REUSING RECYCLED AGGREGATES IN STRUCTURAL CONCRETE

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CERTRIFICATE OF ORIGINALITY

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Abstract of thesis entitled

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ABSTRACT

The construction activities in Hong Kong generate about 19 million tones 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.

Research studies on the reuse of recycled aggregates in concrete have continuously been conducted since the end of the 2nd World War. The findings indicated that recycled aggregate derived from demolished concrete or masonry can be extensively used in civil infrastructure projects including the production of Portland cement concrete, sub-base materials in road construction projects and the production of masonry units. But in practice, recycled aggregate is not commonly used in the production of concrete. One of the reasons is that Portland cement concrete is produced to form structural elements which have to meet strict strength and durability requirements. Extensive research is required to verify the properties of

recycled aggregate concrete before it can be confidently adopted by the concrete industry.

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

The characteristics of the recycled aggregates produced both from the laboratory and sourced from a commercially operated pilot C&D material recycling plant was first studied. A mix proportioning procedure was then established to produce six series of concrete mixtures using different percentages of recycled coarse aggregates with and without the use of fly ash. The water-to-cement (binder) ratios of 0.55, 0.50, 0.45 and 0.40 were used.

The fresh properties of recycled aggregate concrete (RAC) were first quantified. The influences of recycled aggregate on the slump, air content and bleeding of the fresh concretes were also investigated. The results confirmed that 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. Delaying the starting of bleeding tests reduced the bleeding rate and bleeding capacity of recycled and conventional aggregate concrete. The replacement of cement by 25% fly ash increased the slump of RAC mixtures and reduced the bleeding rate and bleeding capacity.

The effect of fly ash on the hardened properties of RAC was then studied and compared with those RAC prepared with no fly ash addition. The test results showed that the use of fly ash as a partial replacement of cement decreased the compressive strength, tensile splitting strength and static modulus of elasticity. However, the use of fly ash as an additional mineral admixture in RAC increased the compressive strength, tensile splitting strength and static modulus of elasticity. Also, the use of fly ash both as a partial replacement of cement and as an additional mineral admixture in RAC was able to reduce the drying shrinkage and creep and increased the resistance to chloride-ion penetration of the RAC. By adjusting the W/C ratio it was possible to match the designed compressive strength of the RAC containing 100% recycled aggregate with that of the corresponding natural aggregate concrete.

Furthermore, the effects of steam curing on the hardened properties of RAC were investigated. The results showed that steam curing at 65 ºC increased the early ages (1, 4, and 7-day) strength of all concrete mixtures. However the 28 and 90-day strengths and Young's modulus of the steam cured concrete were lower than those of the water cured concrete. Steam curing reduced the drying shrinkage and creep and increased the resistance to chloride-ion penetration of RAC and fly ash RAC.

In terms of micro-structural properties, the interfacial transition zones of the original aggregates and the old mortar/cement paste of the recycled aggregates and the interfacial transition zones between natural and recycled aggregates and the new cement pastes were analyzed by SEM and EDX-mapping. The effect of recycled aggregate on the pore size distributions of the RAC was also studied and found to be dependent on the percentage of coarse aggregate substituted and whether or not fly ash was used. The experimental results indicated that steam cured conventional aggregate concrete was more porous with distinct cracks formed when compared with the steam cured RAC. The total porosity and the average pore size of the RAC increased with an increase in the recycled aggregate content. The replacement of cement by fly ash reduced the total porosity and the average pore size of both the conventional aggregate concrete and RAC.

Moreover, a detailed set of results on the fracture properties for RAC were obtained. It was found that recycled aggregates increased the matrix-aggregate interfacial bond strength and fracture energy. Fly ash replacement at a level of 25% also increased the bond strength and fracture energy of RAC. The experimental results showed a substantial improvement in the post-peak ductility for the RAC when fly ash was used.

Based on the detailed experimental results, a number of recommendations were made on how to optimize the use of recycled aggregates for structural concrete production. Also, suggestions were made on improving the production process of concrete using recycled aggregate.

PREFACE

This thesis is submitted for the degree of Doctor of Philosophy at The Hong Kong Polytechnic University, Hong Kong, China. The work described in this thesis was carried out by the candidate during the years 2002 to 2005 in Department of Civil and Structural Engineering at the Hong Kong Polytechnic University under the supervision of Professor C. S. Poon, the chief supervisor, and Dr. L. Lam, the Co-supervisor.

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

Academic Journal Papers

1. C. S. Poon, S. C. Kou and L. Lam, "Use of Recycled Aggregates in Moulded Concrete Bricks and Blocks" *Construction and Building Materials. 16 (2002) 281-289.*

2. Poon, C. S., Shui, Z. H., Lam, L., and Kou, S. C. "Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of hardened concrete." *Cement and Concrete Research, 34(1), 31-36 (2004).*

3. C. S. Poon, S. C. Kou, and L, Lam. "Influence of recycled aggregate on slump and bleeding of fresh concrete". *Accepted by Materials and Structure for publication (2006).*

4. S. C. Kou, C. S. Poon, and L. Lam. "The effect of recycled aggregate paving blocks with classified fly ash and rejected fly ash with the addition of anhydrite and flue gas desulphrisation sludge (FGDS)". *Accepted by Journal of Wuhan University of Technology (2005).*

5. S. C. Kou, C. S. Poon, and D. Chan. "Influence of fly ash as a cement replacement on the properties of recycled aggregate concrete. *Submitted to ASCE Materials in Civil Engineering for publication (2005***).**

6. S. C. Kou, C. S. Poon, and D. Chan. "Influence of fly ash as a cement addition on the properties of recycled aggregate concrete. *In preparation: to Cement and Concrete Composite for publication.*

7. C. S. Poon, S. C. Kou and Dixon Chan "Influence of steam curing on properties of recycled aggregate concrete" *Accepted by Magazine of Concrete Research for Publication (2005).*

Conference Papers

1. C. S. Poon, S. C. Kou and L. Lam, "A Novel Method for Making Environmentally Friendly Bricks and Blocks from Recycled Aggregates"

International Conference on Innovation and Sustainable Development of Civil Engineering in the 21st Century*, Beijing China. Aug, 2002*

2. C. S. Poon, S. C. Kou. "Properties of Steam Cured Recycled Aggregate Concrete". *Proceeding of the International Conference on the Sustainable Waste Management and Recycling: Challenges and Opportunities, Construction Demolition Waste Edited by Mukesh C Limbachiya and John J Roberts, 14-15 September 2004. London. pp. 1-12*

3. S C Kou, C S Poon, L Lam, D Chan. "Hardened Properties of Recycled Aggregate Concrete Prepared with Fly Ash". *Proceeding of the International Conference on the Sustainable Waste Management and Recycling: Challenges and Opportunities, Construction Demolition Waste Edited by Mukesh C Limbachiya and John J Roberts, 14-15 September 2004. pp. 189-197.*

4. S. C. Kou, C. S. Poon and D. Chan. "Properties of Steam Cured Recycled Aggregate Fly Ash Concrete". *Proceeding of the International RILEM Conference on the Use of Recycled Materials in Building and Structures, Edited by E. Vazquez, Ch. F. Hendriks and G. M. T Janssen. Volume 2. pp.590-599. 8-11 November 2004, Barcelona, Spain..*

Patent:

1. C. S. Poon, S. C. Kou, C. W. Chan, C. S. Lam. (2005) "Production of Construction Blocks Using Recycled Glass Aggregates". *Patents Registry,*

Intellectual Property Department The Government of the Hong Kong Special Administrative Region, application no. 05105305.4

2. C. S. Poon, W. S Ho, S. C. Kou, (2003) "A Kind of Self Compacting/Consolidation Concrete". *Patents Registry, Intellectual Property Department The Government of the Hong Kong Special Administrative Region, application no. 031040255.8*

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CHAPTER 1: INTRODUCTION

1.1GENERAL 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 of the 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.

The situation in Hong Kong with its geographical make up and lacking the clear and necessary motivation shown by the European has resulted in an evident delay in the use of recycled material at market level.

Present Situation in Hong Kong

In Hong Kong, a huge quantity of construction and demolition (C&D) waste is produced every year. According to the Hong Kong Civil Engineering Development Department in 2004, 19.0 million tons of C&D materials were generated. Of this amount, over 85% were inert materials. The remaining proportion represented less than 20% of total C&D materials generated in 2003, these were non-inert materials. C&D waste has been taking up valuable landfill space, on this trend Hong Kong landfill space will run out within 6 to 10 years.

In mid-July 2002, the HKSAR Government established a pilot C&D materials recycling facility in Tuen Mun to produce recycled aggregates for use in government projects and for research and development works. The plant had a designed handling capacity of 2,400 tons per day. The recycled aggregate produced by recycling of C&D waste materials had already been used in different areas.

In Hong Kong, due to limited experience in using recycled aggregates and Hong Kong's different nature of building construction, a more prudent approach has been adopted. After detailed laboratory investigations and plant trials, the government has formulated two sets of specifications governing the use of recycled aggregates for concrete production.

For lower grade applications, concrete with 100% recycled coarse aggregate is allowed. Recycled fines are not allowed to be used in concrete. The target strength is specified at 20 MPa and the concrete can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures.

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 fresh properties, hardened properties and durability of concrete made with recycled aggregates.
- To investigate the influences of steam curing on properties of recycled aggregate OPC concrete and recycled aggregate PFA concrete

- To investigate the microstructure of recycled aggregate concretes, fly ash recycled aggregate concretes and steam cured 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; (3) summarizes related research conducted on the effect of fly ash on fresh and hardened properties of concrete and (4) summarizes related research conducted on the effect of steam curing on properties of concrete.

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. The aim of this chapter is to understand the effects of recycled aggregate on the fresh properties and to understand the influence of fly ash on the fresh properties of recycled aggregate concrete.

In chapter 5, the experimental results on the hardened properties of fly ash recycled aggregate concretes are presented. The aim of this chapter is to understand the effect of fly ash on the hardened properties of recycled aggregates concrete. In this chapter, fly ash is used as a replacement of cement or as an additive admixture to the concrete. This part of work includes the determination of compressive strength, splitting tensile strength, static modulus of elasticity, chloride ion penetration, drying shrinkage and creep of the concrete. This chapter indicates the tendency of drying shrinkage and creep of recycled aggregate with fly ash at different levels of replacement or additional, which has not been reported in the literature.

In chapter 6, the experimental results on the hardened properties of steam cured recycled aggregate concrete was presented. The aim of this chapter is to understand the effect of steam curing on the hardened properties of recycled aggregates concrete. In this chapter, the concrete specimens underwent standard water curing and steam curing regimes. This part of work includes the determination of compressive strength, splitting tensile strength, static modulus of elasticity, chloride ion penetration, drying shrinkage and creep of the concrete.

In chapter 7, the results of microstructure study of recycled aggregate concretes, fly ash recycled aggregate concretes and steam cured recycled aggregate concretes are presented. The influence of fly ash and steam curing on the durability of the recycled aggregate concrete is explained. The influence of recycled aggregates in the durability of the concrete is explained. It is based on fly ash and steam curing on properties of recycled aggregate concrete, distribution and amounts of pores in the concrete, effective water-cement ratio, the interfacial transition zone and the composition of recycled aggregates using Scanning electronic microscope (SEM and EDX-maps). Attempts will also be made to provide recommendations regarding their application.

In chapter 8, presents the experimental results into the fracture properties and compressive stress-strain behavior of recycled aggregate concrete and fly ash recycled aggregate concrete with standard water curing and steam curing. The flexural strength, fractural energy of the concretes was determined from the three-point bending tests of the notched beams. The experimental stress-strain characteristics of recycled aggregate concrete were also presented.

In chapter 9, 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 (Mehta, 1999; Topcu et al 2004; Terro, 2005).

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 (Mehta, et al 1993; Poon et al 2004).

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.

The curing method used for precast concrete products differs from the normal curing method. Steam curing is usually employed in precast concrete because it accelerates the rate of strength development. However, this curing method alters the properties of the produced concrete. It was found that steam curing reduced the creep of concrete by up to 50 % compared to that of normal mosit-cured concrete (Brooks et al 1996). Although plenty of information is available on the effect of steam curing on conventional concrete properties, there is limited data relating to steam cured recycled aggregate concrete. There is a need to gain more information on the effect of steam curing on the strength and durability of concrete produced with high percentages of recycled aggregates.

Fly ash can be used as a direct replacement for Portland cement in making concrete. Concrete made with fly ash have the following benefits:

- Pozzolanic properties reduce need for cement
- Spheres act like ball bearings, increasing workability
- Fills in voids with cementitious material and acts a filler, reducing total surface area to be covered with cement; reduces permeability, which reduces shrinkage, creep and gives greater resistance to chloride ingress and sulfate attack
- Retards heat of hydration; important for large concrete pours (dams, Hibernia oil platform)
- Improves long term strength performance and durability
- Minimizes the risk of alkali silica reaction
- Makes more cohesive concrete that has a reduced rate of bleeding, is easier to compact, gives better pumping properties and improves the surface finish of the finished structure, e.g. when used in self compacting concrete.

It is shown from previous research that one of the main potential problems of recycled aggregate concrete is the high drying shrinkage value compared to that of conventional concrete. In fact, this shortcoming can be improved by incorporating a certain amount of fly ash into the concrete mixture since fly ash is known to mitigate the drying shrinkage of concrete. However, fly ash can be used as a replacement of cement or as additional cementitious materials in concrete. The different applications of fly ash produce concrete with totally different properties (Costabile, 2001).

Topics addressed in this chapter include:

- Properties of recycled aggregates
- Recommendations about recycled aggregates applicability
- Mechanical properties of recycled aggregates concrete (RAC)
- Durability of RAC
- Influence of fly ash on properties of concrete
- Influence of steam curing on properties of concrete

2.2 AGGREGATES OBTAINED FROM C&D WASTE

2.2.1 Recycled aggregates

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 (Hansen, 1992, Collins, 1994, Mehta et al, 1993, Sherwood, 1995, Dhir et al 1999, Otsuki et al 2003 and Tam et al 2005).

2.2.2 Use of recycled aggregates outside Hong Kong

Europe

It is estimated that C&D waste amounts to around 180 million tones/year in the European Union (EU), or about 1.3 kg/person/day. This compares to an estimation of between 0.55 and 1.6 kg/person/day in North America. There is a significant variation in C&D waste production across the EU, with Germany and the Netherlands producing 1.9 kg/person/day, while Sweden, Greece and Ireland produce less than 0.5 kg/person/day (Crawford et al 2001).

A number of programs and initiatives are underway in the EU to reduce and re-use C&D waste. These range from studies of C&D waste management practice and recommendations on policy, to development of EU-wide standards and specifications.

Although there is a general move towards sustainable development in the EU, there are significant regional differences in policy, implementation and standards. For example, tax structures (both incentives and disincentives) play a significant role in promoting recycling in the highways environment in Denmark, Sweden and the Netherlands. The following sections summarize regional practice within selected EU countries.

1) United Kingdom

Crawford et al (2001) reported that the UK has a well-defined set of standards and specifications for aggregates and their use. BS 812 details testing of aggregates, while BS 882 provides specifications for natural aggregate used in concrete. General guidance on recycled aggregates is given in BS 6543, though this standard is rarely quoted in contract documents. The institution of Civil Engineers has produced model contract documents for a wide variety of application, which are used in most civil engineering contracts, while the Department of Environment, Transport and the Regions (DETR) 'Specification for Highway Works' details specification for both bound and un-bound aggregates, including some guidance on recycled materials. The DETR specifications are used for all truck road and motorway construction in the UK. With increased integration into the European Union, the UK will be expected to adopt European Standards for aggregates, including recycled aggregates, some of which are currently under development.

Quality Control and Quality Assurance (QC/QA) are an important aspect of UK civil engineering construction. All investigation and construction work for the Highway Agency require BS 5750 QC/QA certification, with testing laboratories requiring NAMAS QC/QA accreditation. A joint initiative by the Quarry Products Association, the DETR and the Highways Agency in 1997 to review the 'Specification for Highway

Works' to remove impediments to the use of recycled aggregates that could not be technically justified, identified that a formal quality control procedure was required for recycled aggregates. The result was a recommended procedure, published by the Building Research Establishment (BRE), which is expected to form a BSEN9002 registered QA scheme.

BRE has produced other guidance on the use of recycled aggregates, including Digest 433, which covers the use of crushed concrete and masonry and blends of recycled and natural aggregates (see Tables 2-1 and 2-2), and information paper 5/94, which covers the use of recycled aggregates in concrete. BRE guidance often supplements or precedes specifications and procedures contained in the British Standards, and provides practical advice on design and specifications. BRE Digest 363 on 'Sulphate and acid resistance of concrete in the ground' has been generally adopted as a standard for assessing hazard due to sulphate attack.

BRE Digest 433 defines three classes of recycled aggregate, based on the RILEM proposed classes, which broadly define the composition of the material (see Table 2-1). Suggested maximum levels of impurity for various uses are given (see Table 2-2), together with more detailed guidance on specific end-uses, and discussion of acceptance of additional materials in other jurisdictions.

Table 2-1 Recycled aggregate (RCA) classes (BRE Digest 433)

Class	Origin	Brick content (by wt)	Description
RCA(I)	Brickwork	0 – 100%	Lowest quality material: - low strength - high level of impurity 10% fines (BS 812-111) ≈ 70 kN
RCA(II)	Concrete	0 – 10%	Relatively high quality with low levels of impurity. Primarily crushed concrete, but may contain significant natural aggregate. 10% Fine (BS 812- 111) > 100kN
RCA(III)	Concrete and brickwork	0 – 50%	Mixed material with similar levels of impurity to RCA (I) but wider range of uses e.g., 80/20 blend of natural aggregate/RCA(III) may be acceptable in all grades of concrete.

The Aggregates Advisory Service (AAS), a service of the DETR, has produced a number of reports, available online, providing information on recycling, case histories, sources of information and best-practices guidance. The service is designed to help the government "achieve its objective of reducing the construction industry's dependence on primary aggregates and increasing the contribution from secondary and recycled materials". AAS Digest 101 provides a comprehensive review of requirements for secondary aggregates for use in road construction, including testing requirements and acceptability limits.

Other UK organization that have produced a guidance on the use of recycled materials in construction include CIRIA, a construction industry research organization, and the Transportation Research Laboratory (TRL), a UK government research organization looking primarily at road pavements.

Although measures such as landfill tax have helped to reduce the amount of C&D waste entering landfills in the UK, a number of barriers to increase uptake still exist. In particular, use of recycled aggregates in road construction has declined in the UK, primarily as a result of perceived financial risk under design, build, finance and operate (DBFO) schemes. In addition, there is stiil a lack of acceptance of recycled aggregates within the engineering community for higher value applications.

Table 2-2 Maximum recommended levels of impurity (by wt.) (Crawford et al 2001)

	Use in concrete as coarse aggregate	**Use in road construction-unbound/cement-bound material[1]**	**Hardcore, fill or granular drainage material**
Asphalt and Tar (as lumps, e.g., road planings, sealants)	Included in limit for other foreign material	10% in RCA (I)[2] or 5% in RCA (II)[2] or 10% in RCA (III)[2]	10%[2]
Wood (includes other materials less dense than water)	10% in RCA (I)[2] or 5% in RCA (II)[2] or 10% in RCA (III)[2]	Sub-base Type 1 &2: 1%, or CBM (1-5): 2%, and Capping layer 2%	2%
Glass	Included in limit for other foreign material	Content above 5% to be documented	Content above 5% to be documented
Other Foreign Material (e.g., matels, plastics, clay lumps)	10% in RCA (I)[2] or 5% in RCA (II)[2] or 10% in RCA (III)[2]	1% (by volume if ultra-lightweight)	1% (by volume if ultra-lightweight)
Sulphates	Concrete and CBM: 1% acid-soluble SO_3 [4]. Unbound material: See Digest 363 if near concrete.		

1- Sub-base Type 1 or 2 or CBM 3,4 or 5: RCA(II) only; Capping layer 6F1 or 6F2 or CBM 1 or 2: normally RCA(I) or RCA(III)
2- No limit if physical and mechanical test criteria are satisfied.
3- RCA(III) must not replace more than 20% of natural aggregate. Limits on wood and other foreign matter assume that there will be no contribution from the natural aggregate.
4- Limit of 1% aci-soluble SO_3 applies to 1:4 mixtures of RCA (III): natural aggregate.

2) Germany

Kohler et al (1997) reported that waste prevention and recycling efforts in Germany have focused primarily on legislation, with the most significant contributor being the Closed Substance Cycle and Waste Management Act (1996), which establishes that producers have responsibility for the entire lifecycle of the products they manufacture. Despite strong encouragement, there has not been large increase in the use of recycled materials, particularly in road construction. Government dose not play a strong role in research and marketing for recycled materials, and there are generally no provisions in road or other construction projects to favour the use of recycled materials. Other factor limiting the uptake of recycled materials in Germany includes relatively cheap natural aggregates, and low landfill disposal costs. The lack of specifications and guidelines for the use of recycled materials is perceived as another barrier to futher uptake, though existing specifications do often contain provisions for the use of recycled materials.

3) Netherlands

Crawford et al (2001) reported that the Netherlands has an advanced set of policies, economic tools and regulations, which are highly integrated, in order to increase recycling of C&D waste, and along with Denmark, is highly regarded by the OECD for it's use of recycled materials. The driving forces for this integrated policy system are:

- Recognition of future land requirements for residential, industrial and agricultural land-uses, and
- Environmental protection.

Development of policy, guidelines and specifications has included end-users and industry to ensure workable solution. Co-operative research programs and the development of recycling technology, together with clear and un-ambiguous policy on engineering and environmental requirements have helped ensure the success of Dutch recycling initiatives.

4) Denmark

Lauritzen (2004) reported that the Danish government plays an active role in promoting recycling, through research and development, tax policies on waste disposal and development of guidelines and specifications for recycling. Government also takes an active role in promoting positive public attitudes towards recycling, an additional driving force for increased recycling.

Specifications are developed using a consensus approach, with participation by suppliers, environment agencies, owners and contractors. Field tests and trials of recycled materials, including long-term evaluation of environmental performance is an important part of the Danish recycling initiatives.

Key in the Danish strategy is establishment of forces favourable to the use of recycled materials, e.g., gradual implementation of landfill and disposal taxes. In addition, government-private partnerships have been used to help establish facilities for re-processing waste materials and to increase the value of recycled materials (Lauritzen, 2004).

The use of Recycled Asphalt Pavement (RAP) in Denmark is well established, with mixes routinely containing 50% RAP for base course and up to 30% RAP in the wearing course. Batch plants which recycle only up to 15% RAP are not widely used any more Lauritzen (2004).

North America

Neither Canada nor the United States have national standard for the utilization of C&D waste, though in the absence of national standards, a number of regional jurisdictions have set up their own requirements. In the US, the Federal Highways Administration (FHWA) and the US Geological Survey (USGS) have conducted research on the suitability and economics of re-using (C&D) waste. The FHWA has recently published a detailed report reviewing in EU practice, as part of a Federal initiative to reduce barriers to recycling. A number of States and local governments in the US have passed legislation to promote recycling in road construction. Canadian experience is much the same, with some local governments such as the Greater Vancouver Regional District (GVRD) actively reducing C&D disposal to landfill and encouraging reuse, while other have either not enacted C&D reduction and reuse policy, or have resisted increased use of C&D waste. The following sections describe regional practice in North America in more detail (Crawford et al 2001).

US

US Federal policy currently favours waste reduction and recycling, and this is reflected locally in some States and local governments, notably Washington, Oregon, California and Colorado. A number of US States have very low acceptance of C&D waste recycling (see Figure 2-1) most recycled C&D waste is used in roadbase application (68%), with relatively minor amounts used in asphalt, concrete and fill. Recycled concrete aggregate production has increased significantly, reaching about 4.8% of natural aggregate production in 1998. Approximately 85% of US recycled aggregate is used in road sub-base and general fill applications, due to availability, low transport costs and good physical properties.

Japan

Japan started very early in the research on concrete with recycled aggregates. The 2003 edition of ACI Manual of Concrete Practice (2003) quotes widely from the 1978 report of the Building Contractors Society of Japan: “Study on Recycled Aggregates and Recycled Aggregate Concrete.” However progress in using recycled concrete in actual construction works is not as good as it should be. Japan introduced the Recycling Law as early as 1991. Under the Recycle 21 Programme launched by the Ministry of Construction (MOC) in 1992, targets were set to increase the percentage of recycled demolished concrete in the ensuing years. By 2000, 96% of demolished concrete was recycled against the MOC target of 90%. However practically all the recycled concrete aggregates were used as subbase material for carriageways.

