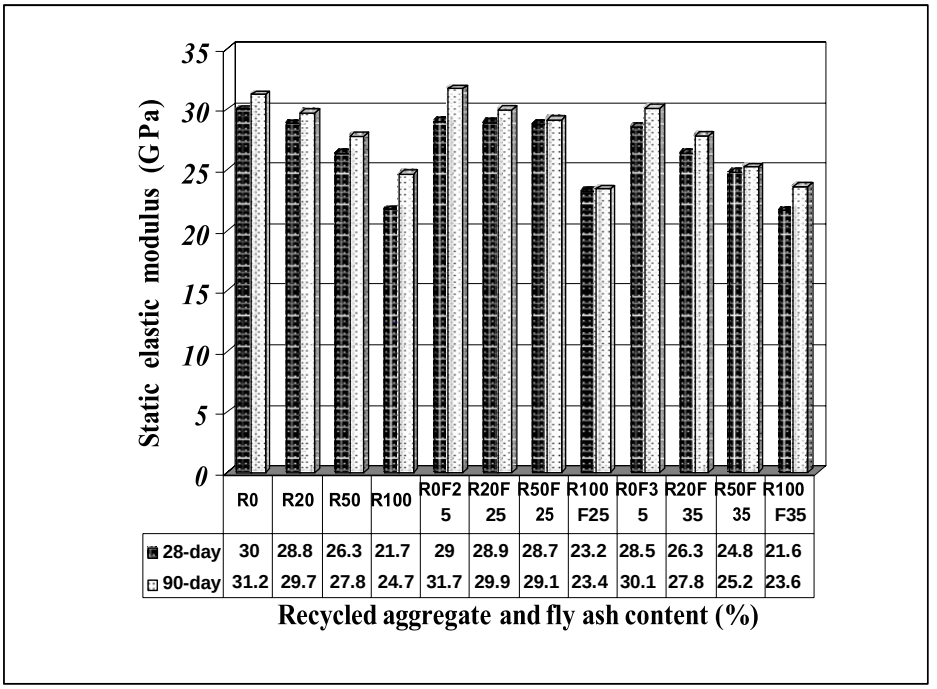


Figure 4-5 - Static elastic modulus of the concrete mixtures in Series I

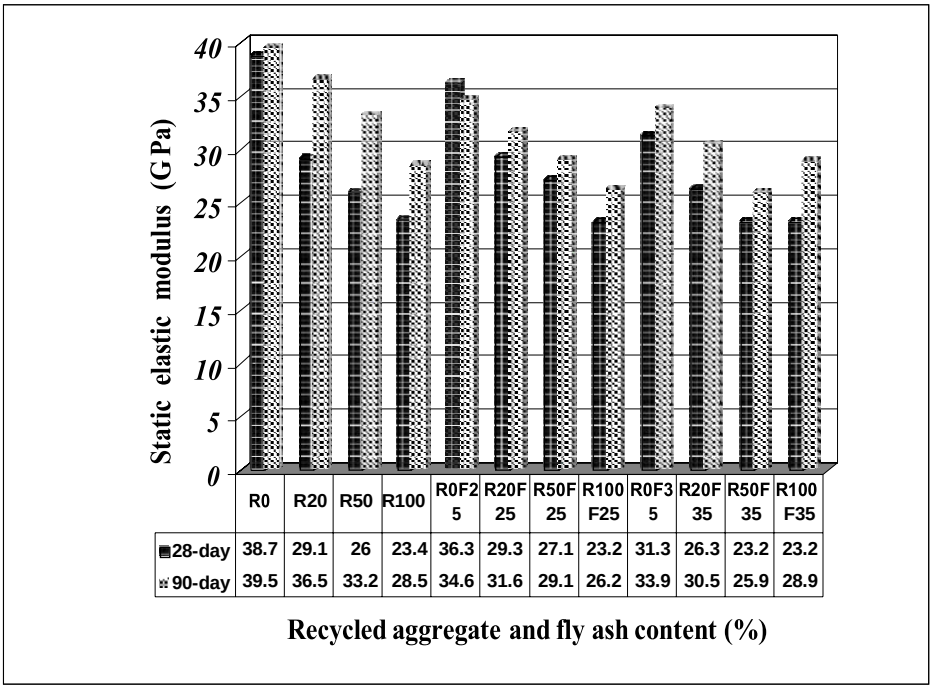


Figure 4-6 - Static elastic modulus of the concrete mixtures in Series II

4.2.6 Drying shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures are shown in Figure 4-7 each presented value is the average of three measurements. It is shown that the drying shrinkage of concrete in Series I (W/B=0.45) was lower than that of the concrete in Series II (W/B=0.55), which indicated that a decrease in the W/B ratio reduced the drying shrinkage. Since W/B ratio reflects the amount of evaporable water in the cementitious paste and the rates at which water can move towards the surface of the specimen (Neville 1995), a lower W/B ratio leads to a lower drying shrinkage value. Furthermore, the drying shrinkage values increased with an increase in the recycled aggregate content. The mortar adhered to the recycled aggregate contributed to an