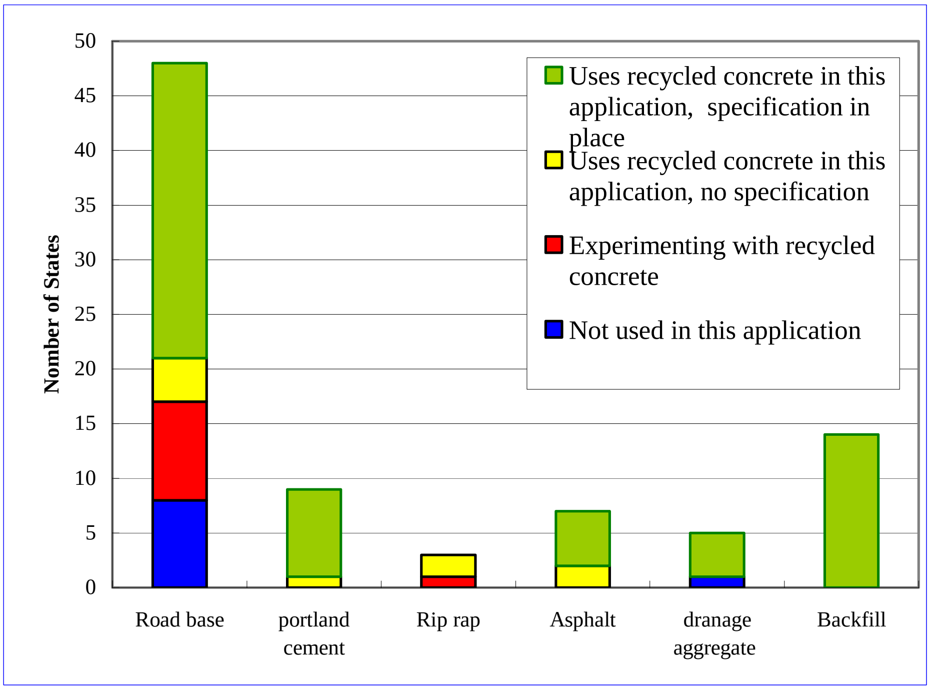


Figure 2-1 US state concrete recycling activity (Weigge et al 1998)

1) Technical Report A 0006

The current Japanese Standard JIS A 5308 for ready mixed concrete does not permit recycled aggregates to be used. In response to the recommendation of the JIS Civil Engineering Committee in 1998, the Japanese Concrete Institute formed a committee to draft a JIS Technical Report (TR), as a preliminary document to be developed into a JIS

Standard. This is the TR A 0006 “Recycled Concrete using 31 Recycled Aggregates”, released in 2000. It permits recycled concrete to be used independently from JIS A 5308. According to TR A 0006, the quality of recycled aggregates should meet the following requirements:

Table 2-3 Quality of recycled aggregates in Japan (JISEC, 2000)

	Coarse aggregate	Fine aggregate
Water absorption	7%	12%
Fine particle content	10%	10%

However the strength of structural concrete is capped at 18MPa, as shown in the table 2-4:

Normal concrete refers to filling concrete that is non-structural. Chloride controlled concrete is basically the same as normal concrete, but containing reinforcement. Flexible concrete may be used for structural purposes, but under the guidance of an engineer who has expert knowledge on recycled concrete.

Table 2-4 Requirements for concretes of different usage (JISEC, 2000)

Class	Nominal strength (MPa)	Grain size Max (mm)	Slump (cm)	Chloride content (kg/m3)
Normal	12	20 or 25	15	
Chloride controlled	12	20 or 25	15	0.6
Flexible use	18	As required	As required	As required

It is worth mentioning that pre-soaking the recycled aggregates is a standard requirement for the control of workability. Also it is mandatory to use blast furnace slag cement or fly ash cement, basically to counteract alkali aggregate reaction (AAR). 32 To make it easier to use recycled aggregates in concrete, sampling, testing methods and inspection requirements were purposely made less stringent. It can be seen that TR A 0006 does very little to promote the use of recycled concrete. In his concluding remark in the paper presented at the 1st fib Congress, H. Kawano said: "JIS/TR is simply a report and has no impact on actual construction, whereas JIS has an influence. The TR will be open to the public for comment for three years, after which the TR may be revised into a JIS or may be abandoned."(Kawano et al 2002).

2) High quality recycled aggregates

The situation is however not totally pessimistic. As an alternative approach, some research has been done with an aim to produce recycled coarse aggregates to comply with current standards, by the proper choice of the crushing process. For example, Yanagibashi et al (2002) reported that by using an eccentric rotor mill such that the rubbing action among the aggregates is increased, the adhering mortar is more readily detached from the stone particles. Basically it aims to regain the natural aggregates used in the original concrete. Recycled coarse aggregates produced in this way were found to meet the Japanese Standard JIS A 5005, which among other things, requires that the particle density be not less than 2450 kg/m^3 and water absorption not greater than 3%. Tests on concrete made with these high quality recycled aggregates indicated that the properties and performance were no different from those of concrete made with natural aggregates, in terms of bleeding, compressive strength, drying shrinkage, freezing and thawing and carbonation depth in the accelerated test with 5% carbon dioxide concentration (Kawano, et al 2004).

2.2.3 Use of recycled aggregate in Hong Kong – current situation

1) Construction and demolition (C&D) material

The construction industry in Hong Kong generates considerable quantities of construction and demolition (C&D) material that accounts for 44% of the total waste produced in the territory. The quantities have been increasing since 1990, and in 2004, reached an alarming quantity 19.0 million tons for the year. While currently the construction industry has slackened slightly, the reduction in C&D material is unlikely to be significant in the coming years (EPD, 2004).

C&D material arises from construction works that include site formation, building construction, demolition and infrastructure works. Within the domain of C&D material, we normally distinguish between materials that are inert or innocuous and those that are either degradable or harmful. The degradable and harmful materials are collectively known as C&D waste. Generally new construction does not generate a lot of waste, particularly if the projects are well managed. In demolition, renovation or refurbishment works, the content of C&D waste is much higher. C&D waste normally includes timber, bamboo, plastics, synthetic material, paper, package and scrap metal.

The disposal outlets for C&D material are public fills and landfills. Public fills are designated locations for land formation, mostly reclamations, where only inert C&D materials are accepted. Landfills are designated locations to accept any kinds of waste. However, if any truckload delivered to a landfill contains more than 20% inert C&D material by volume it will be turned away. This administrative measure is in place to encourage sorting before disposal.

2) The disposal problem

In recent years, 80% of the C&D material is disposed of in public fills while the remaining 20%, in landfills. However the capacities of public fills and landfills are depleting rapidly. With the increase in environmental awareness, it is unlikely that projects involving new reclamation will ever be approved. The latest estimate is that, by mid 2005 all the public fills will be exhausted if the current trend continues. The situation of landfills is by no means any more optimistic, with perhaps another 6 to 10 years before they are completely filled up.

3) The 3-Rs

In the run up to 2000 it became imperative to do something before things got worse. In May 1999, the Waste Reduction Task Force for the Construction Industry was set up with a mission to help the industry in reducing construction and demolition waste, thereby relieving the pressure on both public fills and landfills. The Task Force was chaired by a representative of the Hong Kong Construction Association, with the Environmental and Food Bureau and the Environmental Protection Department performing the coordinating role. Members were drawn from the academic and professional institutions, representatives from developers, concrete producers, the two railway companies and concerned government departments. The policy statement can be summarized in 3Rs which are:

- Reduce
- Re-use
- Recycle

While acknowledging that the role of recycling would not be significant in extending the life of public fills and landfills, it is nonetheless a worthwhile objective in the long term (Fung, 2005).

4) Recycling

In mid-July 2002, the HKSAR Government established a pilot C&D materials recycling facility in Tuen Mun to produce recycled aggregates for use in government projects and for research and development works (Chan et al, 2002). The plant (Figure 2-2) has a designed handling capacity of 2,400 tons per day. The processing procedure for recycled aggregate comprises the following processes: 1) a vibrating feeder/grizzly for sorting the hard portions from the inert C&D materials which are suitable for subsequent recycling; 2) a jaw crusher (primary crusher) for reducing the sorted materials to sizes of 200 mm or smaller which can be handled by secondary crushers; 3) a magnetic separator, manual picking gallery and air separator for removal of impurities before the materials are fed into the secondary crusher; 4) cone crusher (secondary crusher) for processing the clean materials into sizes smaller than 40 mm; 5) vibratory screens for separating the crushed recycled aggregates into different sizes; and 6) storage compartment for temporary storage for recycled aggregates. The facility is able to produce Grade 200 rockfill and recycled aggregates of various sizes, ranging from 40 mm, 20 mm and 10 mm coarse aggregates to fine aggregates (<5 mm) for different applications.

Due to the varying sources of incoming materials, a prudent quality control approach has been adopted by the recycling plant. Only suitable materials (e.g. crushed rocks, concrete) are processed at the plant. Brick and tiles are generally not allowed. The produced recycled aggregates are sampled and tested daily. Since production commenced in July 2004, the facility has already produced approximately 480,000 tons of recycled aggregates with consistent high quality which meets the specification requirements.

Figure 2-2. C & D Material Recycling Facility at Tuen Mun Area 38 Started operation in July 2002

2.2.4 Specifications for recycled aggregates

The recycled aggregates produced from the recycling plants have to fulfill certain requirements. In this chapter first the European requirements for recycled aggregates are mentioned. On European level the requirements are still recommendations. In the Netherlands, where over 80% of the demolition waste is recycled, the requirements are clear. A distinction is made between recycled aggregates for use in concrete and recycled aggregates for use in road-structures.

1) Requirements in European standards

According to European recommendations, RILEM-1989, DIN 4226-100, 2000 and prEN13242:2002 (final Draft), recycled aggregates are classified based to their composition.

RILEM-1989 proposed to classify of recycled coarse aggregates into the following three categories:

- Type I: aggregates that are mainly derived from masonry rubble.
- Type II: aggregates that are mainly derived from concrete rubble.
- Type III: aggregates that are a mixture – not less than 80% natural aggregates.

  not more than 10% type I Aggregates

  (ie up to 20% type II aggregate)

In addition to complying with limits for all aggregates in the harmonized European standards, extra controls for impurities are suggested:

- foreign materials (metals, glass, bitumen, soft material…..)

  Type I ≤5%; type II & III ≤ 1%

- total organic material

  Type I ≤ 1%; type II & III ≤ 0.5%

Type III aggregate would be permitted in all concrete applications currently allowed for natural aggregates, Type II to a maximum cube strength class of C60 (ie all but very high strength concrete) and type I to a maximum cube strength class of C37 (C20 for aggregates with a density less than 2000 kg/m3) and mild exposure conditions.

2) Requirements in Dutch regulation (use in concrete)

The Dutch standard for aggregates in concrete (NEN 5905) can be used to determine if the recycled LWAC-aggregate can be used in concrete. It covers aggregates with a density over 2000 kg/m^3. This standard gives more detailed information on the different types of recycled aggregates (I, II, and III) (Larranaga et al 2004).

I) Recycled concrete-aggregate

- More than 90% of the material, mass to mass, is concrete with a density of the dry grains which has to be more than 2100 kg/m3.
- In the NEN-EN 1097 1994 the Los Angeles Abrasion Test (ASTM C131) is mentioned. The value has to be below 40.
- The amount of impurities like rubber, metals, plastics, glass, and so on, must be below 1% on volume base.

II) Mixture of recycled brickwork- and concrete-aggregate

- More than 50% of the material, mass to mass, is concrete with a density of the dry grains which has to be more than 2100 kg/m^3.

- In the NEN-EN 1097 1994 the Los Angeles Abrasion Test (ASTM C131) is mentioned. The value has to be below 50.
- The amount of impurities like rubber, metals, plastics, glass, and so on, must be below 1% on volume base.

III) Recycled brickwork-aggregate

- This type of aggregate originates from selective crushing of brickwork.
- Demands: Building-regulation, VBC 1995, VBT 1995, NEN 5950

When not more than 10%, on volume base, is being used, than it is not necessary to make any changes in the calculating rules.

4) Requirements in Hong Kong

In Hong Kong, due to our limited experience in using recycled aggregates and Hong Kong's different nature of building construction, a more prudent approach has been adopted. After detailed laboratory investigations and plant trials (SCCTCPA, 2001), the government has formulated two sets of specifications governing the use of recycled aggregates for concrete production (WBTC No, 2002).

For lower grade applications, concrete with 100% recycled coarse aggregate is allowed. Recycled fines are not allowed to be used in concrete. The target strength is specified at

20 MPa and the concrete can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures. The specification requirements for recycled aggregate are listed in Table 2-5.

For higher grade applications (up to C35 concrete), the current specifications allow a maximum of 20% replacement of virgin coarse aggregates by recycled aggregates and the concrete can be used for general concrete applications except in water retaining structures. As of the end of October 2003, there have been over 10 projects registered to consume over 22,700 m^3 of concrete from Grades 10 to 35 using recycled aggregates. The usage varies from reinforced pile caps, ground slabs, beams and parameter walls, external building and retaining walls, to mass concrete.

Table 2-5: Specification requirements for recycled aggregate for concrete production in Hong Kong (Fong, et al, 2002)

Requirements	**Limit**	**Test method**
Min. dry particle density (kg/m3)	2000	BS 812: Part 2
Max. water absorption	10%	BS 812: Part 2
Max. content of wood and other material less dense than water	0.5%	Manual sorting in Accordance with BRE Digest 43
Max. content of other foreign materials (e.g.,metals, plastics, clay lumps, asphalt, glass, tar)	1%	
Max. fines	4%	BS 812: Section 103.1
Max. content of sand (< 4 mm)	5%	BS 812: Section 103.1
Max. sulphate content	1%	BS 812: Part 118
Flakiness index	40%	BS 812: Section 105.1
10% fines value	100 kN	BS 812: Part 111
Grading	Table 3 of BS 882: 1992	
Max. chloride content	Table 7 of BS 8820.05% by mass of chloride ion of combined aggregate	

2.3 PROPERTIES OF RECYCLED AGGREGATES OBTAINED FROM CRUSHED CONCRETE

Physical properties

Recycled aggregate looks like crushed stone (Figure 2-3). 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 2-3 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.

Nagataki (2002) concludes that with the same quantity of mortar, a recycled aggregate that 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. There are several authors who tried to find a correlation:

According to Sanchez et al (2002) who tested 11 samples of recycled aggregates Taken from a recycling plant in Madrid, had an absorption capacity of more than 7% and all of them had an absorption capacity of more than 5%. It was concluded that due to the aggregates having high absorption capacity; concrete should be produced with a maximum amount of 20% of recycled aggregates.

2.3.3 Strength of recycled aggregate

According to the Los Angeles Abrasion test recycled aggregates obtained by grinding a 40 MPa strength concrete have lower abrasion than aggregates obtained by 16 MPa strength concrete is shown in Table 2-6.

Table 2-6 Los Angeles Abrasion Loss percentage of recycled aggregates obtained by 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 is 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 (Recycled materials Resource Center, 2004 URL: http://www.rmrc.unh.edu/).

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.

Since total elimination of all deleterious contaminants is not practical, experimentation is required to determine acceptable levels and to eliminate unnecessary processing cost while providing a quality product. These issues are currently under investigation.

These chemical-related cautions apply largely only to use of recycled aggregates in new concrete mixes or asphalt concrete. Many, perhaps most, of the uses for recycled aggregate (such as a road-base or erosion control) are not subject to these limitations.

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 (Ravindrarajah et al 1985, 1987, 1988, 1992; Tam et al 1990; Hansen et al 1985; Dhir et al 1999; Topcu et al 2004).

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, et al 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 (Kikuch, et al. 1998).

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.

According to Dhir et al (1999, 2004) concrete made with recycled coarse aggregates and natural sand needs 5% more water than conventional concrete in order to obtain the same workability. If recycled fine aggregate is also used, 15% more water is necessary to obtain the same workability.

If recycled aggregates are employed in dry conditions, concrete's workability is greatly reduced due to their absorption capacity, therefore the recycled aggregates should be saturated or have a high humidity (Nealen et al, 1997).

According to Barra et al (1998), when recycled aggregates are saturated the interface between the aggregates and new paste is not effective, therefore recycled aggregates' humidity should be 80-90% in order to achieve an effective interface.

In general the workability of recycled aggregate concretes is affected by the absorption capacity of recycled aggregates. However, the shape and texture of the aggregates can also affect the workability of the mentioned concretes. This depends on which type of crusher is used (Shokry et al, 1997).

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 some what 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.

Hansen et al (1985) concluded that the natural air content of recycled aggregate concrete may be slightly higher than that of control concretes made with conventional concrete. But it is certainly possible to produce recycled aggregate concrete in laboratory with no significant increase in air content compared with control mixed.

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 or a 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 compressive strength 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% (Otsuki et al 2003), decrease of 12% (Turanti, 1993).

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 2-7 of Dhir et al (2004), and Table 2-8 of Hansen (1992).

Table 2-7: Compressive strength of different concrete (Dhir et al 2004)

W/C	Compressive strength of concrete (MPa)			
	Raw aggregate (original concrete)	Concrete made with recycled aggregate 100% and natural sand	Concrete made with recycled aggregate 30% recycled sand and natural sand	Concrete made with 100% recycled sand
0.26	37.5	76.0	76.0	-
0.24	-	-	-	64.0
0.28	-	-	-	69.0

Table 2-8: 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

b) 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.

Ravindrarajah et al (2000) found that at 28 days conventional concrete has 5.4% higher compressive strength than concrete made with 50% of recycled aggregate and 8.9% higher strength than concrete made with 100% of recycled coarse aggregate. (See Figure 2-4).

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 dose 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 2-9.

Table 2-9: 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%

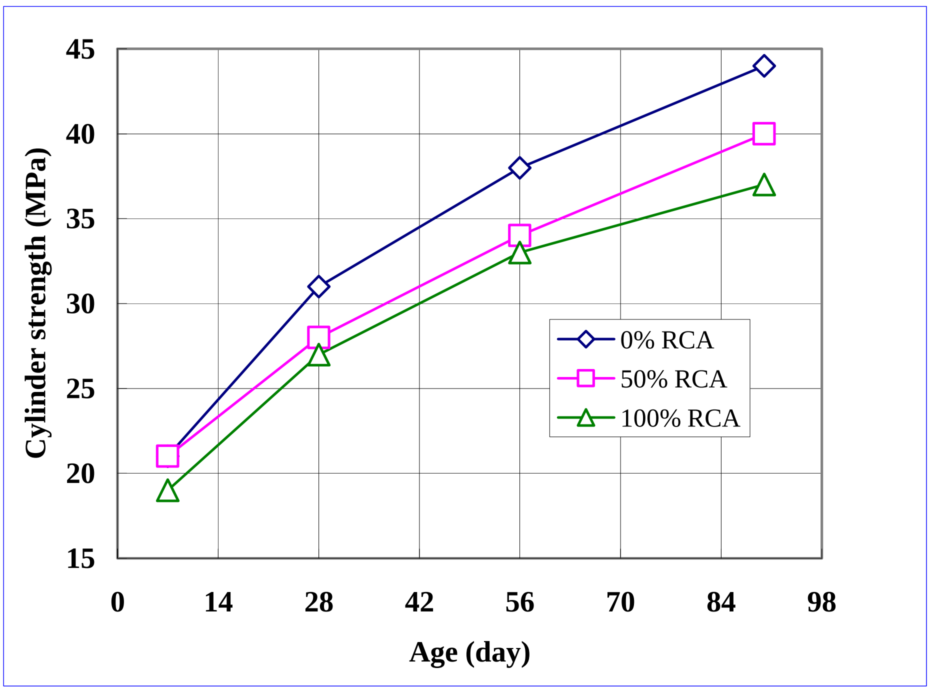


Figure 2-4 Compressive strength over time of concrete of different quantities of recycled aggregate. Ravindrarajah (2000)

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 2-10:

Table 2-10: 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 of Concrete 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

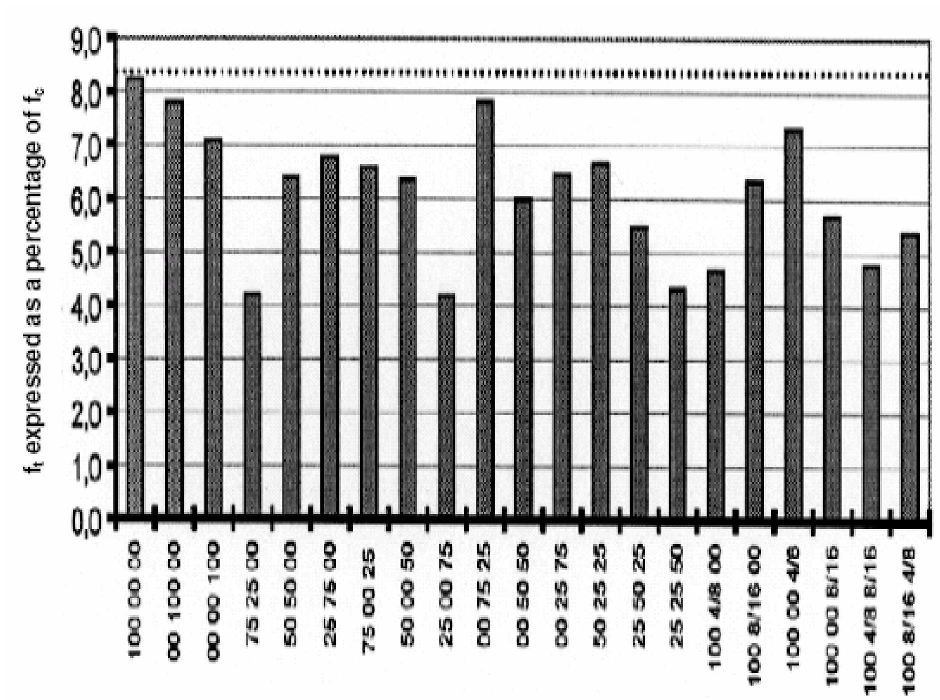


Figure 2-5: The relationship between cylinder splitting tensile strength and cube compressive strength (Grubl et al 1998)

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

Won (1999) found that the use of both coarse and fine recycled aggregates significantly reduced the modulus of elasticity of new concrete (see Table 2-11). 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 2-11: 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.

According to the studies carried out by Limbachiya et al (1998), the increase of shrinkage in concrete of 30 MPa design strength only became noticeable when the concretes contained over 50% recycled coarse or fine aggregates. The concrete mixes had been however adjusted to cater for the effect of recycled aggregates to achieve the target design strength by reducing the water cement ratio.

The tests of Fraaij et al (2002) indicated that creep deformation in concrete containing 50% recycled fines and 100% recycled coarse aggregates was nearly twice as that of the reference concrete. With natural sand as fines and 100% recycled coarse aggregates creep deformation was much reduced, but still 25% more.

Results of creep tests carried out by de Pauw et al (1998). The coarse aggregate in the reference concrete was crushed limestone while the recycled concrete contained 100% crushed concrete rubble. It should be noted that the specimens were unsealed throughout the tests and the deformation measured was therefore the combined effect of shrinkage and creep. It is noted that using a lower cement content and making up the workability with superplasticiser could reduce shrinkage and creep significantly in the reference concrete; this effect was however less marked in concrete containing 100% recycled coarse aggregates.

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.

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 had a lower resistance to freezing and thawing compared to natural concrete. Otsuki et al (2003) reported that the carbonation resistance of recycled aggregate concrete was inferior 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.

There is no difference in the absorption capacity of recycled aggregate and conventional concrete when the concretes are produced approximately with the same water-cement ratio of the original concrete. However, the absorption capacity of the concrete made with recycled aggregate increases with respect to conventional concrete when the w/c ratio used in concrete production is lower than that of the original concrete (Rasheeduzzafar and Khan, 1984).

Sulphate resistance

The resistance of recycled aggregate concrete to sulphate (found in sea water) is about the same or slightly inferior to that conventional concrete. Sulphate resistance generally improves with proper proportioning and the use of fly ash, ground slag, or silica fume.

Carbonation, chloride penetration and reinforcement corrosion

Carbonation appears to be somewhat higher for recycled aggregate concrete when compared to conventional concrete at the same water-cement ratio. According to Rasheeduzafar (1984), concrete with already carbonated recycled aggregate suffers 65% more of carbonation than conventional concrete. Rust occurs in the steel reinforcement with 2-3 mm of clean cover at 2 months. The rust risk in reinforced recycled aggregate concrete is higher than conventional concrete. However this risk is can be decreased with lower w/c ratio in recycled aggregate concrete than conventional concrete.

According to Barra et al (1997) the carbonation risk of recycled aggregate concrete using a higher amount of cement than 400 kg/m^3 of concrete mix is large than in conventional concretes. The carbonation depth in recycled aggregate concrete and conventional concrete is similar when the amount of cement used in the mix is between 300 kg/m^3 and 400 kg/m^3. This occurs when the cement is added, the aggregate are saturated or very humid. In poor concretes using less than 300 kg/m^3 of cement, the carbonation depth is similar in both concretes.

Holzmann (1998) observed that with increasing recycled aggregate content, the depth of carbonation tended to increase. The depth of carbonation measured in concrete with 100% recycled coarse aggregate was considerably greater than that in normal concrete. However in concrete with 20% to 60% recycled coarse aggregate, the depth of carbonation was, on many occasions, even less than that in normal concrete. The test results were scattered.

Alkali silica reaction

The rubble processed at recycling plants may originate from structures which were attacked by alkali silica reaction (ASR) or which were potentially reactive, but did not react due to lack of favourable conditions (such as humidity).

According to Desmyter et al (2003), preventive measures such as the use of lower alkali Portland or blast furnace slag cement, may increase the durability of the recycled aggregate concrete as far as ASR is concerned.

2.5 INFLUENCE OF FLY ASH ON PROPERTIES OF CONCRETE

Mineral admixtures such as silica fume, fly ash, and ground granulated blast-furnace slag improve the engineering properties and performance of concrete when they are used as mineral additives or as partial cement replacements (Malhotra et al, 1996 and Hassan et al, 2000). Economic (lower cement requirement) and environmental considerations have also played a great role in the rapid increase in usage of mineral admixtures. Compared with Portland cement, cement with pozzolan helps to have concrete with less permeability and a denser calcium silicate hydrate (C–S–H) is obtained. Ground granulated blastfurnace slag, silica fume, metakaolin, and rice-husk ash can be used in concrete as supplementary cementing materials (SCM) in addition to fly ash. Compared to fly ash, the availability of these materials is rather limited. One of the major institutional barriers against the use of fly ash and other supplementary cementing materials is the prescriptive type of specifications and standards (Ferraris et al, 2001).

Fly ash is a by-product of the coal power generation and consists mainly of SiO2, Al2O3, Fe2O3, and CaO and some impurities. According to ASTM C618, fly ash belongs to Class F if (SiO2 + Al2O3 + Fe2O3) > 70%, and belongs to Class C if 70%> (SiO2 + Al2O3 + Fe2O3)>50%. Usually, Class F fly ashes have a low content of CaO and exhibit pozzolanic properties, but Class C fly ashes contain up to 20% CaO and exhibit cementitious properties.

Low-calcium fly ash (FL) is produced by burning anthracite or bituminous coal, and high-calcium fly ash (FH) is produced by burning lignite or sub-bituminous coal. FL is categorized as a normal pozzolan, a material consisting of silicate glass, modified with aluminum and iron (Jueshi et al, 2001 and Papadakis et al 1999). The mechanism is that when pozzolanic materials are added, calcium hydroxide Ca(OH)2 is transformed into secondary calcium silicate hydrate (C–S–H) gel, causing the transformation of larger pores into finer pores as a result of pozzolanic reaction of the mineral admixtures. Hydrated cement paste contains approximately 70% C–S–H, 20% $Ca(OH)_2$, 7% sulpho-aluminate, and 3% of secondary phases. The $Ca(OH)_2$, which appears as the result of the hydration, affects the quality of the concrete negatively by forming cavities because of its solubility in water and its low strength. The use of mineral admixtures has a positive effect on the quality of the concrete by binding the $Ca(OH)_2$ (Memon et al 2002, Papadakis,et al 2002):

Cement hydration: Cement (C_3S; C_2S) + H_2O → CSH -gel + $Ca(OH)_2$

Pozzolanic reaction: $Ca(OH)_2$ + SiO_2 + CSH - gel

The fly ash concrete mix techniques can generally be divided into three main categories. Simple replacement method involves direct weight replacement of a part of Portland cement with fly ash, with a subsequent adjustment of concrete for yield. Addition method involves direct weight addition of fly ash to cement, replacing part of the aggregate in concrete, in order to achieve the correct yield. Partial replacement method involves replacement of a part of the Portland cement with excess weight of fly ash, replacing also part of the aggregate in order to achieve the correct yield. The third method is divided in itself into two as modified replacement method and rational proportioning method. In the modified replacement method, the fly ash content in the mixture is modified and it is shown that the strength of fly ash concrete at early stages becomes comparable to that of the control concrete. The results of the studies have shown that to get equal strength of the control concretes between 3 and 28 days old, the amount of added fly ash in concrete must be more than the amount of removed cement.

2.6 INFLUENCE OF STEAM CURING ON PROPERTIES OF CONCRETE

The negative effects of recycled aggregate on concrete quality limit the use of this material in structural concrete. However, the disadvantages of using recycled aggregate can be minimized in the precast concrete industry since it is easier to ensure the quality of such products due to the presence of an existing quality assurance system. The target precast concrete products can be in the forms of partition walls, road dividers, bridge fencing, noise barriers and paving blocks which do not require very high performance standards. In Hong Kong, a development has already been made to produce bricks and blocks with recycled aggregates (Poon et al 2002).

The curing method used for precast concrete products differs from the normal curing method where steam curing is usually employed because it accelerates the rate of strength development. However, this curing method alters the properties of produced concrete. It was found that steam curing reduced the creep of concrete by up to 50 % compared to that of normal moist-cured concrete (Brooks et al 1981, 1996). Boukendakdji et al (1996) found that steam curing decreased the drying shrinkage of Portland cement and slag concretes by about 14 and 23 % respectively. Ho et al (2003) found that steam cured concrete was more porous than water cured concrete. Erdem et al (2003) indicated that steam curing increased the 1-day compressive strength of concrete compared to that of normal cured concrete. However, lower longer term strengths were observed for the steam cured concrete when compared to the normal water cured concrete. Recently, Liu et al (2005) found that the detrimental effects of steam curing on long term compressive strength (28-day) can be minimized by incorporating ultrafine fly ash and slag as 30 to 40 % replacements of cement.

Although plenty of information is available on the effect of steam curing on conventional concrete properties, there is limited data relating to steam cured recycled aggregate concrete. There is a need to gain more information on the effect of steam curing on the strength and durability of concrete produced with high percentages of recycled aggregates.

2.7 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. Recycled aggregates properties: density, water absorption, porosity, Los Angeles abrasion, 10% fine value, freezing and thawing resistance are inferior in quality to those of original aggregates.

- According to RILEM recommendations, the recycled aggregates obtained from crushed concrete, should be defined as type II. Type II is a material that originated primarily from concrete rubble. The recycled aggregate must have a lower than 10% water absorption capacity and a minimal dry particle density of 2000 kg/m^3. Recycled aggregate concrete is allowed to achieve 50/60 Mpa. It dose not require an additional test to be used in exposure class 1. In order to use in other exposure classes ASR expansion and Bulk freeze-thaw test are required.

- 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. Therefore, recycled aggregate concrete (using more than 50% of recycled coarse aggregates) more cement than conventional concretes is necessary to achieve the same workability and 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.

- With respect to durability:

  1. Concrete made with recycled aggregates needs to have a lower effective w/c ratio to achieve lower permeability.
  2. The freezing and thawing resistance is lower in recycled aggregate concrete than in conventional concrete. However it can be improved if the recycled aggregates are humid and the air-entrainment is used at concrete production.
  3. The resistance of recycled aggregate concrete to sulphate is about the same or slightly inferior to that of conventional concrete.

2.8 RESEARCH NEEDS

In summary, the review of previous works indicated that the mechanical and durability properties of concrete made with a high percentage (>30%) of recycled aggregate are inferior to those of the corresponding conventional aggregate concrete. This drawback limits the utilization of the recycled material in concrete.

There is a need to develop a technique for utilizing a higher percentage of recycled aggregate in concrete. The principal objective of this thesis is study possible techniques of improving the properties of recycled aggregate concrete that is made with high percentages (≧50%) of recycled aggregate. These techniques include: (a) using lower water-to-cement ratios in the concrete mix design; (b) using fly ash as a cement replacement or as an additional mineral admixture in concrete mixture, and (c) precasting recycled aggregate concrete with steam curing regimes.

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. The recycled aggregates employed in the study were taken from the Recycling Plant at Tuen Mun Area 38 in Hong Kong. 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 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 were 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 the natural coarse aggregate.

3.2 MATERIALS

3.2.1 Cement and fly ash

The Portland cement used was “Green Island” cement equivalent to ASTM Type I, from China Cement (H.K) Co. Ltd. The fly ash used was a low-calcium fly ash equivalent to ASTM Class F, from China Light & Castle Peak Power Plant. 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 (please see Figure 2-2) in Hong Kong was used. The nominal sizes of the natural and recycled coarse aggregates were 20 and 10 mm 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.

Recycling facility at Tuen Mun Area 38 in Hong Kong

The reclamation project at Tuen Mun Area 38 received inert materials, mostly C&D material from all sources. Opportunity was taken to set up a pilot recycling plant to process suitable materials into recycled aggregates that could be used for different engineering purposes. The recycling plant with a production capacity of 1200 tons per day came into operation in mid July 2002(CED of HK, 2002).

Sorting was first done to the incoming materials through grizzlies, to set aside broken rock and concrete rubble suitable for recycling. The material was then passed to a primary jaw crusher which reduces the size to less than 250mm. Impurities such as wood, paper, plastics etc. were removed manually while on the conveyor belt. The rock and concrete rubble were then crushed in two secondary cone crushers, and sorted into 40mm, 20mm, 10mm sizes and fine fractions (5mm down) through a set of sieves. The process is illustrated in Fig. 3-1.

Quality checks were conducted for every 300 tonnes of recycled aggregates produced, to determine whether the limits in Table2-5 of the Particular Specification were met. Aggregates that did not pass the tests are separately stockpiled for lower grade use. According to the Civil Engineering Department, most of the aggregates produced met the quality standards. 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.

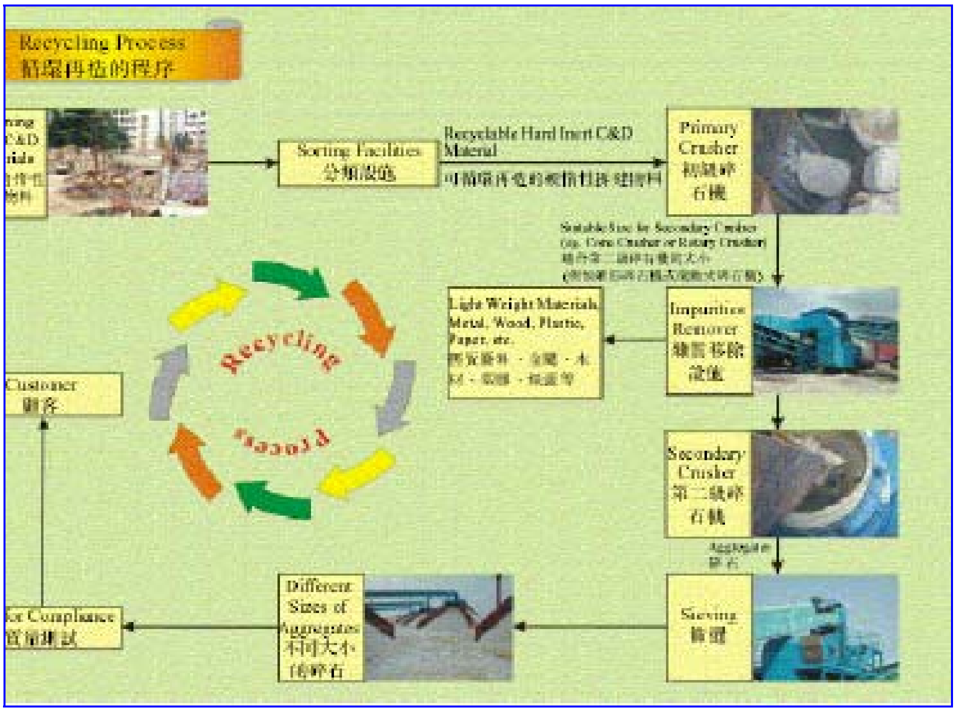
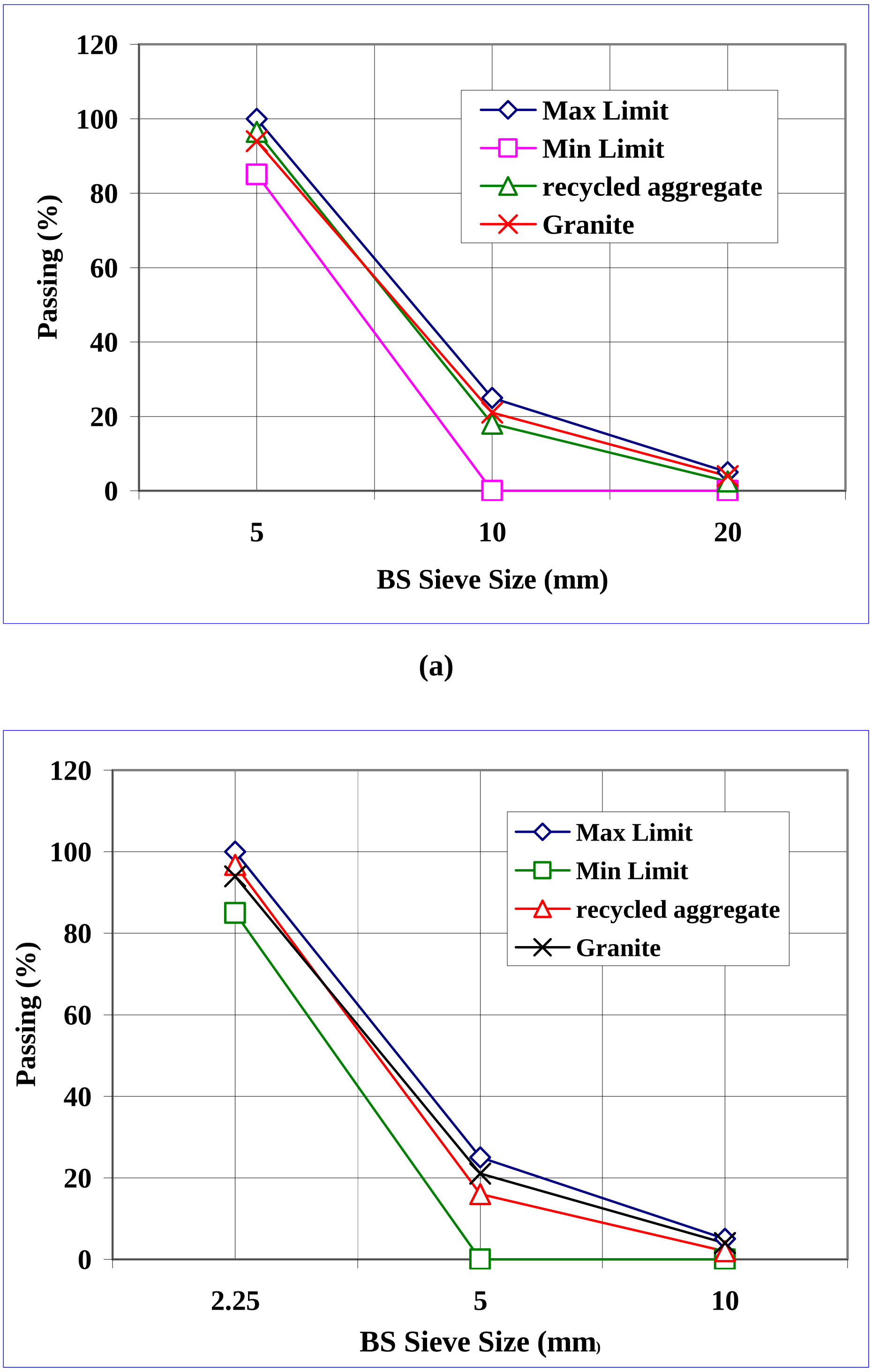


Figure 3-1 The recycling process (From fact sheet of Civil Engineering Department of HK, 2002)

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.



(b)

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

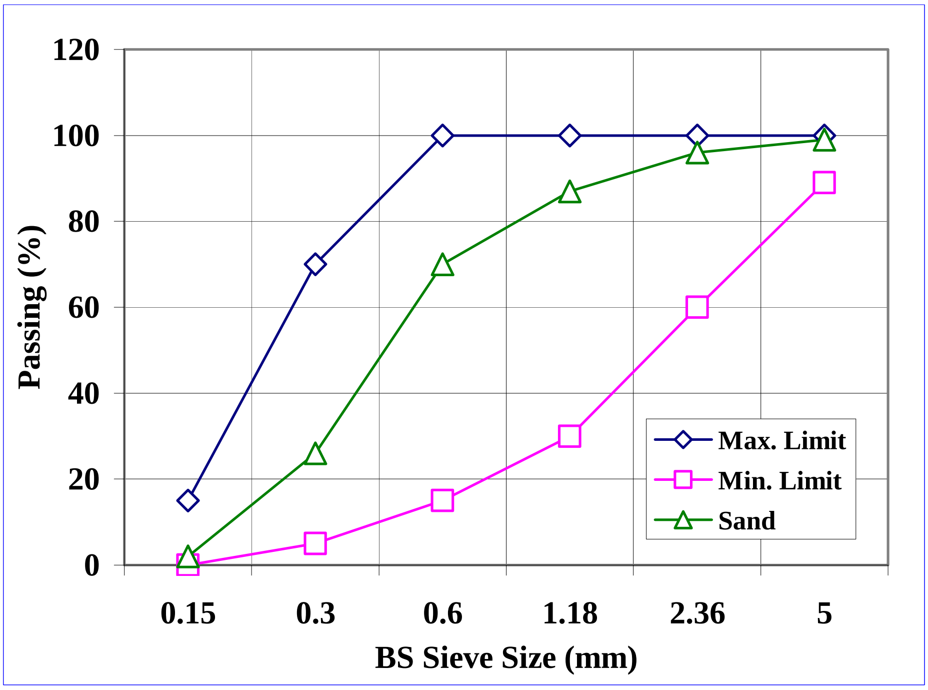
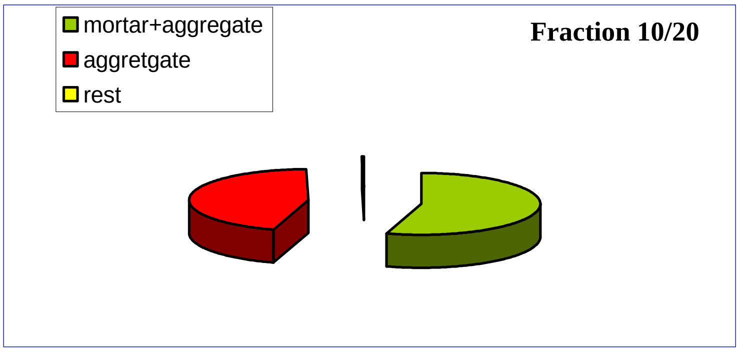


Figure 3-3 Sand grading according to BS 882

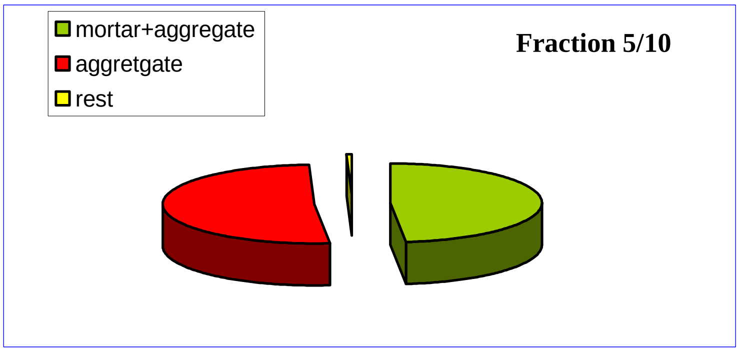
2) Recycled aggregates composition

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.

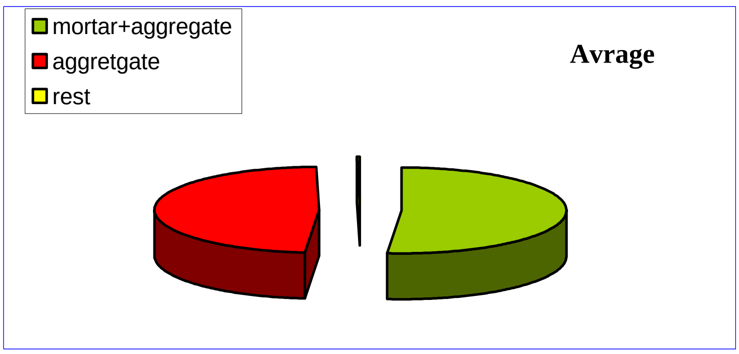
Figure 3-4 is divided into 3 graphics; (a) and (b) represented the different fractions by mass and (c) is the average composition calculated from the relative percentages of the different fractions in the aggregates.



(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) Mechanical properties of recycled aggregates

In this section all the mechanical properties of the recycled coarse aggregates, natural coarse aggregates and also river sand are determined by required tests. These aggregates should be used in concrete production, and the values of their mechanical properties must be in concordance with introduction BS 812 requirement and European standards for recycled aggregates to be used in concrete.

Density

All the necessary tests were carried out for recycled aggregates, raw natural coarse aggregates and river sand. Evidently, as defined in chapter 2, the density of recycled aggregate was lower than that of convention aggregates. The average value of density of recycled coarse aggregate in a saturated and surface-dry condition was 2530 kg/m^3. This value equated with the information contained in chapter 2 and was consequently expected. The density values of recycled coarse and natural aggregates were quite similar. Recycled aggregates have lower density due to the adhered mortar. However, the most important difference between these two aggregates is their water absorption capacity and porosity. The recycled aggregates have mortar adhered to them and this material is porous, so the capacity to absorb water is much higher. This high absorption of water is one of the most important factors to take into consideration in the determining of material mix proportion in concrete production.

According to RILEM the recycled aggregates are defined as Type II and according to DIN 4266-100 recycled aggregates are defined as Type I. Both types of the recycled aggregate described are appropriate for their use in concrete. As previously mentioned, the sand and conventional aggregates were much denser and therefore had less absorption capacity than coarse recycled aggregate.

Table 3-3 Properties of the aggregates

Properties	Size of BS Test Sieve (mm)	Percentage Passing (%)				
		20mm granite	**10mm granite**	**20mm recycled aggregate**	**10mm recycled aggregate**	**Sand**
Sieve analysis	37.5	100	-	100	-	-
	20	95	-	96	-	-
	14	18	100	19	100	-
	10	4	94	4	96	100
	5	-	21	-	20	99
	2.36	-	4	-	4	96
	1.18	-	-	-	-	87
	0.6	-	-	-	-	70
	0.3	-	-	-	-	26
	0.15	-	-	-	-	2
Density (g/cm^3)		2.62	2.62	2.58	2.49	2.63
Strength (10% fines KN)		159		126		-
Porosity (measured by MIP)		1.62		8.69		-
Water absorption (%)		1.11	1.12	3.52	4.26	0.87

Porosity

As shown in Table 3-3, the porosity of the recycled aggregates measured by MIP was much larger. Evidently this may be due to several factors, firstly because the recycled aggregates had some adhered mortar which was extremely porous, and secondly the recycled aggregate had suffered from “manufacturing” and the quality of the original aggregates had been reduced (negatively affected).

Water absorption

It can be seen from Table 3-3 that the water absorption of the recycled aggregates was 4.26% and 3.52% for 10 mm and 20 mm, respectively. None of the fraction exceeded the BS's limit of 5% with respected to use in structural concrete. The water absorption of raw coarse granite aggregates and the river sand were 1.11% and 0.88%, respectively. For proportion of the concrete mixtures, all the absorption capacities have to be taken into account, besides the humidity of the aggregates.

According to RILEM and DIN 4226-100, the recycled aggregates were Type II and Type I respectively. Both of this types recycled aggregate were appropriate for use in concrete.

Strength of aggregate (10% fine value)

The 10% fine values of recycled and conventional coarse aggregates were tested in according with normative BS 812-111. Recycled aggregates had lower strength than conventional aggregates see Table 3-3. This was an expected result and was caused by the adhered mortar on the original aggregates, this material being much less resistant than that of the conventional aggregates. In accordance with BS 812-111, the aggregates with >100 KN of "10% fine value force" are able to be used in concrete.

3.2.3 Superplasticizer

For the concrete mixtures in Series III, IV, V and VI, a sulfonated naphthalene formaldehyde condensate (Darex Super 20) obtained from Hong Kong Grace Construction Products was used. This superplasticizer 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 3-4. The absolute volume method was adopted to design the mix proportions of the concrete mixtures in Series I -VI as shown in Table 3-5 – Table 3-10, 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 “Crocker Brand” pan mixer of 0.11 m^3 capacity (Figure 3-6) 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, 100x100x500 mm beams 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 demolded. 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°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 ± 1°C until other test ages were reached.

Table 3-4 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 3-11.

Table 3-5 - 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 3-6 - 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 3-7 - 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 3-8 - 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 3-9 - Proportioning of the concrete mixtures in Series V

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
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

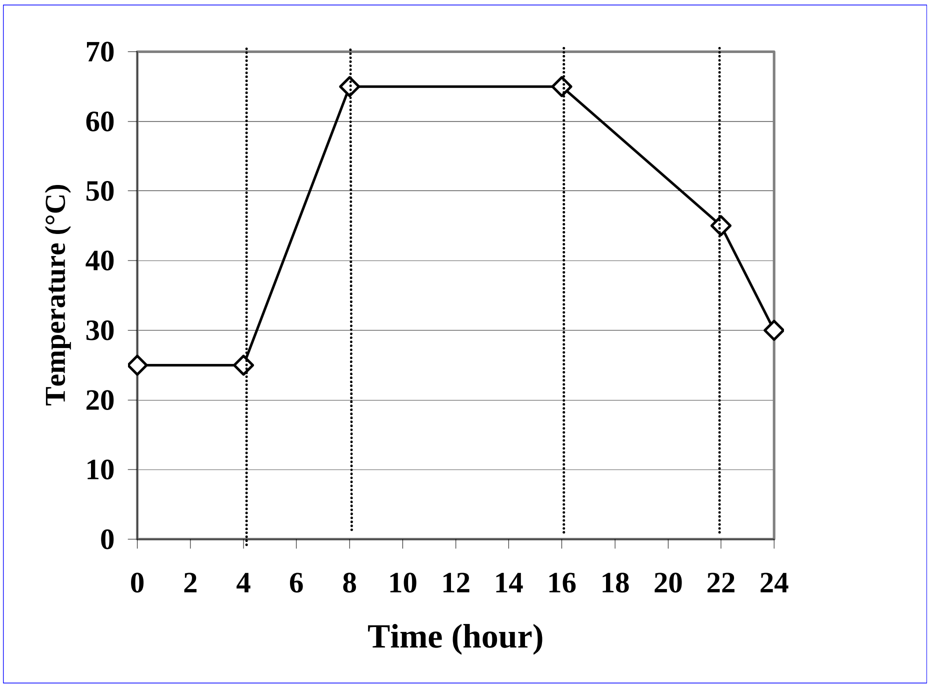


Figure 3-5 One-day steam curing cycle

Table 3-10 - Proportioning of the concrete mixtures in Series VI

Notation	Fly ash (%)	Recycled aggregate (%)	Constituents (kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	160	400	729	1140	0
R20	0	20	160	400	729	912	221
R50	0	50	160	400	729	570	554
R100	0	100	160	400	729	0	1107
a-R0 F25	25	0	160	500	685	1071	0
a-R20F25	25	20	160	500	685	214	208
a-R50F25	25	50	160	500	685	536	520
a-R100F25	25	100	160	500	685	0	1040

Table 3-11 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 3-6 “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 3-7).