increase in the volume of the paste (old + new), thus increasing the drying shrinkage of the resulting concrete (Tavakoli et al 1996). Moreover, the use of fly ash as a partial replacement of cement reduced the drying shrinkage of the concrete. According to Atis et al. (2004), the reduction in the drying shrinkage was attributed to the dilution effect of the fly ash particles.

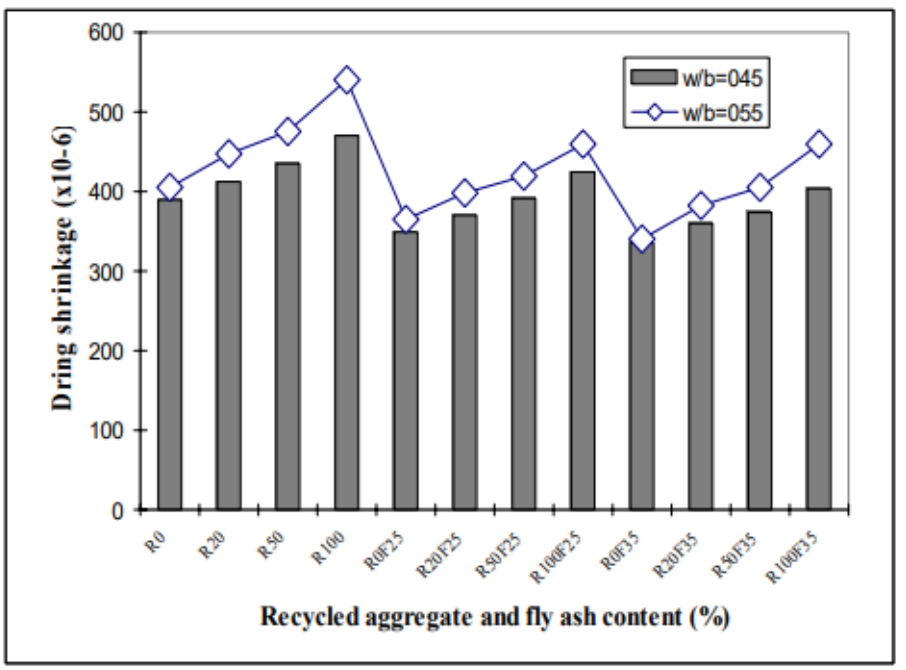


Figure 4-7 - Drying shrinkage of the concrete mixtures in Series I and II

4.2.7 Creep strain

Figure 4-8 and Figure 4-9 show the creep strain measured at 120 days and the creep development of the concrete mixtures in Series II, respectively. Each presented value is the average of three measurements. Since the creep test was started after 28 days, the effects of the moisture movement and autogenous shrinkage on the creep strain were less significant. It was obvious that the deformation of the concrete specimens increased