Figure 3-7 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 3-8) 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:

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

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:

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

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

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 3-8 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 3-9). 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 3-9 "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 3-10). 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 3-10 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. (Figure 3-11) 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.

Figure 3-11 Creep test

3.4.8 Determination of chloride diffusivity

The method used to measure the chloride diffusivity of the concrete was a rapid determination procedure in accordance with ASTM C1202-94 (1995). The test concrete specimens were 100mm in diameter and 50mm thick, which were sliced from the prepared concrete cylinders (Fig. 3-12). The specimens were evacuated in a desiccator using a vacuum pump to a pressure of 76 cm Hg which was for at least 3 hours. Distilled water was filled into the desiccator with the vacuum pump still running. The specimens were then soaked in distilled water for 18 hours. Thereafter, a potential difference of 60 V dc was maintained across the ends of the specimens, one of which was immersed in a 3.0% sodium chloride solution, the other in a 0.3 N sodium hydroxide solution. The current was recorded using a multi-micrometer at 30 min intervals. (Figure 3-12) The chloride diffusivity of the specimens was expressed as an electrical indication: the total charge passed in coulomb during the test period of 6 hours, which was given by:

$$Q=900(I_0+2I_{30}+2I_{60}+\cdots\cdots+2I_{300}+2I_{330}+2I_{360}) \qquad (3\text{-}3)$$

Where Q = charge passed (coulombs);

I_0 = current (amperes) immediately after voltage is applied, and

I_t = current (amperes) at t min after voltage is applied.

The test method used in this study was an indirect measurement providing a rapid indication of their resistance to chloride ion penetration. According to ASTM C1202-94 (1995), in most cases the electrical conductance results showed good correlation with chloride ponding tests, such as AASHTO T259 (1986). Based on the charge passed, the chloride penetrability of concrete can be assessed as given in Table 3-13 (ASTM C1202-94, 1995).

Table 3-12 Chloride-ion penetration based on charge passed

Charge passed (coulombs)	Chloride ion penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Figure 3-12 Chloride-ion penetration test

3.4.9 Determination of pore size distribution

The porosity and pore size distribution of the concrete samples were measured using a "Pore Size 9320" mercury intrusion porosimeter (MIP) with a maximum mercury intrusion pressure of 210 MPa (Fig. 3-13). The concrete samples were obtained from the concrete cylinders prepared in 3.3.3. Small cylindrical cores of 21 mm in diameter and 20 mm in height were drilled from the concrete cylinder specimens at mid height using a diamond drilling machine. The concrete cores were immersed in acetone to stop the hydration. After the hydration was stopped, the concrete samples were dried at 60 °C for 72 hours. A cylindrical pore geometry and contact angle θ of 140 ° were assumed (Day and Marsh 1988, Taylor 1990). The mercury intruded pore diameter d_p at an intrusion pressure of P_{In} was calculated by $d_p=-4\gamma cos\,\theta/P_{In}$, where γ = 0.483 Mm^{-1}, the surface tension of mercury.

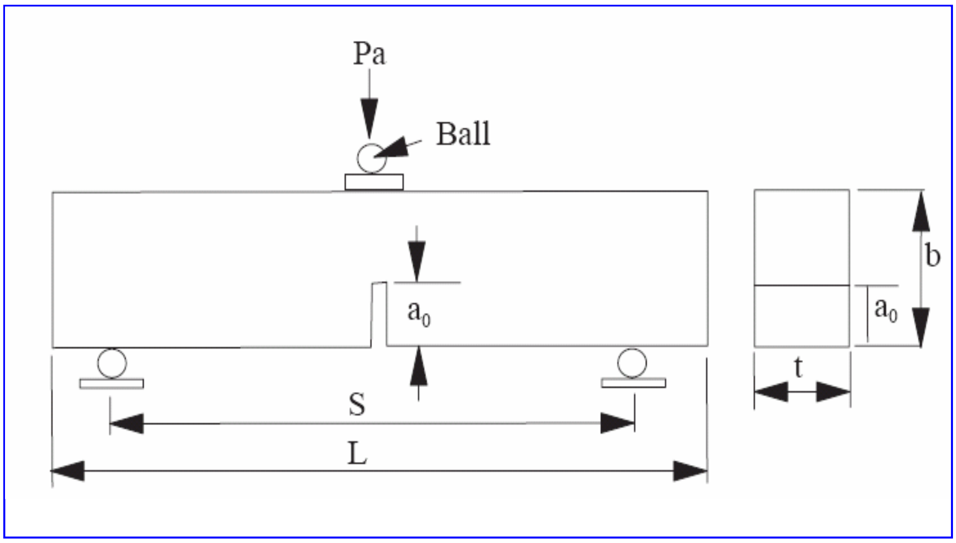
To perform a MIP test, about 20g of sample was weight into a tube-like penetrometer. The penetrometer was evacuated in the instrument to a pressure below 50 μm Hg. Mercury was filled and then intrusion pressure was applied by compressed air to a pressure of 0.021 MPa. Thereafter, the penetrometer was transferred to the hydraulic chamber of the instrument and hydraulic pressure was applied to a maximum pressure of 210 MPa. The intruded volume of mercury each different pressure level was recorded and a corresponding pore size distribution curve was obtained.

Figure 3-13 Pore size 9320 mercury intrusion porosimeter

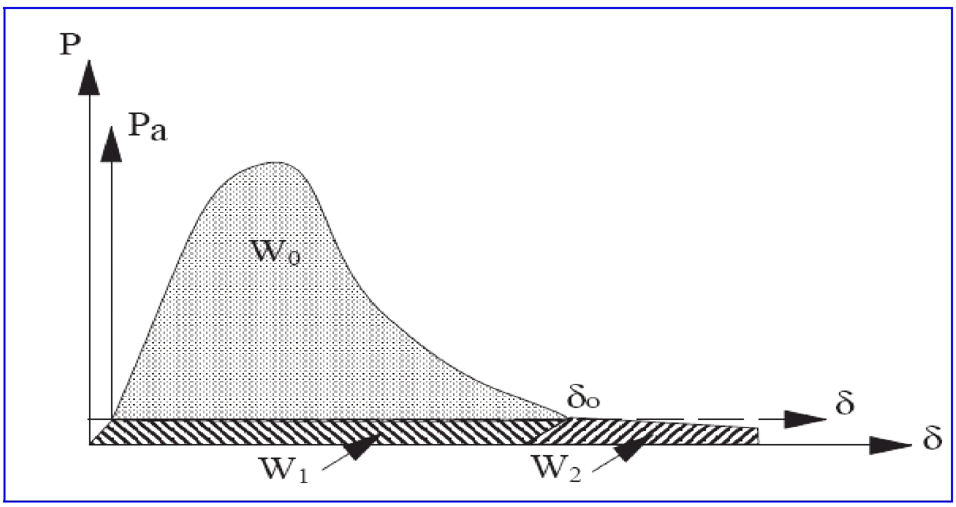
3.4.10 Determination of the fracture energy of recycled aggregate concrete

Three-point bend beam specimens were used in the present study for the determination of fracture energy (G_f) according to the RILEM recommendation (RILEM 1985). The geometry of the beam specimens is shown in Fig. 3-14. The ratio of the span to the depth of the beam (L/b) was 5.0 for all the specimens. The ratio of the notch length to the beam depth .a_0/b. was 0.30 for all the specimens. The ratio of the total length to the beam span was 1.2. In this way, all the beams were geometrically similar in the two dimensions (see Fig. 3-13 and Fig. 3-14). The thickness of all beams was 100 mm. After 28 days of curing, the beam specimens were notched at mid span for a depth of 0.3b (30 mm) and subjected to tests.

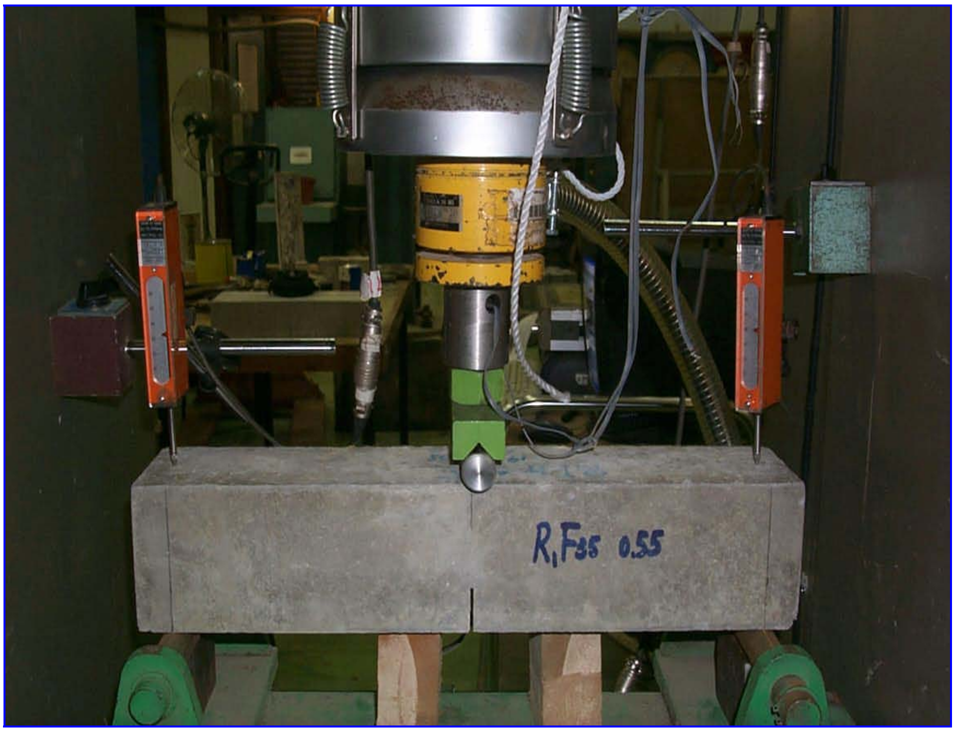
The Three-Point bending tests were performed using a closed loop servo controlled MTS testing system (Fig. 3-14 (c)). The loading frame had 4000 kN capacity and the maximum loading applied was less than 10 kN. The central load was measured using a 20 kN load cell calibrated for a working range of 15 kN. The mid-span deflection was measured using three linear variable displacement transducers (LVDT). The load was applied at constant rate of 0.05 mm/min for notched concrete beam. The set up of Three-Point bending test is shown in Fig. 3-14.



(a) Notched beam for three-point bending test



(b) Load displacement curve for evaluation of fracture energy



(b) showing the actual test arrangement

Figure 3-14 Set up of three-point bending test

CHAPTER 4 FRESH PROPERTIES OF RECYCLED AGGREGATE CONCRETE

4.1 INTRODUCTION

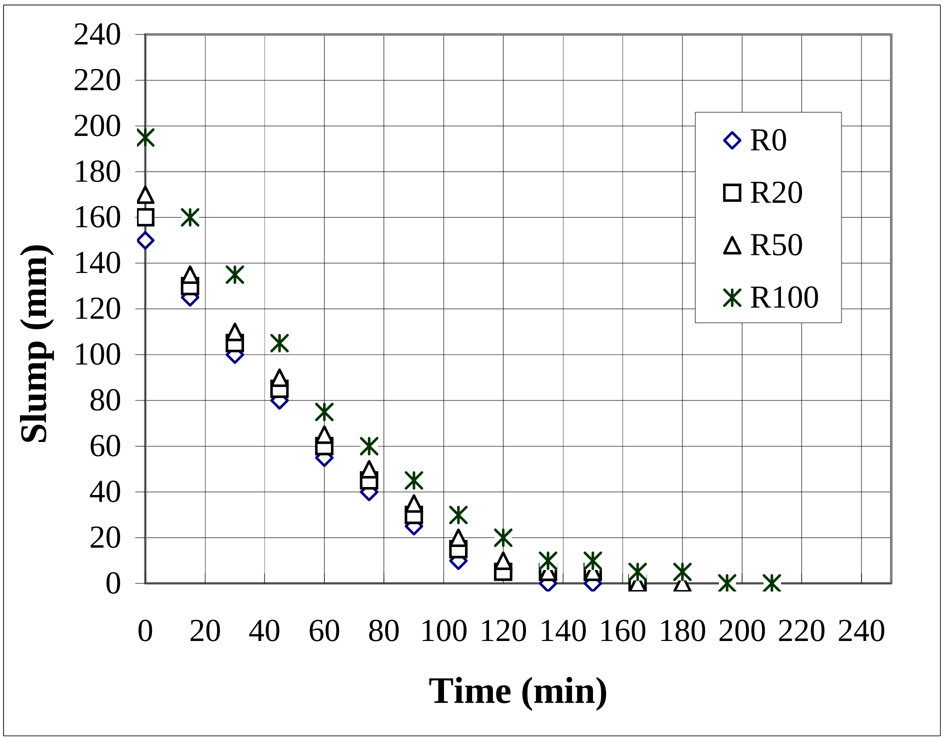
The objectives of this chapter are to present and discussed the test results of the fresh properties of recycled aggregate concrete and the concrete made with class-F fly ash in Series I and Series II. These properties include slump, slump lose, air content, fresh density and bleeding. The influences 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 are explored.

4.2 TEST RESULTS AND DISCUSSION

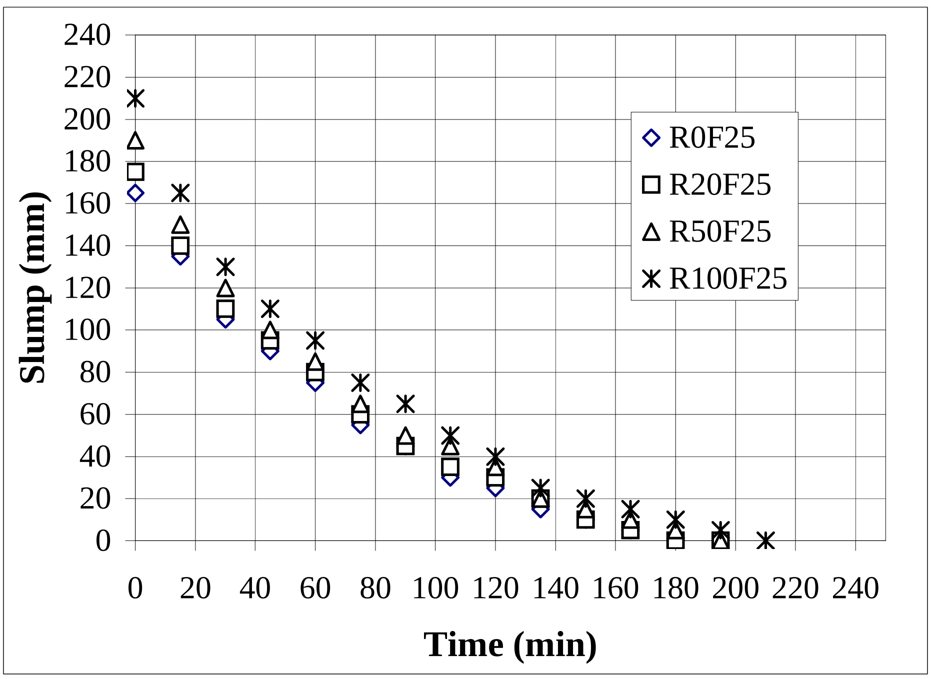
4.2.1 Initial slump and slump loss

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

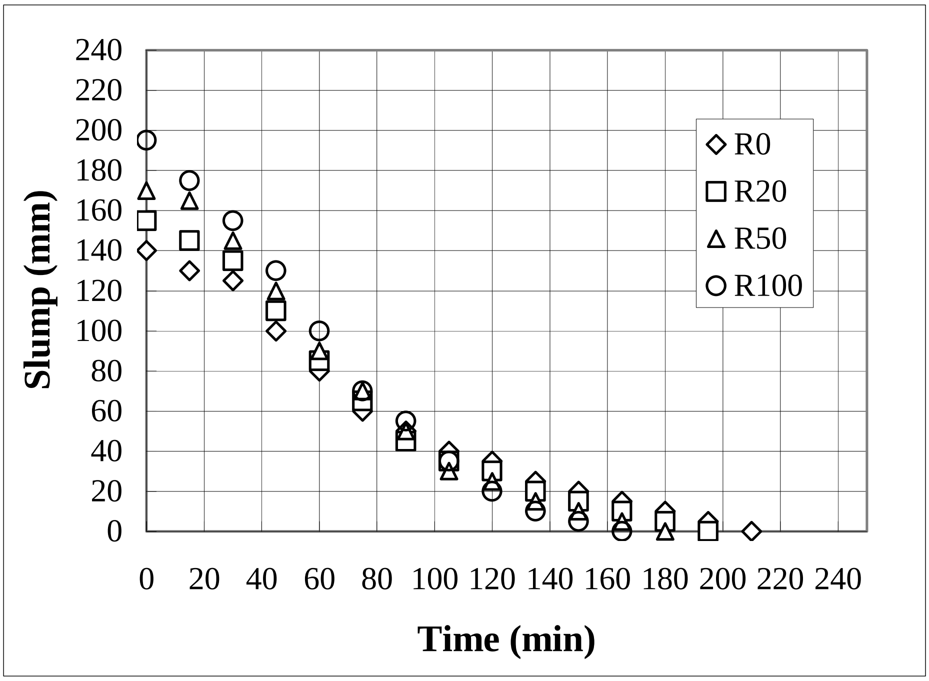


(a)

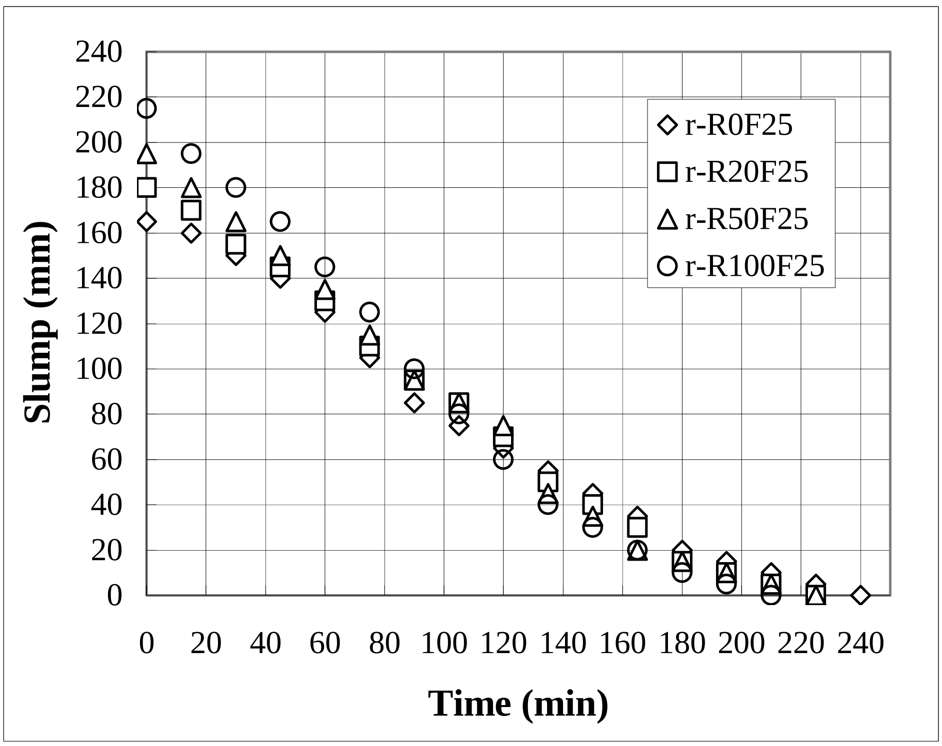


(b)

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

conventional aggregate or 20%, and 50% recycled aggregates. So the effect of W/C ratio on the rate of slump loss was significant.

Figure 4-1 (b) and Figure 4-2 (b) show the changes of concrete slump with time for the Series II mixes with 25% fly ash, where averages of two measurements are also used. All the mixes showed higher initial slumps when compared with the corresponding mixes without fly ash. The highest initial slump of 210 mm and 215 mm was recorded for the mix with 100% recycled aggregate in series I and series II concrete mixture, respectively. The rate of slump loss with time was also lower for the mixes with fly ash. As a result, these mixes took longer to reach the zero slumps than the mixes without fly ash. The beneficial effect of fly ash on the workability of concrete might be due to use of fly ash increased the absolute volume of cementitious materials (cement plus fly ash) compared to non-fly-ash concrete; therefore, the paste volume was increased, leading to a reduction in aggregate particle interference and enhancement in concrete workability. The spherical particle shape of fly ash might also participate in improving workability of fly ash concrete because of the so-called "ball bearing" effect.

4.2.2 Rate of slump loss

Figures 4-3 and 4-5 show the rate of slump loss for the concrete mixtures without fly ash in Series I and II, respectively. It is evident that in the first 60 mins the rate of slump loss of concrete mixtures were significantly higher than that the corresponding losses between 75-135 mins. The rate of slump loss was increased with an increase in recycled aggregate content. The concrete mixtures R100 with 100% recycled aggregate in Series I and II had a rate of slump loss of 2.0 mm/min and 1.58 mm/min respectively; whereas the corresponding values for the concrete mixtures R0. The above observations are due to the higher water absorption capacity of the recycled aggregate which had been used at the air dried condition with moisture content of the aggregates at mixing much lower than the water absorption capacity.

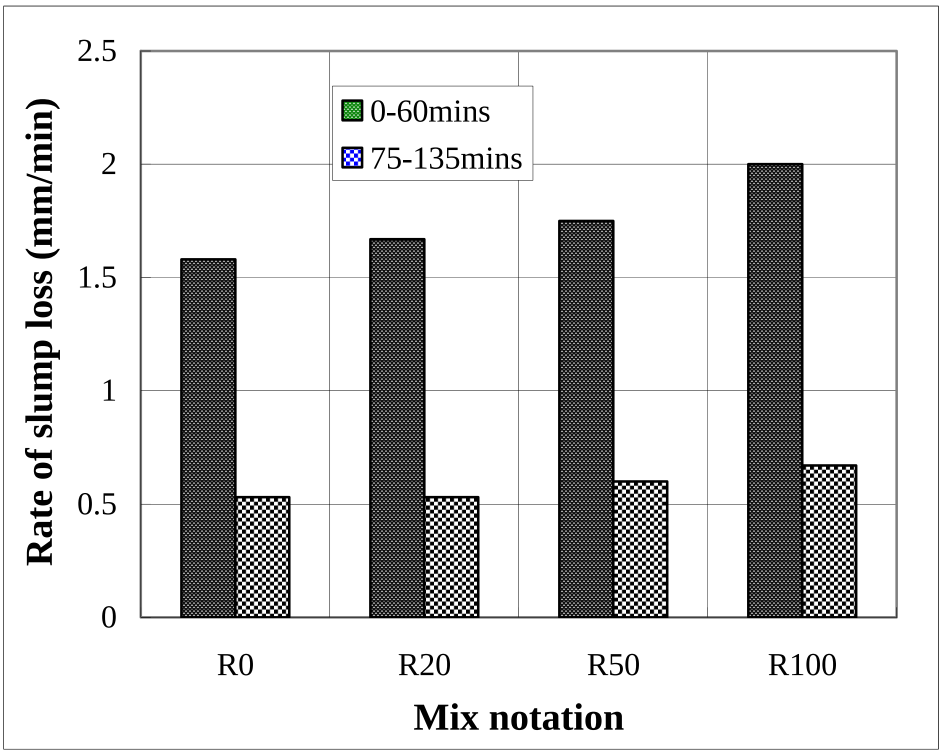


Figure 4-3 Rate of slump loss of concrete mixture without fly ash in Series I

Figures 4-4 and 4-6 show the rate of slump lose for the concrete mixtures with 25% fly ash in Series I and II, respectively. It can be noticed similar to the concrete mixtures without fly ash, the rate of slump loss was increased with an increase recycled aggregate content.

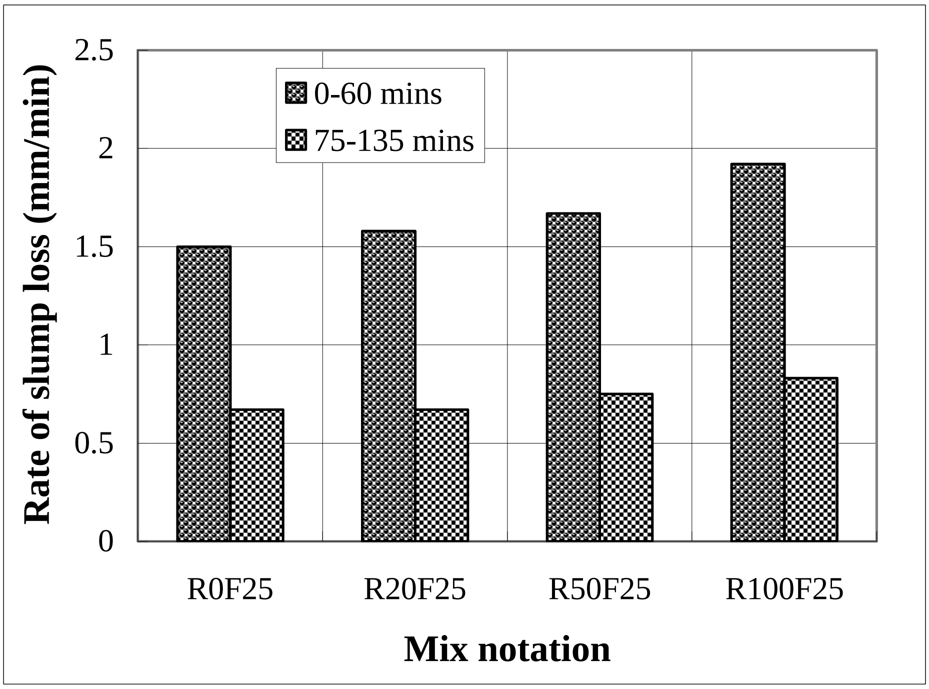


Figure 4-4 Rate of slump loss of concrete mixtures with 25% fly ash in Series I

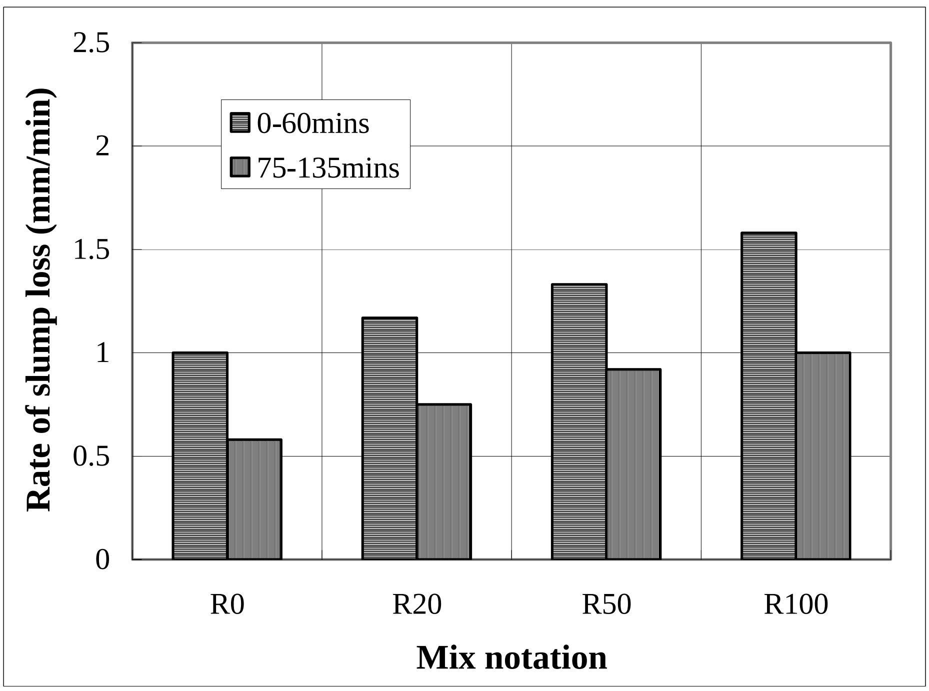


Figure 4-5 Rate of slump loss of concrete mixture without fly ash in Series II

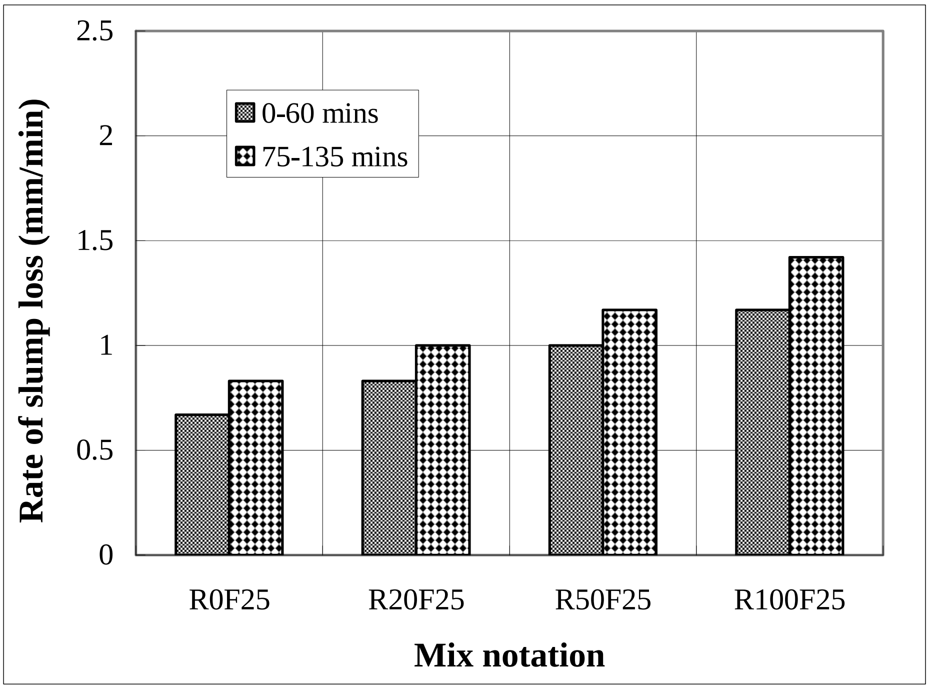


Figure 4-6 Rate of slump loss of concrete mixture with 25% fly ash in Series II

4.2.3 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 4-7, 4-8, 4-9 and 4-10 for Series I, Figs 4-11, 4-12, 4-13 and 4-14 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 indicated that the use of recycled aggregates, even at an air-dried state, resulted in higher bleeding rates 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. For example, for the mix with 100% recycled aggregates, a 30-minute delay of the starting time of bleeding test reduced the bleeding rate by about 63 % and the bleeding capacity by 26%. These results were similar to the results reported by Wainwrigt et al. on the bleeding of concrete containing ground granulated blast furnace slags (Wainwright et al (2000)). The reduction in bleeding rate and bleeding capacity might be attributed to the initial hydration of cement which reduced the content of free water in the system. It should be noted the delays slightly prolonged the process of bleeding. When the tests were started immediately after mixing, it took about 220 minutes for the bleeding of water to stop. However, when the starting time of tests was delayed by 30 and 60 minutes, the same process took about 300 minutes. The effect of recycled aggregate and the starting time of bleeding test can also be seen from Figs 4-7, 4-8, 4-9 and 4-10.

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

The results of concrete mixture in Series II as shown in Table 4-2 indicated that the bleeding rates and bleeding capacities of all mixes were decreased with a decrease in the water-to-cement ratio. When concrete made with 100% recycled aggregates, the use of W/C of 0.45 decreased the bleeding rate and bleeding capacity by 5.9% and 25.3% respectively compare to the concrete made with a W/C of 0.55. Similarly results were obtained for the concrete mixture with W/C ratios of 0.55 and 0.45. A delay in the starting time of bleeding tests resulted in significant reductions in both the bleeding rate and bleeding capacity for all the concrete mixes. For example, for the mix with 100% recycled aggregates, a 30-minute delay of the starting time of bleeding test reduced the bleeding rate by about 51 % and the bleeding capacity by 32%. When the tests were started immediately after mixing, it took about 190 minutes for the bleeding of water to stop. However, when the starting time of tests was delayed by 30 and 60 minutes, the same process took about 300 minutes. The effect of recycled aggregate and the starting time of bleeding test can also be seen from Figs 4-11, 4-12, 4-13 and 4-14.

It is clear from Table 4-2 that the replacement of cement by 25% fly ash reduced the bleeding rate and bleeding capacity for all the mixes in series II, 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 17.4% and

15.3% respectively, when compared with the mix without fly ash. This value was higher that the concrete made with W/C of 0.55. Further reductions in the bleeding rate and bleeding capacity were observed when the starting time of bleeding tests was delayed.

The beneficial effect of fly ash on the bleeding of concrete might be due to its lower density and higher specific area as compared to cement, which held more free water and blocked the paths of water channels, and using fly ash in concrete mixtures usually reduces bleeding by providing greater fines volume and lower water content for a given workability (ACI Comm. 226, 1987; Idorn et al, 1984). Although increased fineness usually increases the water demand, the spherical particle shape of the fly ash lowers particle friction and offsets such effects. Concrete with relatively high fly ash content will require less water than non-fly-ash concrete of equal slump (Admixtures and ground slag for concrete, 1990).

Fly ash can act like a superplasticizing admixture when used in concrete. The phenomenon is attributable to three mechanisms. First, fine particles of fly ash get absorbed on the oppositely charged surfaces of cement particles and prevent them from flocculation. The cement particles are thus effectively dispersed and will trap large amounts of water that means that the system will have a reduced water requirement to achieve a given consistency. Secondly, the spherical shape and the smooth surface of fly ash particles help to reduce the interparticle friction and thus facilitates mobility. Thirdly, the “particle packing effect” is also responsible for the reduced water demand in plasticizing the system. It may be noted that both portland cement and fly ash contribute particles that are mostly in the 1 to 45 μm size range, and therefore serve as excellent fillers for the void space within the aggregate mixture. In fact, due to its lower density and higher volume per unit mass, fly ash is a more efficient void-filler than portland cement.

4.2.4 Air content and fresh density

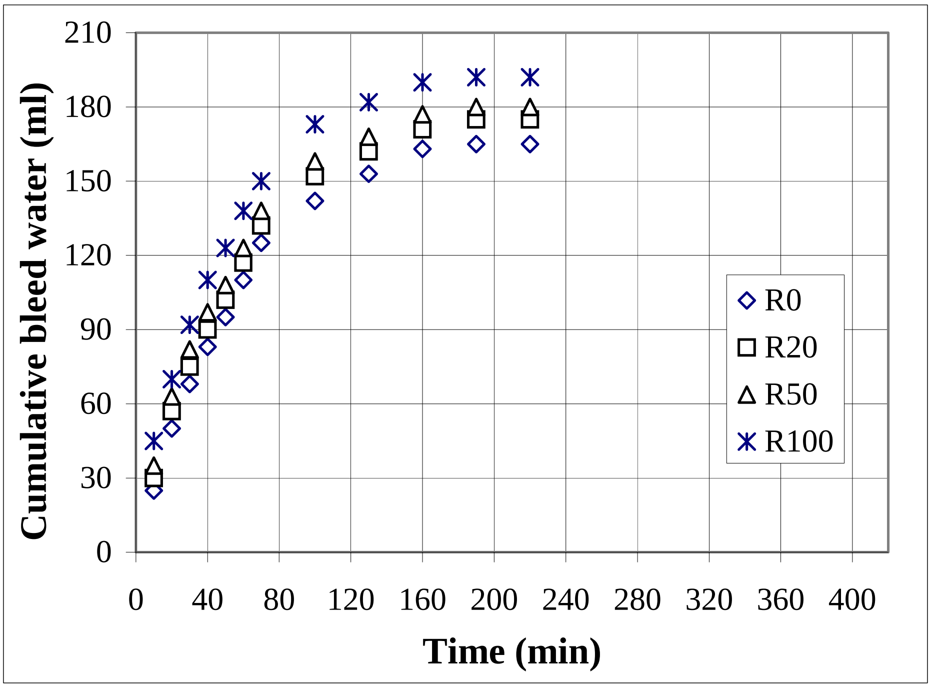
The air content and fresh density of conventional and recycled aggregates concrete in both series are shown in Table 4-3. Each presented value is the average of two measurements. It can be seen from Table 4-3 that the air content of the concrete in both series was increased with an increase in the recycled 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.

The relative air content indicated in Figure 4-15 was the ratio of the air content of the fresh concrete to that of the conventional aggregate in series I. Figure 4-15 shows that the cement replacement by fly ash decreased the air content of the conventional and recycled aggregate concrete. This is might due to the spherical particle shape of fly ash helped to improving workability.

It can be obtained from Table 4-3 that the fresh density of the concrete in both series is decreased with in 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



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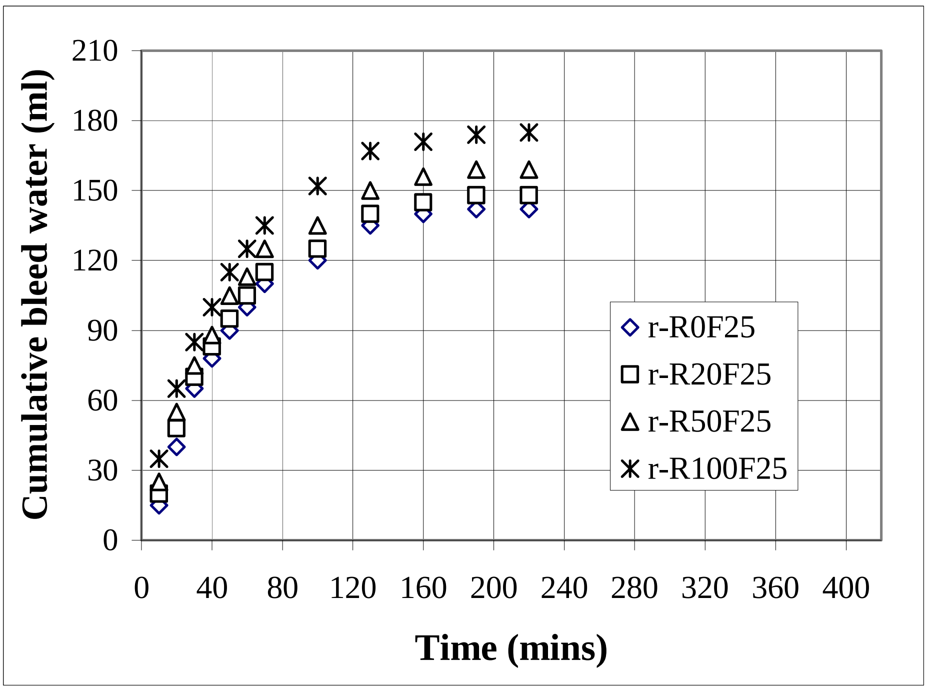
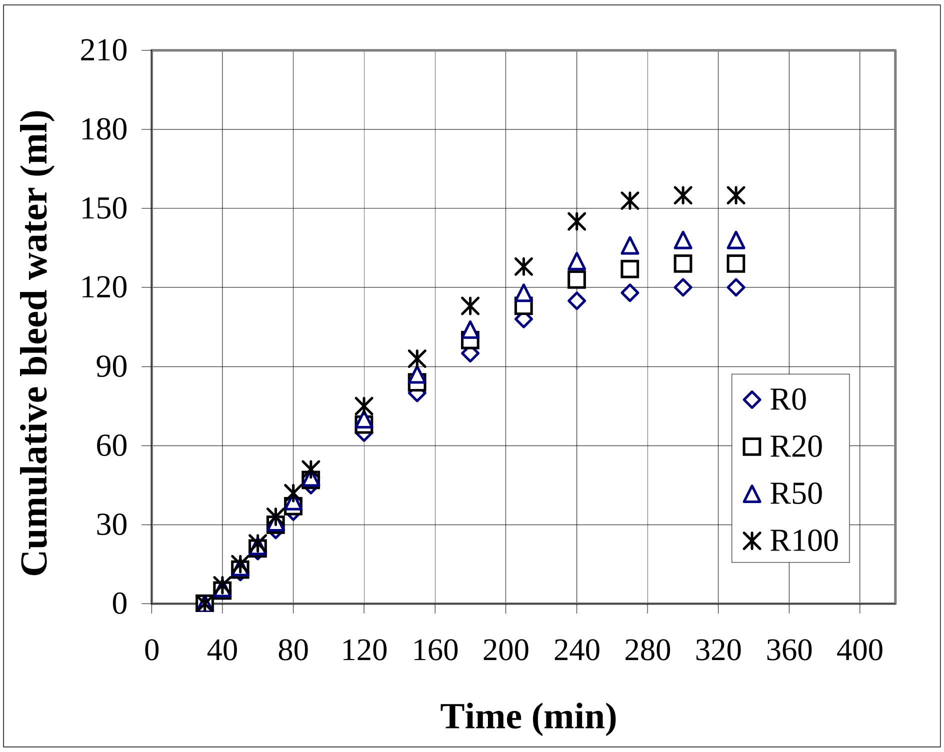


(b)

Figure 4-7 Cumulative bleeding curves of Series I mix, Tests started immediately after mixing (a) without fly ash and (b) with 25% fly ash



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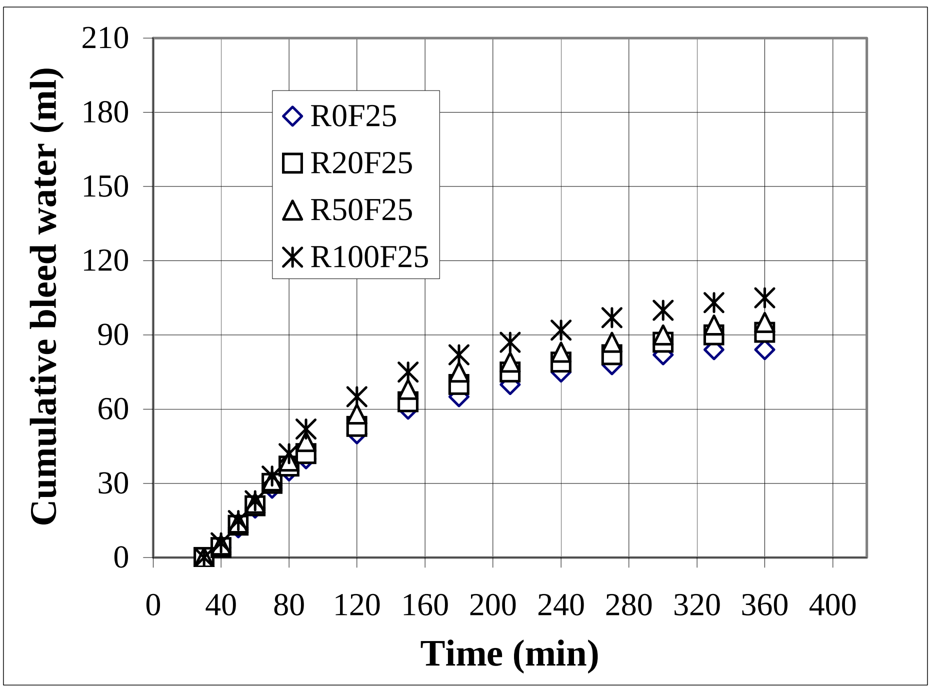
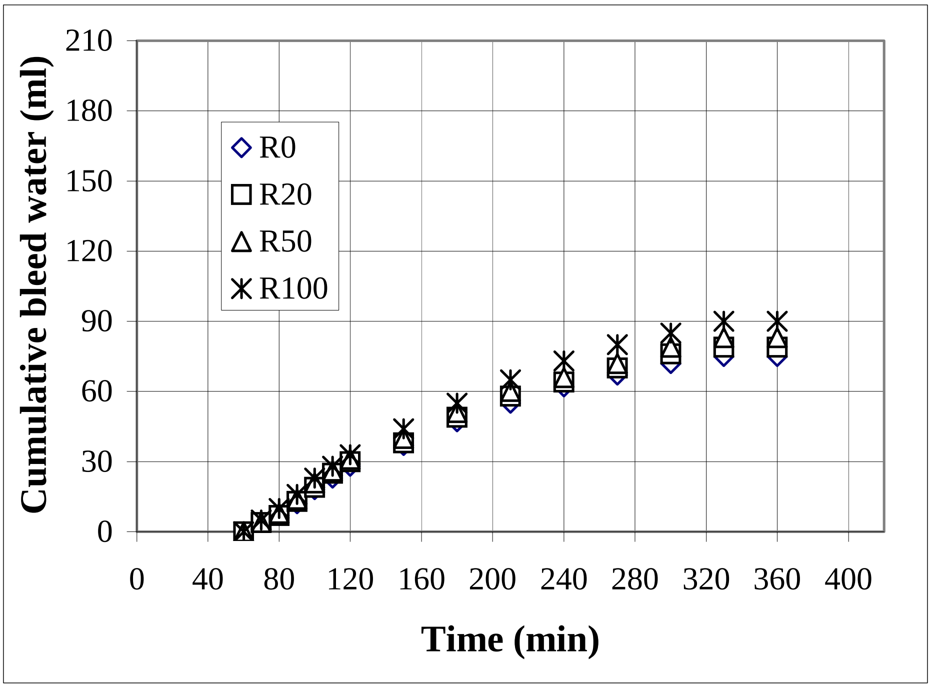


(b)

Figure 4-8 Cumulative bleeding curves of Series I mix, Tests started at 30 minutes after mixing (a) without fly ash and (b) with 25% fly ash



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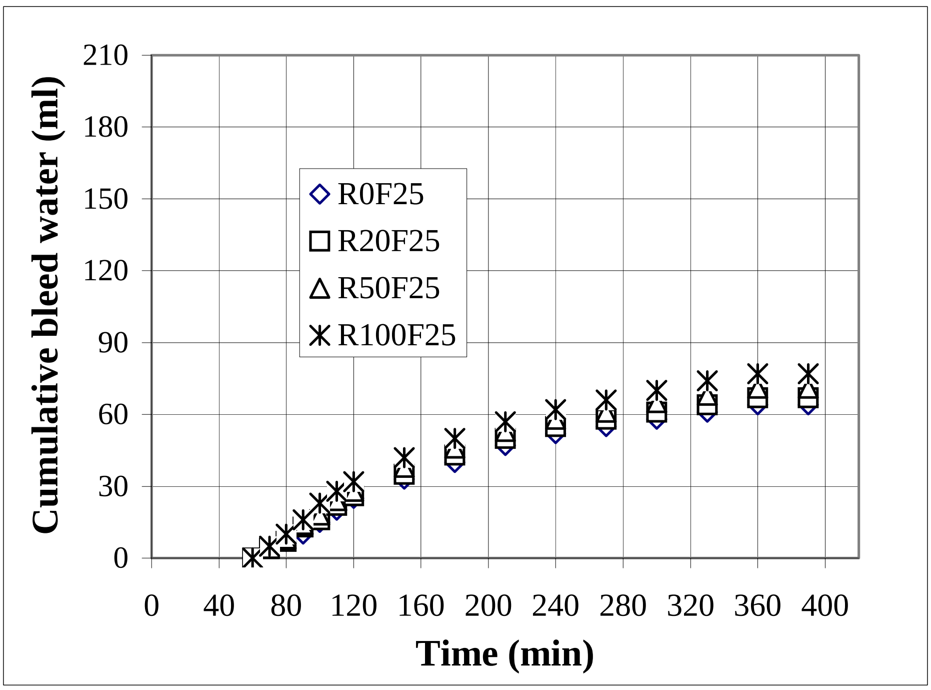
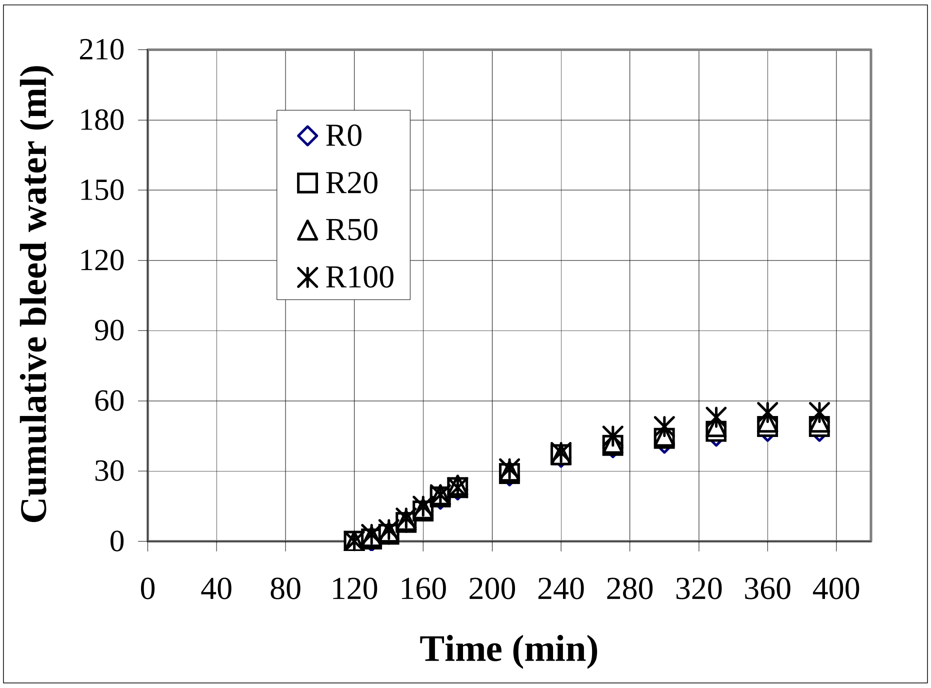
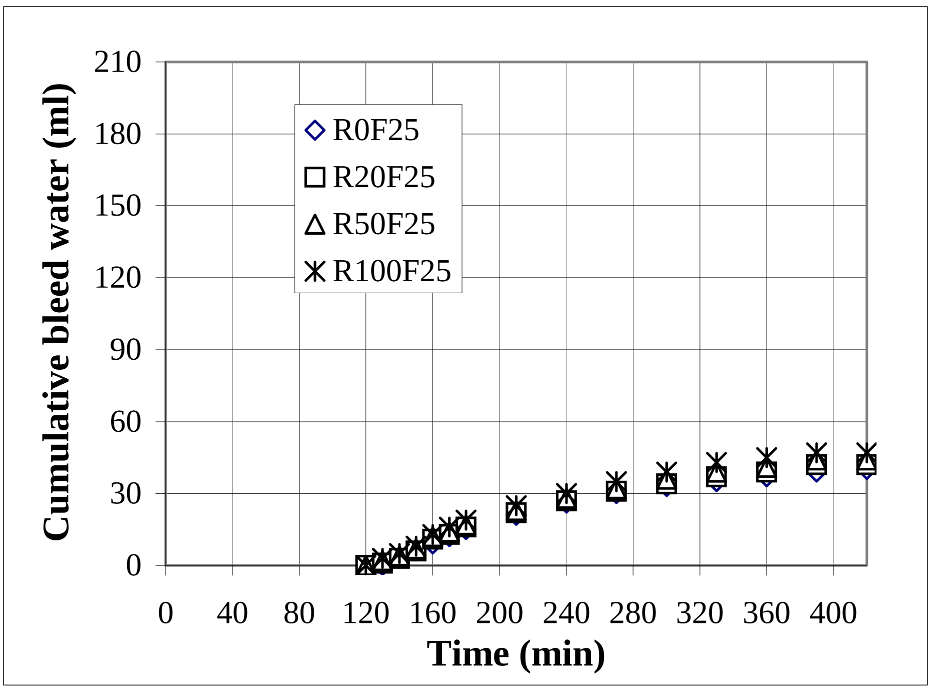