with an increase in the recycled aggregate content. This was attributed to the increased volume of mortar in the recycled aggregate concrete compared to that in the conventional concrete. It was found that the use of fly ash as a partial replacement of cement reduced the creep strain of the recycled aggregate concrete and conventional concrete. In the creep test, the applied load was equivalent to 35 % of the 28-day compressive strength of the concrete. According to Dhir et al. (1986), the lower creep for concrete prepared with fly ash hinged on the gain in strength of concrete following the application of the load. As indicated in Table 5-1and Table 5-2 the gain in strength was much greater for concrete which contained fly ash as a partial replacement of cement. Since the strength gain for concrete prepared with fly ash was greater, the actual stress/strength ratio for concrete prepared with fly ash was lower compared to that for concrete prepared without fly ash during which the creep test was performed. The lower measured creep strain for concrete prepared with fly ash was therefore attributed to the lower stress/strength ratio during the period of the creep test.

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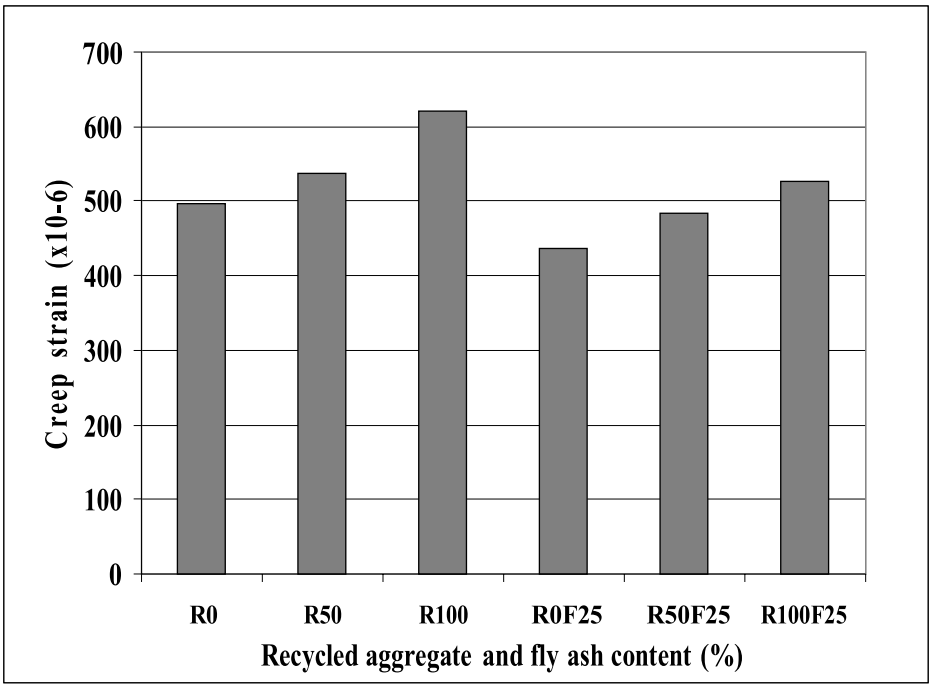