(b)

Figure 4-9 Cumulative bleeding curves of Series I mix, Tests started at 60 minutes after mixing (a) without fly ash and (b) with 25% fly ash

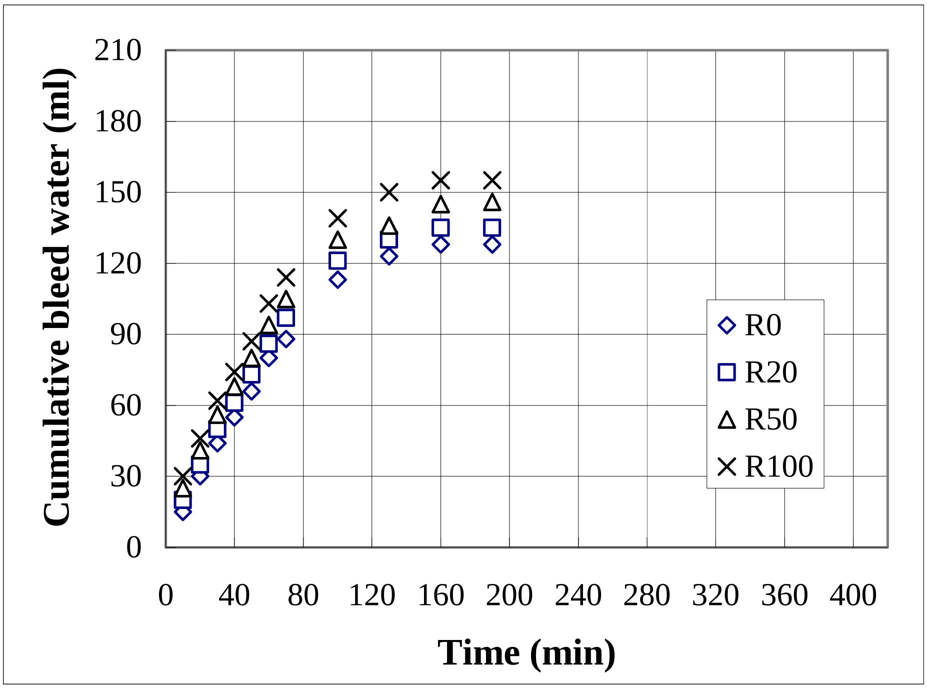


(a)

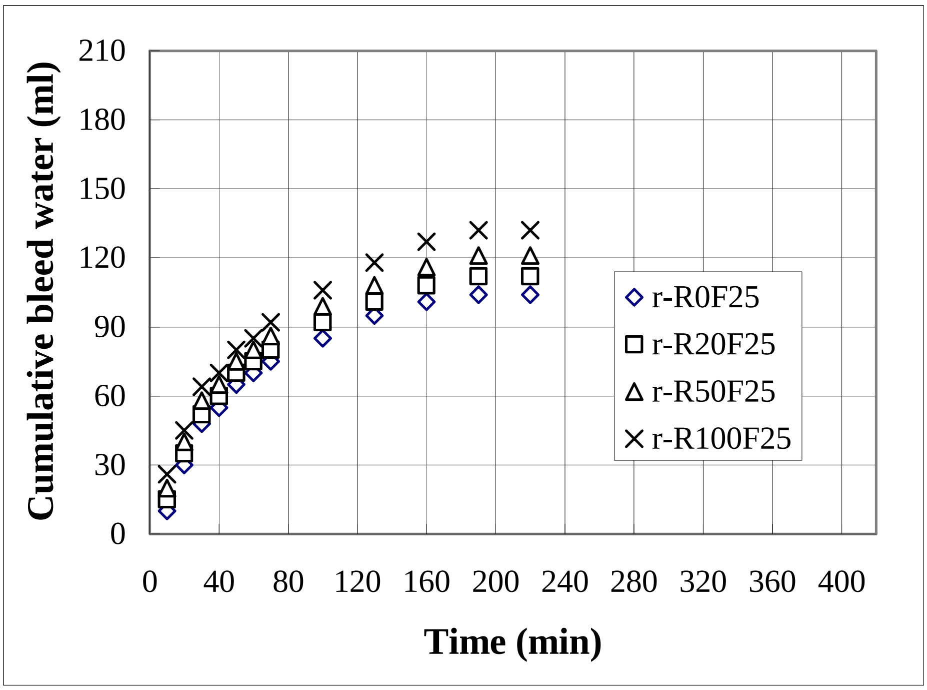


(b)

Figure 4-10 Cumulative bleeding curves of Series I mix, Tests started at 120 minutes after mixing (a) without fly ash and (b) with 25% fly ash

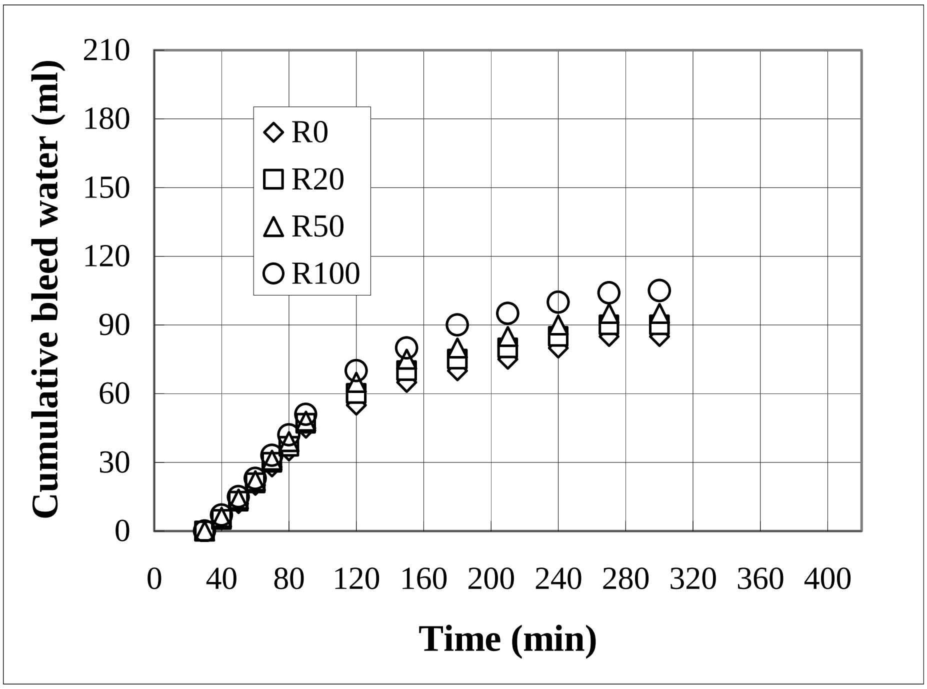


(a)

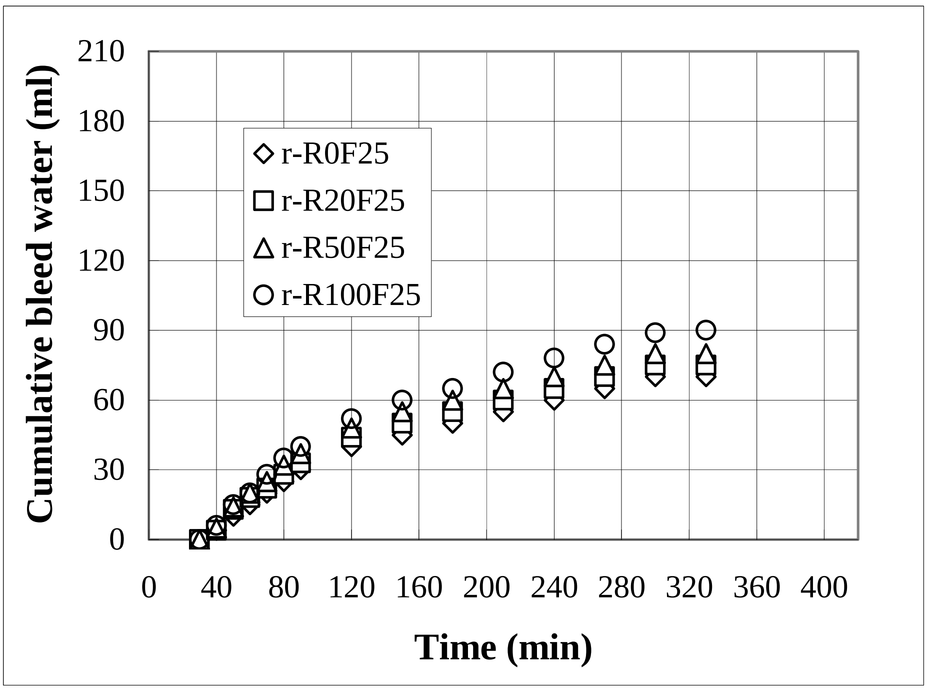


(b)

Figure 4-11 Cumulative bleeding curves of Series II mix, Tests started immediately after mixing (a) without fly ash and (b) with 25% fly ash

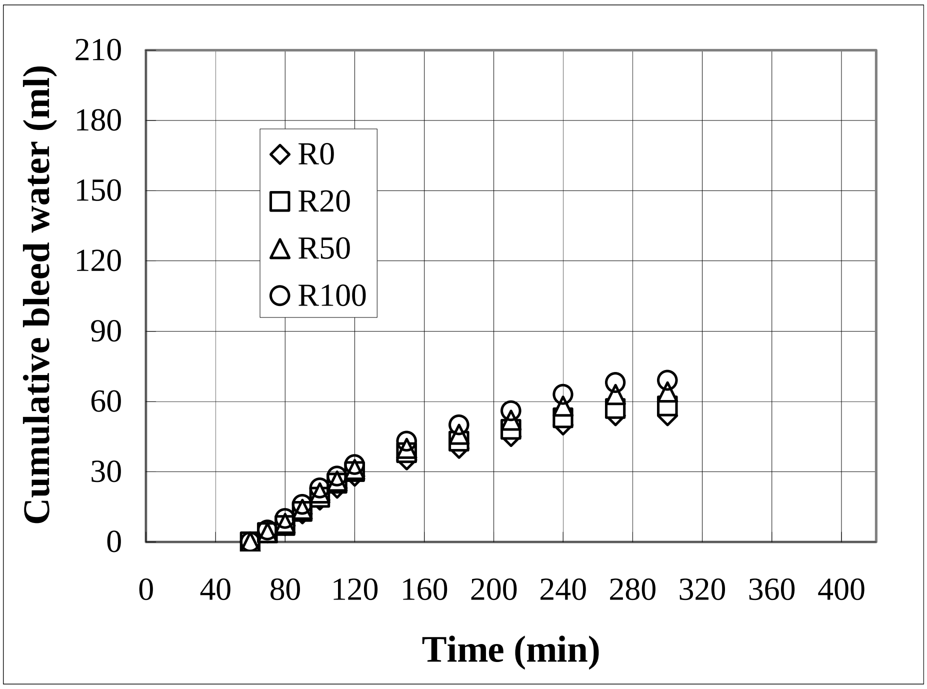


(a)



(b)

Figure 4-12 Cumulative bleeding curves of Series II mix, Tests started at 30 minutes after mixing (a) without fly ash and (b) with 25% fly ash



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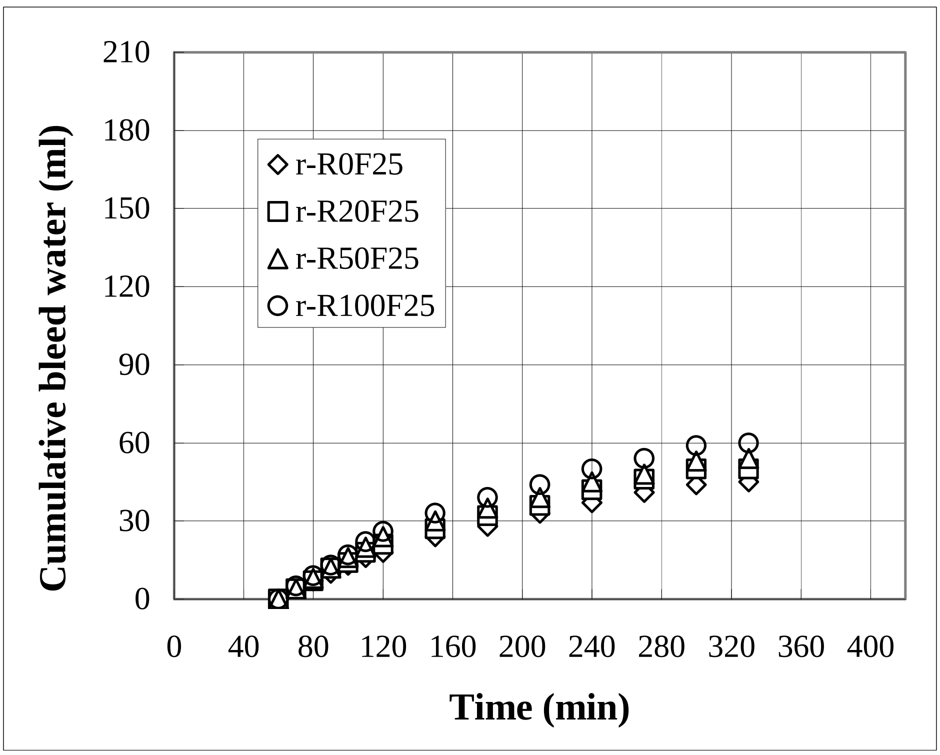
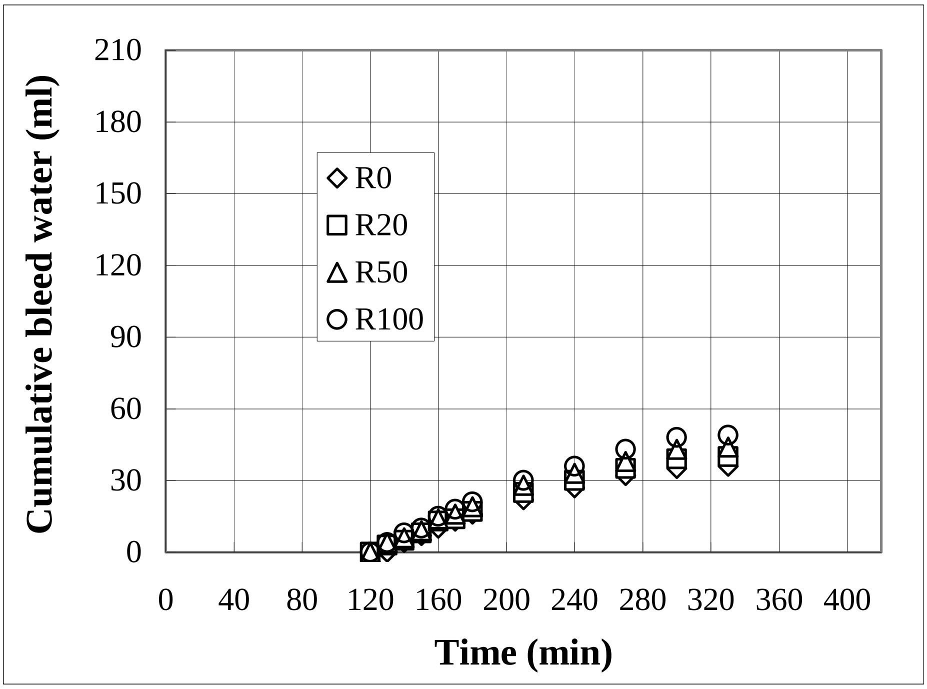
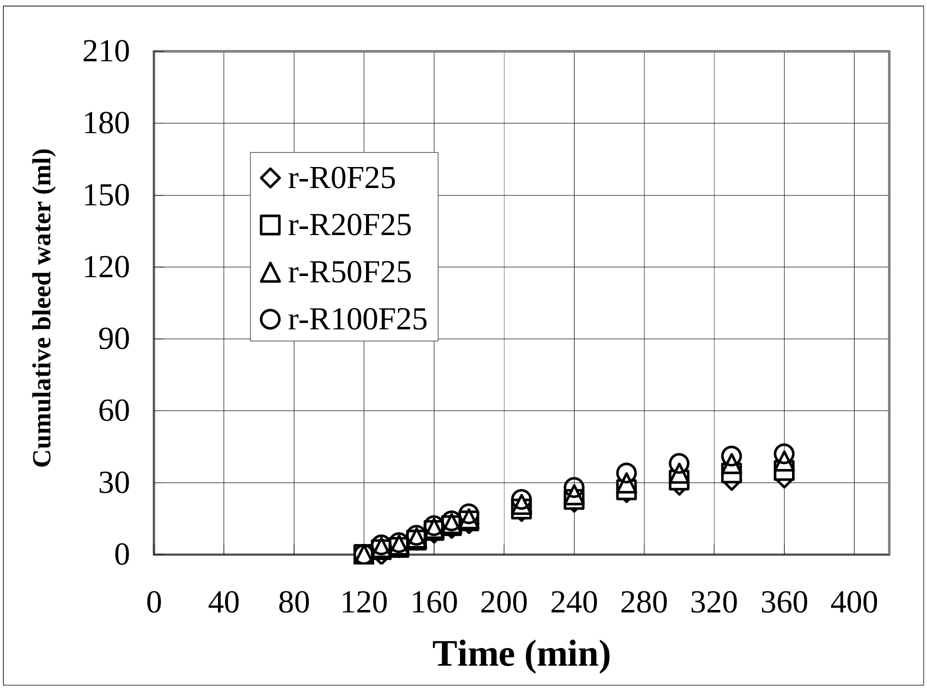


(b)

Figure 4-13Cumulative bleeding curves of Series II mix, Tests started at 60 minutes after mixing (a) without fly ash and (b) with 25% fly ash



(a)



(b)

Figure 4-14 Cumulative bleeding curves of Series II mix, Tests started at 120 minutes after mixing (a) without fly ash and (b) with 25% fly ash

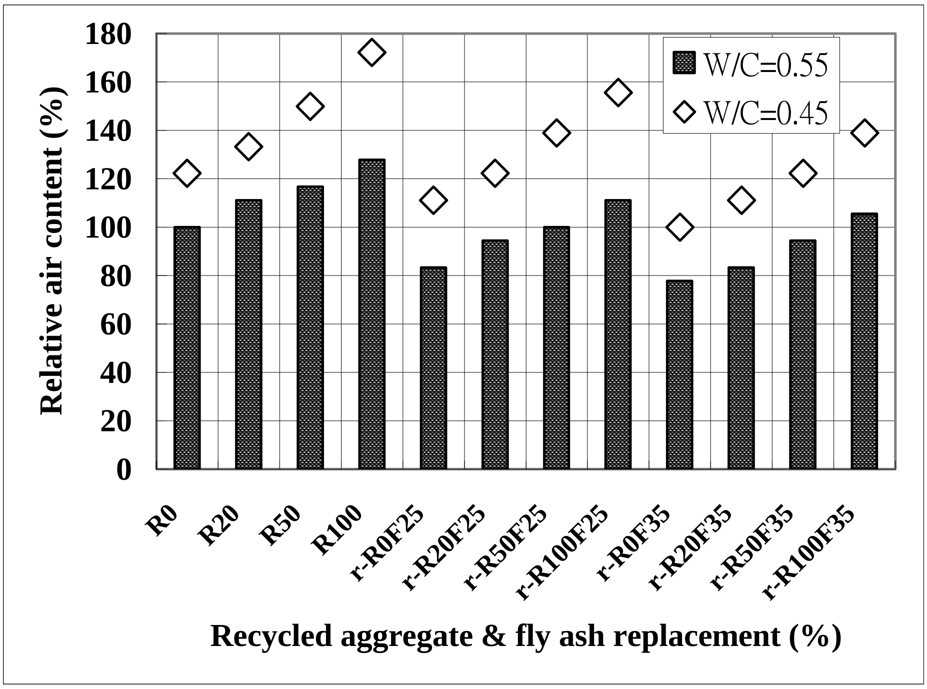


Figure 4-15 Relative air content of concrete mixture in Series I and Series II

4.2.5 Comparison of compressive strength of concretes cast with and without the removal of bleed water

A comparison of compressive strength of concrete mixture determined on specimen prepared with and without bleed water removed at 28 days and 90 days is shown in Table 4-4 and Table 4-5, respectively. Each value is the average of three measurements.

The compressive strength of concrete with bleed water removed was increased. This is due to the removed bleed water decreased the free water in the concrete mixtures. So in the case of using the recycled aggregate in the SSD or pre-wetted 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 suitably adjusted, taking into account the possible reduction in concrete compressive strength.

Table 4-4 Compressive strength of concrete mixes cast with and without the removal of bleed water (Series I)

Notation	Recycled aggregate (%)	Fly ash (%)	Compressive strength (MPa)			
			No bleed water removed		with bleeding water removed	
			28 days	90 days	28 days	90 days
R0	0	0	48.6	52.7	52.9	57.3
R20	20	0	45.3	50.8	50.1	55.6
R50	50	0	42.5	49.5	47.8	53.4
R100	100	0	38.1	45.5	43.5	50.1
r-R0F25	0	25	43.6	57.9	47.5	62.2
r-R20F25	20	25	42.8	57.3	45.7	60.1
r-R50F25	50	25	41.7	53.4	44.2	57.3
r-R100F25	100	25	36.8	50.1	41.2	54.2

Table 4-5 Compressive strength of concrete mixes cast with and without the removal of bleed water (Series II)

Notation	Recycled aggregate (%)	Fly ash (%)	Compressive strength (MPa)			
			No bleed water removed		with bleed water removed	
			28 days	90 days	28 days	90 days
R0	0	0	66.8	72.3	69.3	74.5
R20	20	0	62.4	68.0	65.8	70.5
R50	50	0	56.8	61.5	59.4	65.8
R100	100	0	52.1	57.2	55.3	60.6
r-R0F25	0	25	54.4	69.0	57.6	72.5
r-R20F25	20	25	49.7	68.7	53.4	70.1
r-R50F25	50	25	44.3	65.2	47.8	68.4
r-R100F25	100	25	39.5	52.3	44.3	57.6

4.3 SUMMARY

This chapter presented the experimental results of the properties of fresh concrete prepared with recycled aggregates. The following conclusions can be drawn based on the results of the investigation:

- 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.

- 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.

- The replacement of cement by 25% fly ash increased the slump of concrete mixtures with and without recycled aggregates.

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

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

- The replacement of cement by 25% fly ash decreased the air content of concrete mixtures with and without recycled aggregates. This due to the spherical particle shape of fly ash participates in improving workability of fly ash concrete because of the so-called "ball bearing" effect.

- The compressive strength of concrete after bleed water was removed was increased. 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.