Figure 4-8 - Creep strain at 120 days of the concrete mixtures in Series II

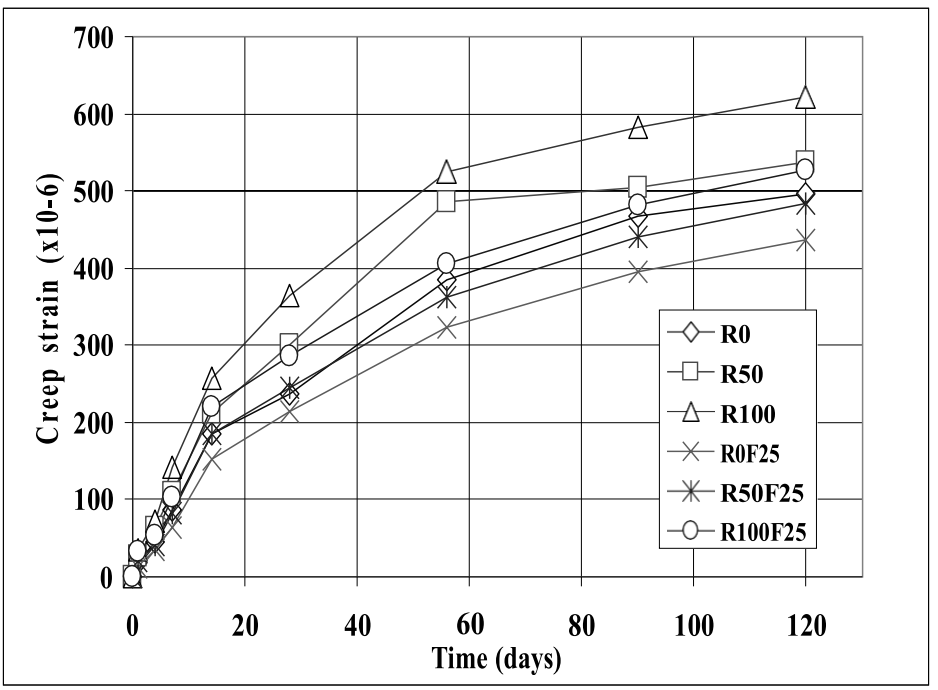


Figure 4-9 - Creep strain vs. time since loading of the concrete mixtures in Series II

4.3 SUMMARY

- The compressive strength, tensile splitting strength and static modulus of elasticity decreased as the recycled aggregate content increased. However, the reduction could be adequately compensated by the use of a lower W/B ratio.

- At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as a partial replacement of cement decreased the compressive strength, tensile splitting strength and static modulus of elasticity.

- At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as an additional mineral admixture in concrete increased the compressive strength, tensile splitting strength and static modulus of elasticity.

- by adjusting the W/C ratio (or water-to-binder ratio) it was possible to match the designed compressive strength of the concrete containing 100% recycled aggregatewith that of the corresponding natural aggregate concrete.

- The drying shrinkage of concrete increased with an increase in the recycled aggregate content. However, the use of fly ash as a partial replacement of cement and an additional mineral admixture in concrete was able to reduce the drying

shrinkage of the recycled aggregate concrete. Furthermore, a decrease in the W/B ratio also led to a reduction in the drying shrinkage.

- The creep of concrete increased with an increasing recycled aggregate content. The use of fly ash as a partial replacement of cement and an additional mineral admixture in concrete was able to reduce the creep of concrete as a result of the greater long term strength development due to the pozzolanic reaction of fly ash and it acting as fine aggregate.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

The aim of this thesis has been to i) develop a technique for utilizing a higher percentage recycled aggregate in concrete; ii) clarify the dependence of the strength, durability and compressive behavior of recycled aggregate concrete on the characteristics of the matrix-aggregate interfaces; and iii) clarify the effect of fly ash and steam curing on the properties of recycled aggregate concrete. The results of an experimental investigation into the fresh properties of recycled aggregate concrete prepared with locally available materials have been explored in chapter 3. An investigation into the microstructureproperties of the cement matrix-aggregate interfaces in recycled aggregate concrete has been presented in chapter 4.

In this chapter, the conclusions of the present research will be drawn. Recommendations for designing recycled aggregate structural concrete will be make and problems that need further research will also be identified.

5.2 CONCLUSIONS

5.2.1 Fresh Properties of Recycled Aggregate Concrete

In chapter 4, the fresh properties of recycled aggregate concrete were investigated. The parameters tested included slump, air content, bleeding and fresh density. The

results obtained are consistent with the previous studies. The main observations of this chapter are concluded below:

1. The use of recycled aggregates at an air-dried state in concrete resulted in higher initial slumps which took longer to decrease to zero when compared with the concrete with natural aggregates. The use of recycled aggregates also resulted in a higher rate of bleeding and bleeding capacity.

2. Delaying the starting of bleeding tests reduced the bleeding rate and bleeding capacity for both concrete mixes with and without recycled aggregates. However, this delay prolonged the process of bleeding.

3. The bleeding rate and bleeding capacity were reduced by using lower water-to-cement ratio.

4. The air content of concrete was increased and the density was decreased with an increase the recycled aggregate content.

5. In the case of using the recycled aggregate in the SSD state, the high water content inside the aggregate particles may result in ‘‘bleeding’’ during casting. Consequently, the compressive strength of the concrete would be reduced. In practice, the use of SSD or over wetted recycled concrete should be avoided; otherwise, the w/c ratio of the mix should be adjusted, taking into account the possible reduction in concrete compressive strength.

5.2.2 Hardened Properties of Recycled Aggregate Concrete

In chapter 4, the hardened properties of recycled aggregate concrete were investigated. Based on the results of this investigation and discussions, the following conclusions can be drawn:

1. The compressive strength, tensile splitting strength and static modulus of elasticity decreased as the recycled aggregate content increased. However, the reduction could be adequately compensated by the use of a lower W/B ratio.

2. At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as a partial replacement of cement decreased the compressive strength, tensile splitting strength and static modulus of elasticity.

3. At the same recycled aggregate replacement level and W/C ratio, the use of fly ash as an additional mineral admixture in concrete increased the compressive strength, tensile strength and static modulus of elasticity.

4. By adjusting the W/C ratio (or water-to-binder ratio) it was possible to match the designed compressive strength of the concrete containing 100% recycled aggregate with that of the corresponding natural aggregate concrete.

5. The drying shrinkage of concrete increased with an increase in the recycled aggregate content. However, the use of fly ash as a partial replacement of cement

and an additional mineral admixture in concrete was able to reduce the drying shrinkage of the recycled aggregate concrete. Furthermore, a decrease in the W/B ratio also led to a reduction in the drying shrinkage.

6. The results show that one of the practical ways to utilize a high percentage of recycled aggregate in structural concrete is by incorporating 25 to 35 % of fly ash.

5.2.3 General Conclusions

The general trends observed indicate that when recycled aggregate was used at air-dry states the workability and bleeding would be increased with higher levels of recycled aggregate content in the mixture. However, this instability of recycled aggregate concrete mixtures in the fresh state can be overcome by using filler material such as fly ash.

A procedure was developed to take into account the effects of recycled aggregate content on concrete strength. This involved simple adjustments to the water-to-cement ratio and addition of mineral admixture such as fly ash to compensate for strength losses in concrete containing a high proportion of recycled aggregate.

The results demonstrate that one of the most practical ways to utilize a higher percentage of recycled aggregates in concrete is “precasting” with an initial steam curing stage immediately after casting and by incorporating 25-35 percents of fly ash and with an initial steam curing step.

This study shows that there are no fundamental technical problems with the use of recycled aggregate in structural concrete.

5.3 RECOMMENDATIONS

1. According to RILEM and DIN 4226-100 the recycled aggregates that come from C&D waste considered as Type II and Type I, respectively can be used to produce structural concrete elements.
2. For C20 concrete, 100% recycled coarse aggregate can be used to produce the concrete; For C35 concrete, 100 % recycled coarse recycled aggregate can be used. The optimal water-to-cement ratio was between 0.50 and 0.45 with an additional 25% of fly ash by cement weight. For C45 concrete, 50% recycled coarse recycled aggregate can be used but the water-to-cement ratio must be lowed to less than
   0.45 with an additional 25% of fly ash by cement weight.
3. Generally, fly ash and steam curing regimes can be used to improve the long-term and durability properties such as shrinkage, creep, chloride penetration resistance, alkali-silica reaction and sulfate resistance of recycled aggregate concrete. Therefore a higher percentage recycled aggregate can be used in the precast structure concrete elements.

5.4 LIMITATION OF THE PRESENT STUDY AND SUGGESTIONS FOR FURTHER RESEARCH

The study carried out in this work dealt only with the materials aspect of recycled aggregates concrete. More experimental work is needed in order to verify the structural behavior of the recycled aggregate concrete under different load conditions (for example, sustained loading, reversal loading shear-bending interaction, torsion). In particular, it is of great interest if further studies can be conducted on those aspects that depend on the concrete's tensile strength, such as bond, anchorage and shear fraction and fracture properties.

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