CHAPTER 5 INFLUENCE OF FLY ASH ON HARDENED PROPERTIES OF RECYCLED AGGREGATE CONCRETE

5.1 INTRODUCTION

In this chapter, the results of the use of fly ash as a cement replacement of concrete mixture in Series I, and II and as an additional mineral admixture of concrete mixture in Series III, IV, V, and VI in proportioning the recycled aggregate concrete are presented. The effects of fly ash on the compressive strength, tensile splitting strength, static modulus of elasticity, drying shrinkage, creep and resistance to chloride-ion penetration on the recycled aggregate concrete were presented and discussed.

5.2 TEST RESULT AND DISCUSSIONS

5.2.1 Use of fly ash as a substitution of cement

Compressive and tensile splitting strengths

The compressive strength results are presented in Table 5-1 and Table 5-2 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 5-1 and Table 5-2 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 5-1 - 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

The results of the tensile splitting strength of concrete in Series I and II are presented in Table 5-3 and table 5-4 respectively. Each presented value is the average of three measurements. It is shown in Figure 5-1 that the 28-day splitting tensile strength of the concrete mixtures decreased with an increase in the recycled aggregate content. 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 5-2 - 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

Table 5-3 - 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 5-4 - Splitting tensile strengths of concrete mixtures in Series II

Notation	Fly ash (%)	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

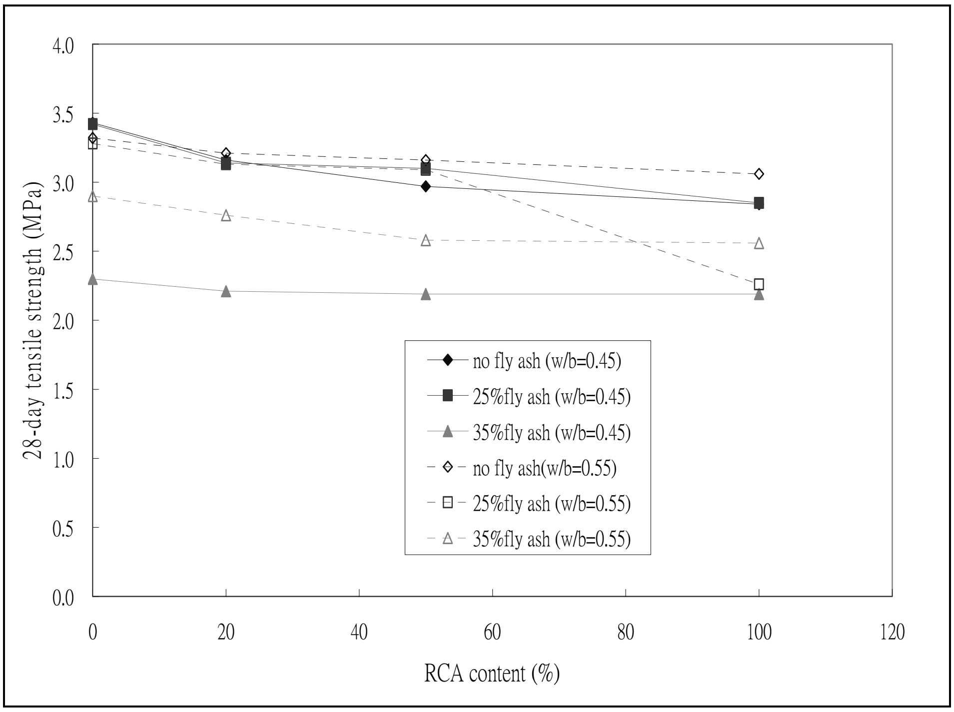
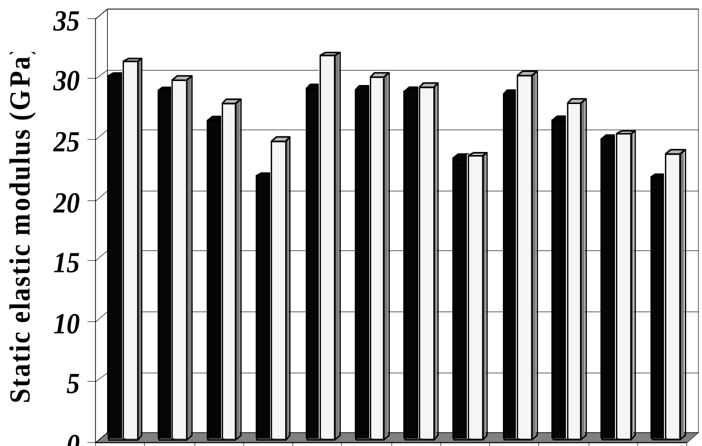


Figure 5-1 – The effects of the incorporation of recycled aggregate on the 28-day splitting tensile strength

Static modulus of elasticity

The static modulus of elasticity values of the concrete mixtures in Series I and II are presented in Figure 5-2 and Figure 5-3 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. However, the magnitude of the reduction in the elastic modulus shrank as the fly ash content increased. For the concrete prepared with 35 % fly ash, the reduction in the elastic modulus, when the recycled aggregate content increased from 0 to 100 %, of the concrete mixtures in Series I and II was 26 and 24 % respectively. Furthermore, at the same recycled aggregate content, the static modulus of elasticity values of the concrete decreased as the fly ash content increased. However, the influence of fly ash on the static modulus of elasticity of concrete prepared with 100 % recycled aggregate was negligible. Also, a higher W/B ratio led to a lower the static modulus of elasticity of recycled aggregate concrete and conventional concrete.

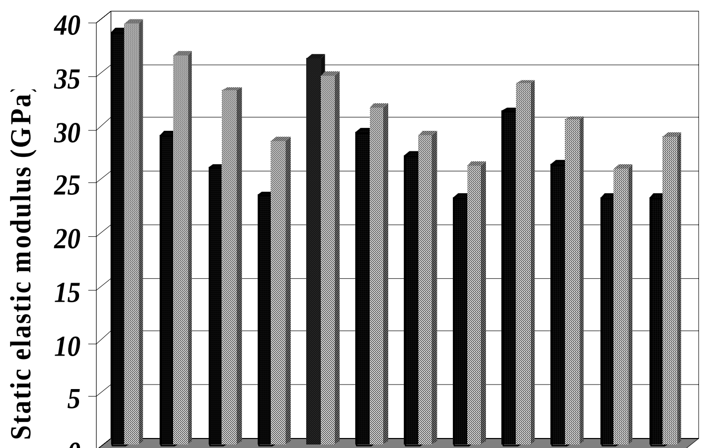
Figure 5-4 shows the relationship between the 28-day compressive strength and the 28-day static modulus of elasticity. The equation suggested by ACI for predicting the modulus of elasticity is also plotted in the graph. It is shown that the ACI equation slightly over-estimates the modulus of elasticity of the recycled aggregate concrete. In other words, the predicted deformation of a structural concrete member prepared with recycled aggregate would be smaller than the actual value.



	R0	R20	R50	R100	R0F25	R20F25	R50F25	R100F25	R0F35	R20F35	R50F35	R100F35
28-day	30	28.8	26.3	21.7	29	28.9	28.7	23.2	28.5	26.3	24.8	21.6
90-day	31.2	29.7	27.8	24.7	31.7	29.9	29.1	23.4	30.1	27.8	25.2	23.6

Recycled aggregate and fly ash content (%)

Figure 5-2 - Static elastic modulus of the concrete mixtures in Series I



	R0	R20	R50	R100	R0F25	R20F25	R50F25	R100F25	R0F35	R20F35	R50F35	R100F35
28-day	38.7	29.1	26	23.4	36.3	29.3	27.1	23.2	31.3	26.3	23.2	23.2
90-day	39.5	36.5	33.2	28.5	34.6	31.6	29.1	26.2	33.9	30.5	25.9	28.9

Recycled aggregate and fly ash content (%)

Figure 5-3 - Static elastic modulus of the concrete mixtures in Series II

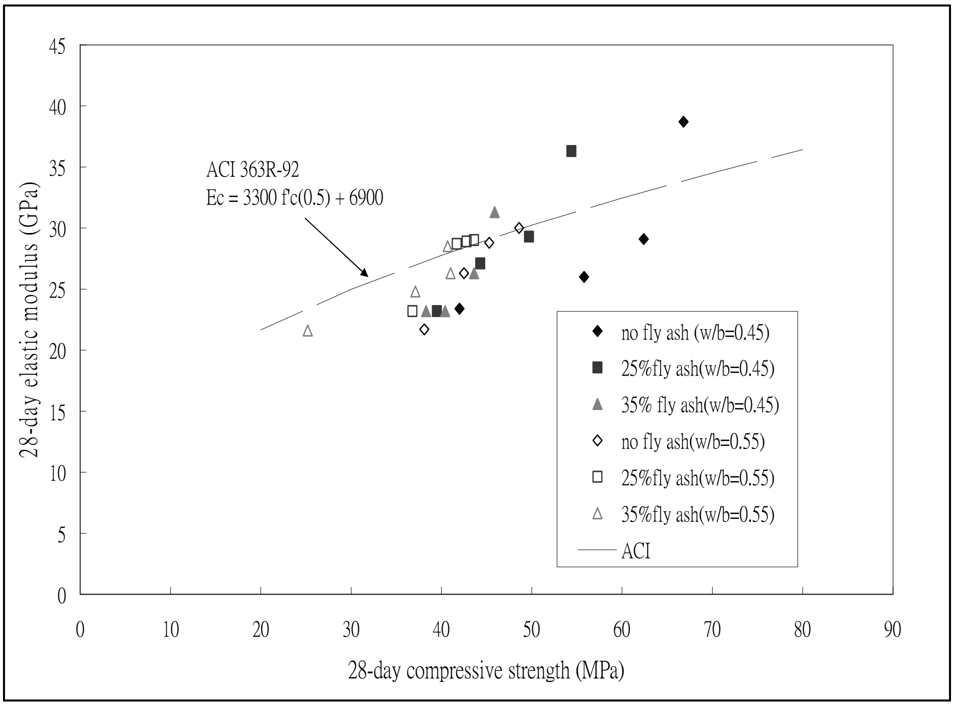


Figure 5-4 – Relationship between 28-day compressive strength and 28-day elastic modulus

Drying shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures are shown in Figure 5-5 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.

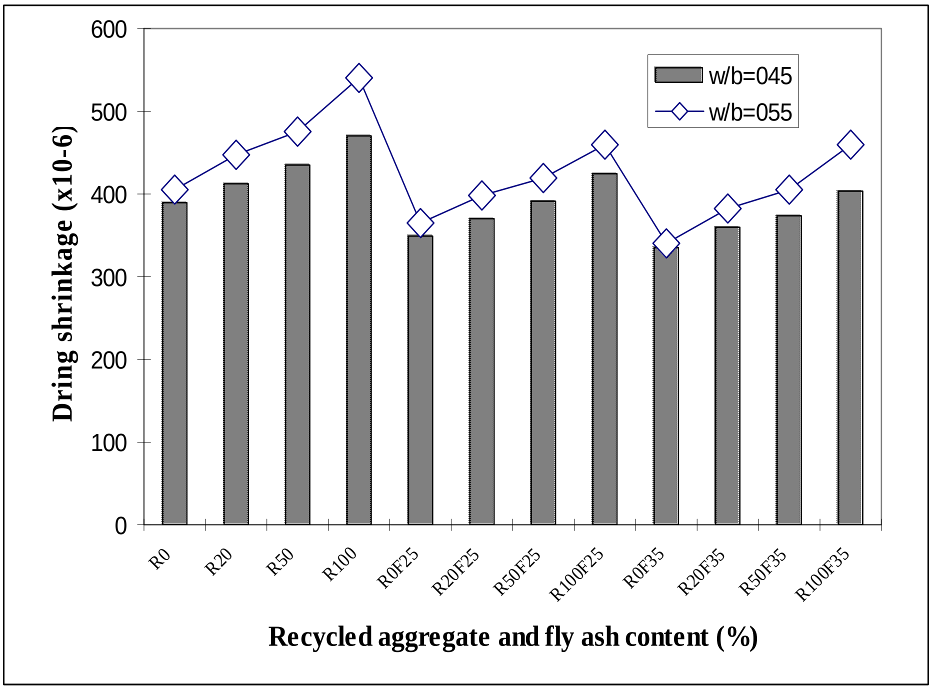


Figure 5-5 - Drying shrinkage of the concrete mixtures in Series I and II

Creep strain

Figure 5-6 and Figure 5-7 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.

Chloride penetrability

The resistances to chloride ion penetration of the concrete mixtures in Series I and II are shown in Figure 5-8 and Figure 5-9, respectively. The results show that the resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, at the same recycled aggregate replacement level, the use of fly ash as a partial replacement of cement increased the resistance to chloride ion penetration. According to Leng et al. (2000), the reasons of the enhanced resistance to chloride ion penetration were: 1) the use of fly ash improved the distribution of pore size and pore shape of concrete, 2) more C-S-H products were formed as fly ash hydrated, which absorbed more chloride ions and blocked the ingress path and 3) the presence of C_3A in fly ash could absorb more chloride ions to form Friedel's salt ($C_3A.CaCl_2.10H_2O$).

Furthermore, it is shown that the reduction in the W/B ratio (a comparison between Figure 5-8 and Figure 5-9) increased the resistance to chloride ion penetration. Since the volume of pores within a concrete reduced as the W/B ratio decreased, the concrete became more impermeable and the resistance to chloride ion penetration increased accordingly. These results also agree with those reported by Leng et al. (2000). Moreover, it was found that the resistance increased as the curing age increased from 28 to 90 days. It was due to the increase in the volumes of hydration products (Mindess et al. 2003), thus forming impermeable regions and increasing the resistance to chloride ion penetration.

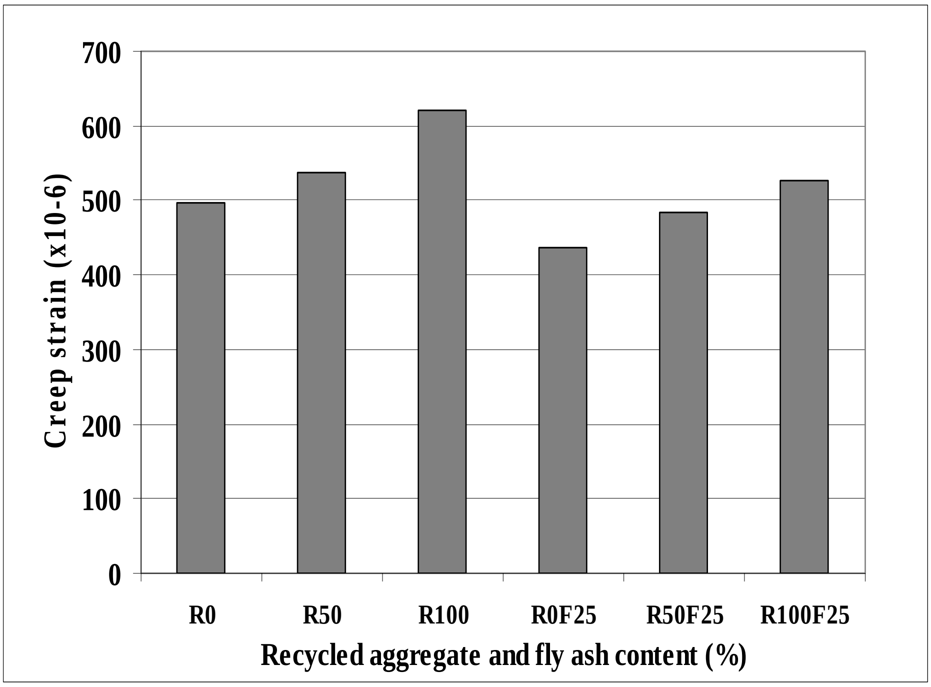


Figure 5-6 - Creep strain at 120 days of the concrete mixtures in Series II

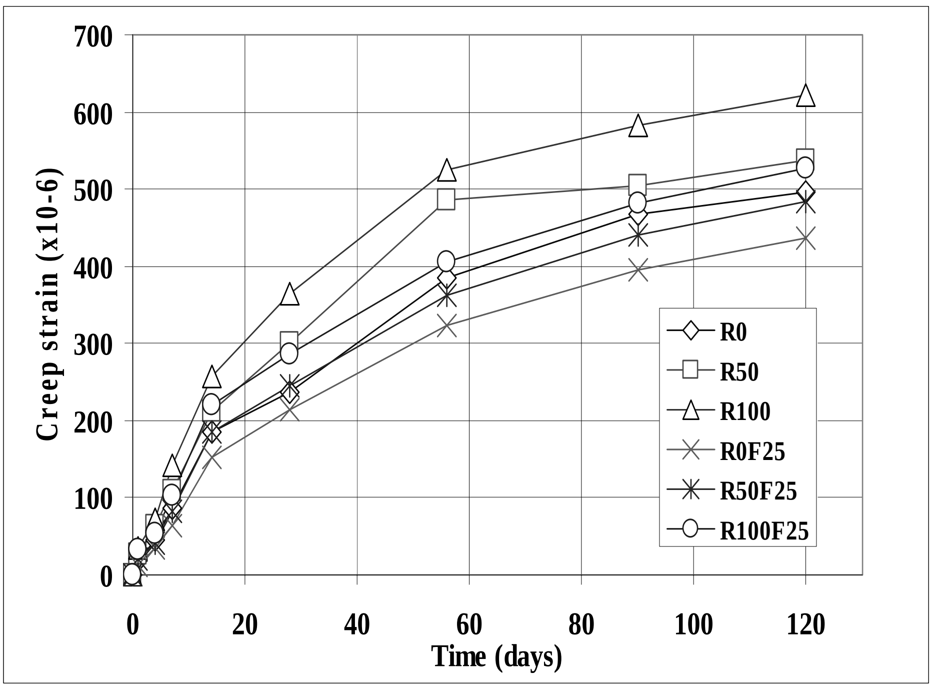


Figure 5-7 - Creep strain vs. time since loading of the concrete mixtures in Series II

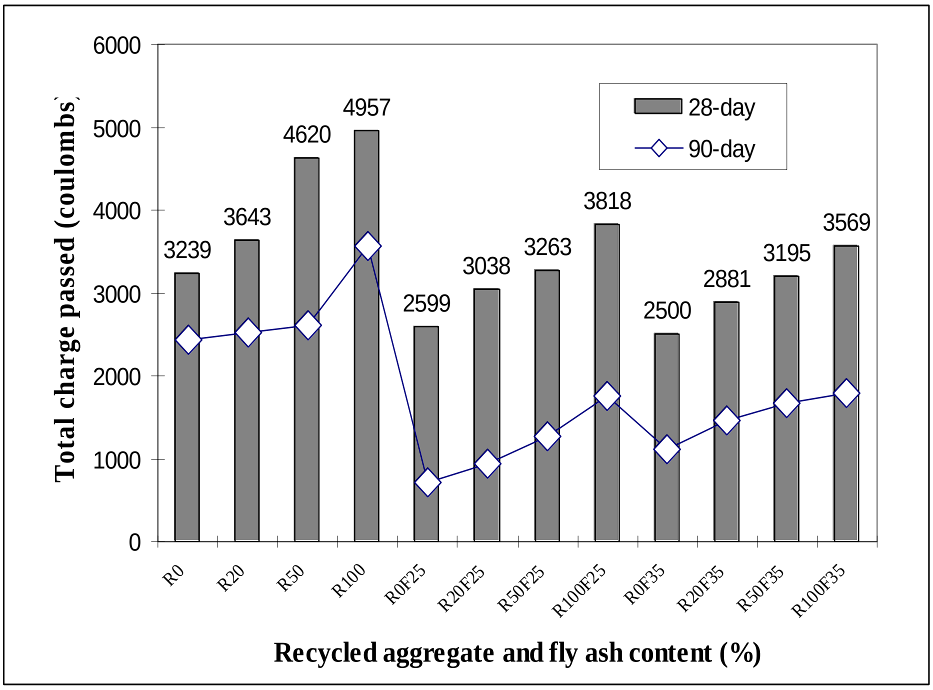


Figure 5-8 - Chloride-ion penetration of the concrete mixtures in Series I

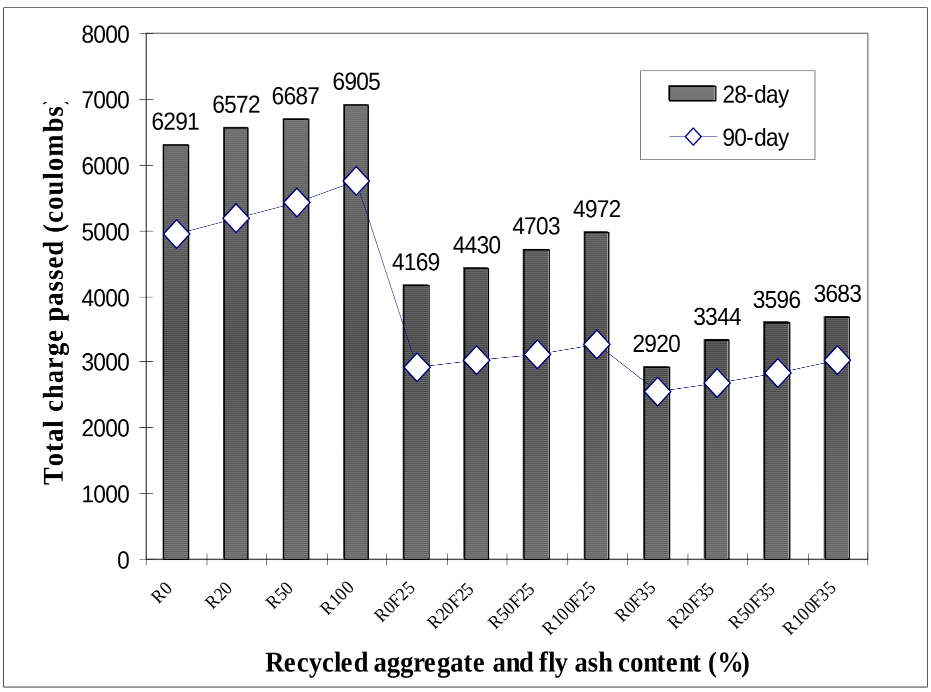


Figure 5-9 - Chloride-ion penetration of the concrete mixtures in Series II

5.2.2 Use of fly ash as an additional mineral admixture

Compressive strength

The compressive strength results of the concrete mixture in Series III, IV, V and VI are presented in Table 5-5, Table 6-6, Table 5-7 and Table 5-8, respectively. Each presented values is the average of three measurements. It can be seen from Table 5-5, Table 5-6, Table 5-7 and Table 5-8 that at the all test age the compressive strength of recycled aggregate concrete in Series III, IV, V and VI 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, V and VI, 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. This is consistent with the results of Topcu et al (2004), and Dhir et al (2004).

Fly ash was used as an additional mineral admixture by cement weight of 25% and 35% were increased the compressive strength of conventional and recycled aggregates concrete at all test age. It can be seen from Table 5-5 that there is increase in strength with increase in fly ash percentages. At 28 days, the compressive strength of concrete made with 100% recycled aggregate and additional 25% and 35% of fly ash was increased by 18.9% and 43.0% compared with corresponding concretes without fly ash in Series III, respectively. It also obtained that from Table 5-6, Table 5-7 and Table 5-8 that at 28 days, the concrete made with 100% recycled aggregate and additional 25% of fly ash had an increase of 18.0%, 17.3% and 17.4% in compressive strength compared with corresponding concrete without fly ash in Series IV, V, and VI, respectively. The results at 90 days indicated that there was continuous significant improvement in strength beyond the age of 28days. At 90 days, the compressive strength of concrete made with 100% recycled aggregate and 25% fly ash was higher 43.7%, 41.0%, 24.0% and 28.1% than those corresponding concrete without fly ash in Series III, IV, V and VI, respectively. This increase in strength due to the additional fly ash is attributed to: 1) the water-to-binder ratio was decreased; and 2) the pozzolanic action of fly ash.

It clearly that fly ash was used as an additional mineral admixture in concrete were significant decreased the water-to-binder ratio of the concrete (see Table 5-5, Table 5-6, Table 5-7 and Table 5-8). For example, in Series III concrete mixture, additional of 25% fly ash, the water-to-binder ratio of concrete from 0.55 decreased to 0.44. When fly ash was added of 35% by cement weight in the concrete, the water-to-binder ratio of concrete mixture was 0.41.

Table 5-5 – 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

Another reason for additional fly ash to increase strength of the concrete is the pozzolanic action of fly ash. In the beginning (early age), fly ash reacts slowly with calcium hydroxide liberated during hydration of cement and does not contribute significantly to the densification of the concrete matrix at early ages. Concrete with fly ash shows higher strength at early ages because inclusion of fly ash as partial replacement of sand and aggregate starts pozzolanic action and densification of the concrete matrix, and due to this strength of fly ash concrete is higher than the strength of concrete without fly ash even at early ages.

The ratio of the compressive strength of the concrete to that of the Series III of natural aggregate concrete without fly ash at 28 days are shown Figure 5-10. It can be found from Figure 5-10 that the reduction in the W/C ratio increased the compressive strength of the conventional and recycled aggregate concrete. The compressive strength of concrete made with 100% recycled aggregate and without fly ash in Series III with W/C ratio of 0.55 was lower 21.6% than that corresponding natural aggregate concrete. However, at the same recycled aggregate replacement level, the strength of the concrete in Series VI mixture with W/C ratio of 0.40 was higher 20.4% than that the natural aggregate concrete with W/C of 0.55. Similar results were obtained for the concrete mixture with fly ash in the all series concrete mixtures. Therefore, 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.

Table 5-6 – 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 5-7 – 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 splitting tensile strength of concrete mixtures in Series III, IV, V and VI 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 5-9, Table 5-10, Table 5-11 and Table 5-12, respectively. Each presented value is the average of three measurements. It can be seen from Table 5-9, Table 5-10, Table 5-11 and Table 5-12 that at the all test age the splitting tensile strength of recycled aggregate concrete in Series III, IV, V and VI 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%, 11.7% and 13.4% compared with those corresponding conventional aggregate concrete in Series III, IV, V and VI, respectively. This is consistent with the results of Won (1999), and Poon et al (2002).

Table 5-8 – Compressive strength of the concrete mixtures in Series VI

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.40	30.8	49.4	57.1	72.3	78.1
R20	0	20	0.40	28.6	47.6	55.2	69.6	75.2
R50	0	50	0.40	25.3	45.1	53.3	65.3	71.6
R100	0	100	0.40	21.5	36.4	45.4	58.5	64.5
a-R0 F25	25	0	0.32	27.4	53.3	59.3	76.7	82.1
a-R20F25	25	20	0.32	23.6	50.1	57.2	73.9	81.4
a-R50F25	25	50	0.32	22.1	48.7	54.4	70.1	80.1
a-R100F25	25	100	0.32	20.9	45.4	50.9	68.7	82.6

Fly ash was used as an additional mineral admixture by cement weight of 25% and 35% were increased the splitting tensile strength of conventional and recycled aggregates concrete at all test age. It can be seen from Table 5-9 that there is increase in splitting tensile strength with the increase in fly ash percentages. For example, at 28 days, the splitting tensile strength of concrete made with 100% recycled aggregate and additional 25% and 35% of fly ash was increased by 2.6% and 5.9% compared with that concrete without fly ash in Series III, respectively. It also obtained that from Table 5-10 and Table 5-11 that at 28 days, the splitting tensile strength of concrete made with 100% recycled aggregate and additional 25% of fly ash had an increase of 2.6% and 3.9% compared with those concrete without fly ash in Series IV, and V, respectively. At 90 days, the splitting tensile strength of concrete made with 100% recycled aggregate and with 25% fly ash was higher 3.1%, 6.1%, 7.4% and 7.2% than those concrete without fly ash in Series III, IV, V and VI, respectively.

It can be seen from Figure 5-11 that the reduction in the W/C ratio increased the splitting tensile strength of conventional and recycled aggregate concrete. At 28 days, the splitting tensile strength of concrete made with 100% recycled aggregate and without fly ash in Series III with W/C ratio of 0.55 was 3.06 MPa, However, at the same recycled aggregate replacement level, the splitting tensile strength of the concrete in Series VI with W/C ratio of 0.40 was 3.59 MPa; an increase of 14.8% in comparison with the strength of the concrete mixture R100 in Series III with W/C ratio of 0.55.

It is evident from Table 5-12 that before the age of 28 days, fly ash was used as an additional mineral admixture decreased the splitting tensile strength of the conventional and recycled aggregate concrete. However, at the age of 90 days the splitting tensile strength of concrete with fly ash of all mixtures continued to increase with the age.

Table 5-9 – 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

Static modulus of elasticity

The static modulus of elasticity values of the concrete mixtures at 28 days and 90 days in Series III, IV, V, and VI are presented in Figure 5-12 and Figure 5-13, respectively. Each presented value is the average of two measurements. For the concrete mixtures in Series III, IV, V and VI, 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 without fly ash in Series III, IV, V and VI was about 25%, 21%, 23% and 22 % lower than that natural aggregate concrete in Series III, IV, V and IV, respectively. However, the magnitude of the reduction in the elastic modulus shrank as the fly ash was added. For the concrete prepared with 25 % fly ash, the recycled aggregate content increased from 0 to 100 %, the reduction in the elastic modulus of the concrete mixtures in Series III and VI was about 19% and 11 % respectively.

Table 5-10 – 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 5-11 – 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

It can be seen from Figure 5-12 and Figure 5-13 that the static modulus of elasticity of conventional and recycled aggregate concrete was increased by the additional fly ash. At 28 days, the static modulus of elasticity of concrete made with 100% recycled aggregate and with 25% fly ash in Series III, IV, V, and VI was higher 8.7%, 8.2%, 11.9% and 12.3% than that the concrete without fly ash in these four series.

Table 5-12 – Splitting tensile strength of the concrete mixtures in Series VI

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Splitting tensile strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
R0	0	0	0.40	2.62	3.25	3.39	4.07	4.16
R20	0	20	0.40	2.42	3.04	3.25	3.86	4.12
R50	0	50	0.40	2.36	2.96	3.14	3.69	3.97
R100	0	100	0.40	2.34	2.84	3.09	3.59	3.76
R0 F25	25	0	0.32	2.25	3.12	3.38	3.58	4.96
R20F25	25	20	0.32	2.14	2.87	3.14	3.36	4.34
R50F25	25	50	0.32	2.10	2.40	2.94	3.22	4.18
R100F25	25	100	0.32	2.03	2.47	2.85	3.18	4.05

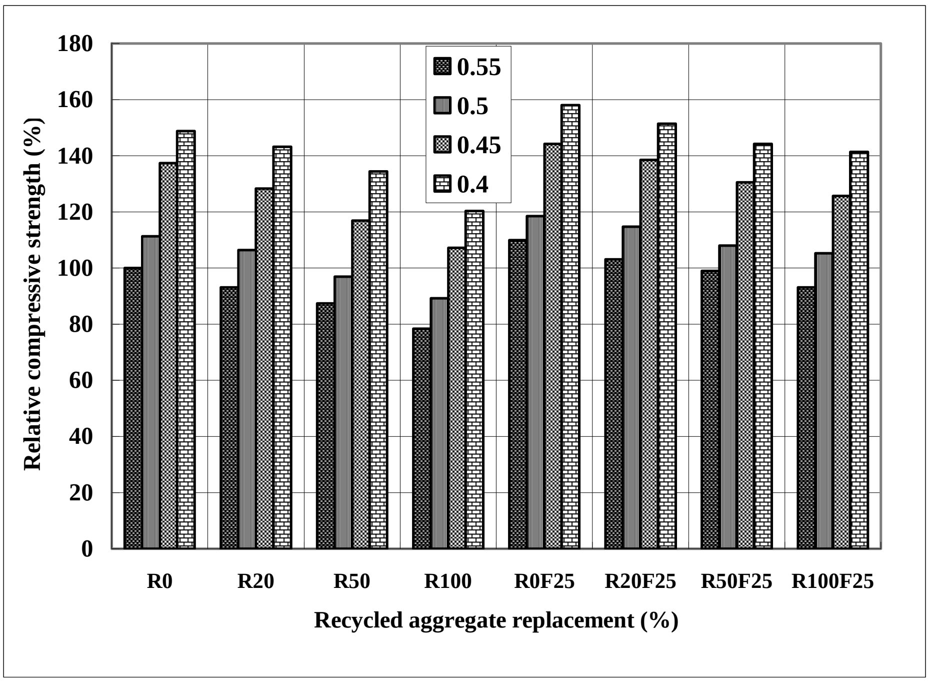


Figure 5-10 - Relative compressive strength of concrete in series III, IV, V and VI mixture at 28 days

It can also be seen from Figure 5-12 and Figure 5-13 that a higher W/B ratio led to a lower the static modulus of elasticity of recycled aggregate concrete and conventional concrete. For example, at 28 days, the static modulus of elasticity of concrete made with

100% recycled aggregate and no fly ash was 24.2 GPa in Series III with water-to-cement ratio of 0.55. However, the static modulus of elasticity of the concrete was 27.9 GPa in Series VI with W/C ratio of 0.40. At 90 days, the results were similar to the age of 28 days. This is due to reduce the W/C ratio of the concrete increased the compressive strength of the concrete. Generally, concrete have higher compressive strength and have higher static modulus of elasticity.

Fly ash was used as an additional mineral admixture increased the static modulus of elasticity of conventional and recycled aggregate concrete could be due to: 1) additional fly ash in concrete reduced the W/C (W/B) ratio; and 2) the result of the unhydrated fly ash particles acting as fine aggregates.

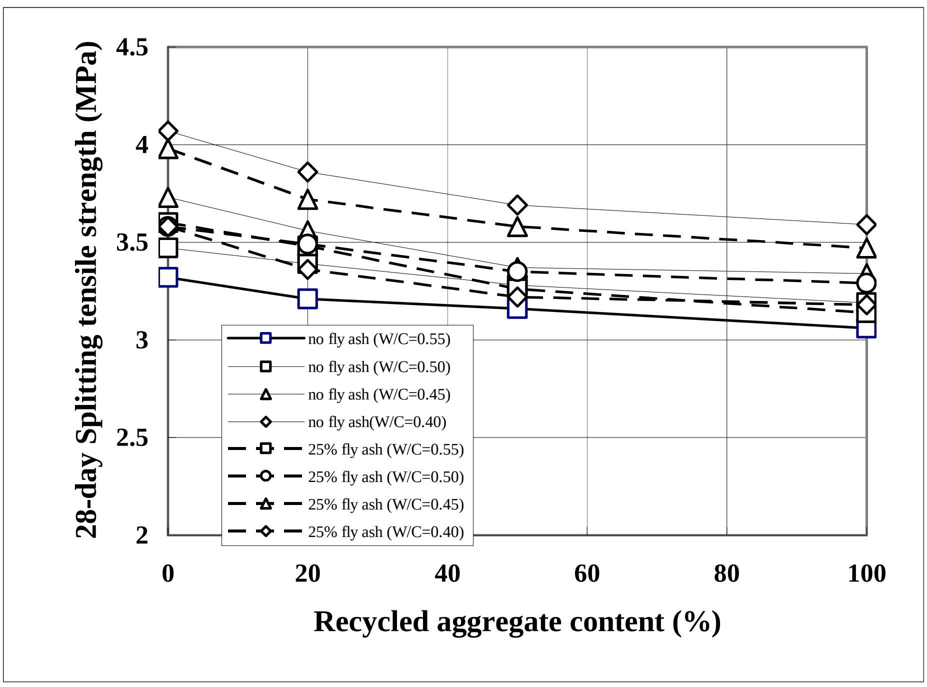


Figure 5-11 The effects of the incorporation of recycled aggregate on the 28 days splitting tensile strength

Drying shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures in Series III, IV V, and VI are shown in Figure 5-14. Each presented value is the average of three measurements. It can be seen from Figure 5-14 that the drying shrinkage value of concrete was increased with recycled aggregate content increased in all four series mixtures. Concrete made with 100% recycled aggregate had largest drying shrinkage value in all series concrete mixtures. 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).This is consistent with the results of Siebel et al (2002), De Pauw et al (1998), and Gomez-Soberon (2001).

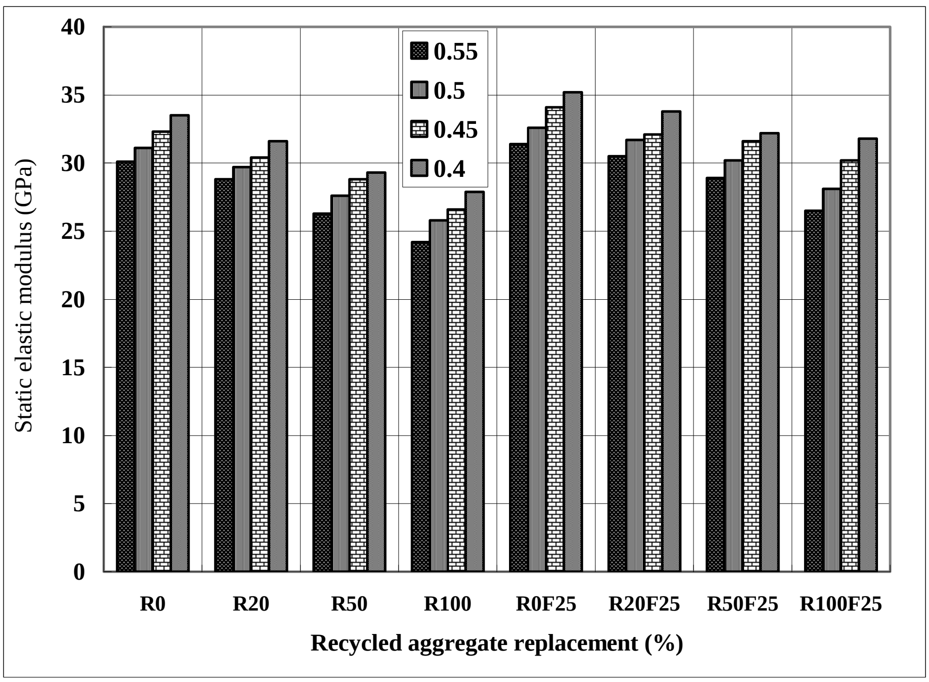


Figure 5-12- Static modulus of elasticity of concrete in four series mixture at 28 days

It was also shown that the reduction in the W/C ratio decreased the drying shrinkage of the concrete in all Series. The drying shrinkage value of concrete in Series VI with W/C ratio of 0.40 was lowest than that of the concrete in other three Series concrete mixtures with W/C ratio of 0.55, 0.50 and 0.45. Since W/C 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 use of fly ash as an additional mineral admixture reduced the drying shrinkage of the conventional and recycled aggregate concrete. Additional fly ash in concrete reduce the drying shrinkage value of concrete could be due to: 1) the water-to-binder ratio of the concrete was reduced; and 2) according to Atis et al. (2004), the reduction in the drying shrinkage was attributed to the dilution effect of the fly ash particles.

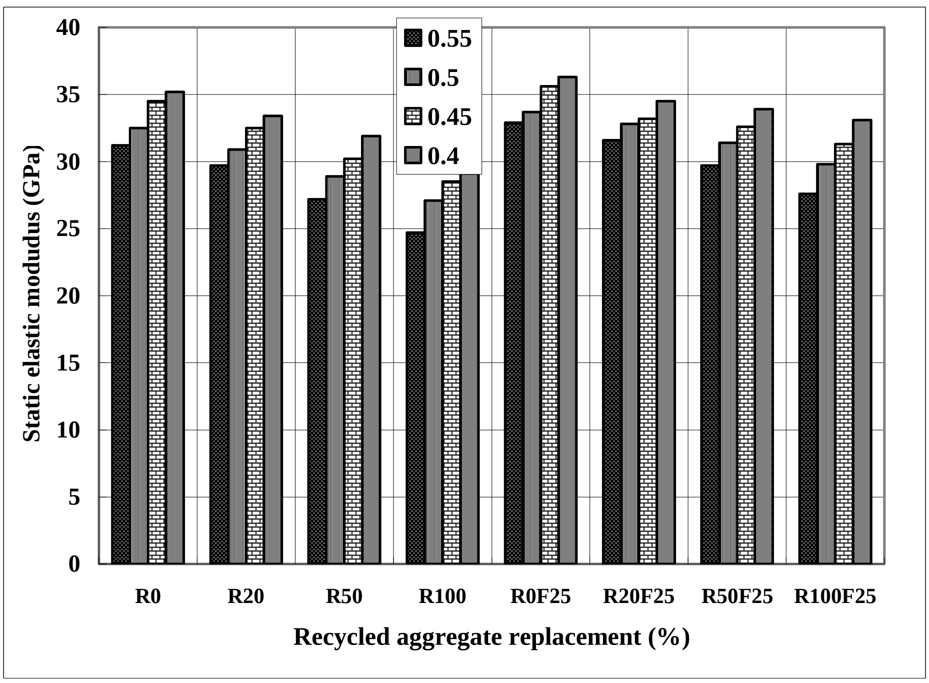


Figure 5-13 – Static modulus of elasticity of concrete in four series mixture at 90 days

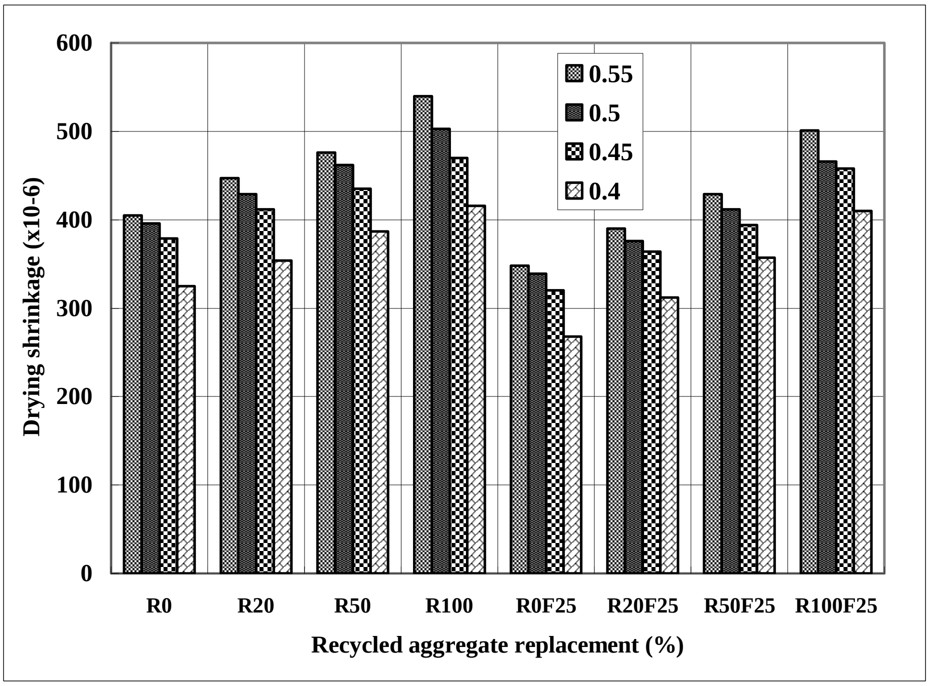


Figure 5-14- Drying shrinkage of concrete in series III, IV, V and VI at test age of 112 days

Chloride penetrability

The resistances to chloride ion penetration of the concrete mixtures in Series III, IV, V and VI at the age of 28 days and 90 days are shown in Figure 5-15 and Figure 5-16, respectively. It can be obtained from Figure 5-15 and Figure 5-16 that at 28 days and 90 days the resistance to chloride ion penetration decreased as the recycled aggregate content increased. Concrete made with 100% recycled aggregate had highest total passed charge in coulombs in four series concrete mixtures. However, at the same recycled aggregate replacement level, the use of fly ash as an additional mineral admixture increased the resistance to chloride ion penetration. At 28 days, the total charge passed (coulombs) of concrete made with 100% recycled aggregate and added 25% fly ash was decreased 38.7%, 42.4%, 55.8% and 59.5% in Series III, IV, V and VI, respectively. At age of 90 days, this decreased value was 52.6%, 49.1%, 52.3% and 49.7% in Series III, IV, V, and VI, respectively. These results may be due to: 1) before 28 days the use of fly ash improved the distribution of pore size and pores shape of concrete. 2) At age of 90 days more C-S-H products were formed as fly ash hydrated which absorbed more chloride ions and blocked the ingress path and the presence of C_3A in fly ash could absorb more chloride ions to form Friedel's salt ($C_3A.CaCl_2.10H_2O$). This is consistent with the results of Leng et al. (2000).

It also can be seen from Figure 5-15 and Figure 5-16 that the reduction in the W/B ratio increased the resistance to chloride ion penetration. For example, at the age of 28 days, the total charge passed in coulombs of concrete made with 100% recycled aggregates were 6905, 5231, 4257 and 3225 in Series III, IV, V and VI concrete mixtures with water-to-cement ratio of 0.55, 0.50, 0.45 and 0.40, respectively. Since the volume of pores within a concrete reduced as the W/B ratio decreased, the concrete became more impermeable and the resistance to chloride ion penetration increased accordingly. Additional 25% of fly ash in the concrete, the water-to-binder ratio in Series III, IV, V and VI were 0.44, 0.40, 0.36 and 0.32, respectively. Hence, the resistance to chloride ion penetration of conventional and recycled aggregates with fly ash was significantly increased. These results also agree with those reported by Leng et al. (2000). Moreover, it was found that the resistance increased as the curing age increased from 28 to 90 days. It was due to the increase in the volumes of hydration products (Mindess et al. 2003), thus forming impermeable regions and increasing the resistance to chloride ion penetration.

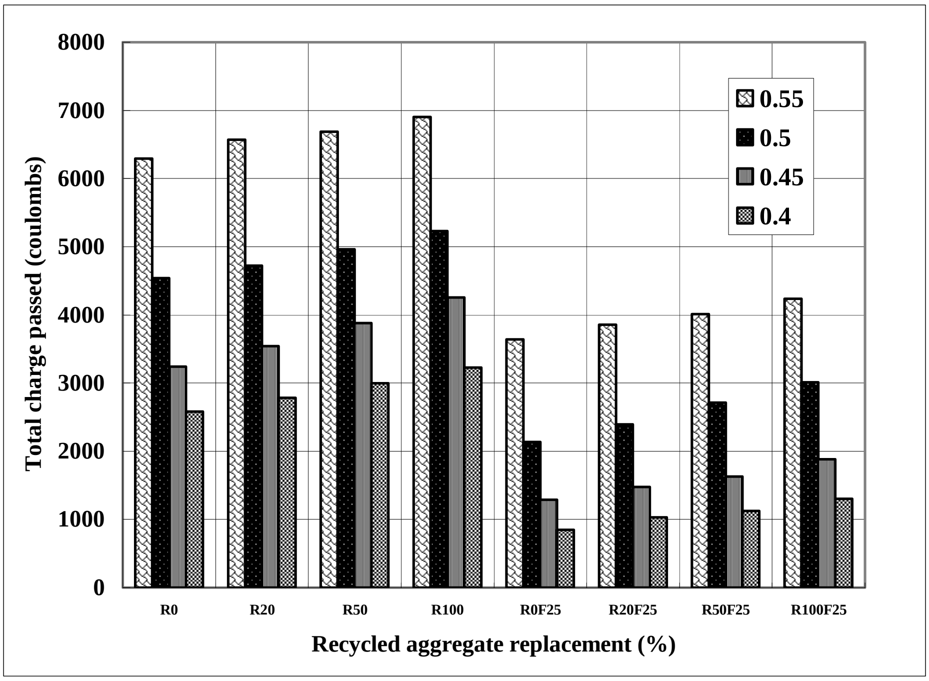


Figure 5-15 – Total charge passed coulombs of concrete in four series mixture at 28 days

Creep strain

Figure 5-17 and Figure 5-18 show the creep strain measured at 120 days and the creep development of the concrete mixtures in Series III, 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. This is consistent with the results of Fraaij et al (2002) and Pauw et al (1998).

It was found from Figure 5-17 and Figure 5-18 that the use of fly ash as an additional mineral admixture reduced the creep strain of the recycled aggregate concrete and conventional concrete. 25% fly ash by cement weight was added in concrete decreased the creep strain of conventional and recycled aggregate concrete about 20%. According to Carette et al. (1991), the creep strain of fly ash concrete was lower compared to those normal concrete without fly ash. This could be the result of large portion of fly ash remaining unreacted in the concrete and thus acting as fine aggregate, providing increasing restraint against creep.

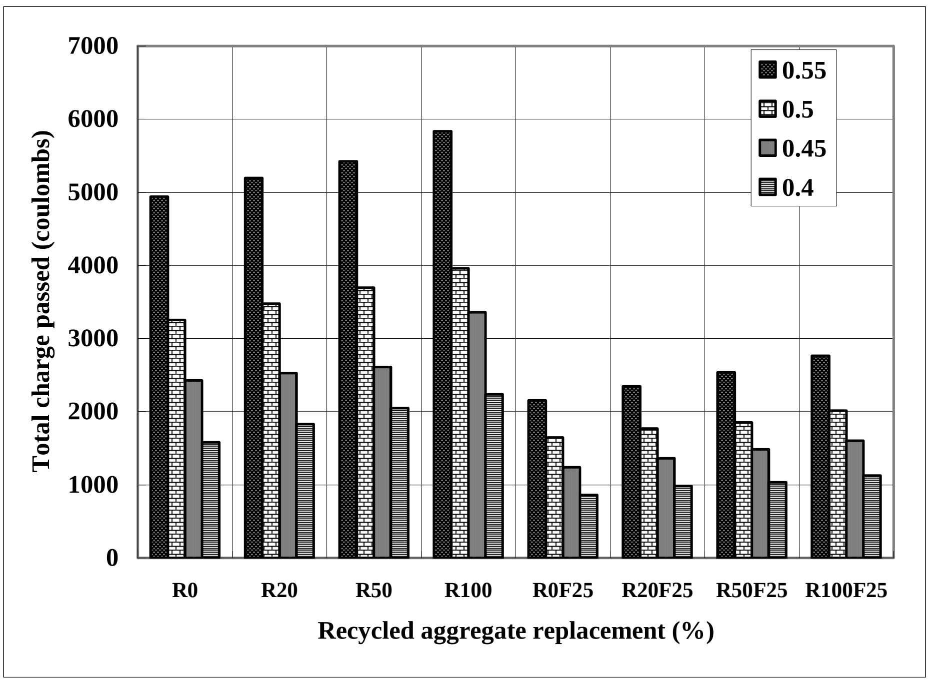


Figure 5-16- Total charge passed coulombs of concrete in four series mixture at 90 days

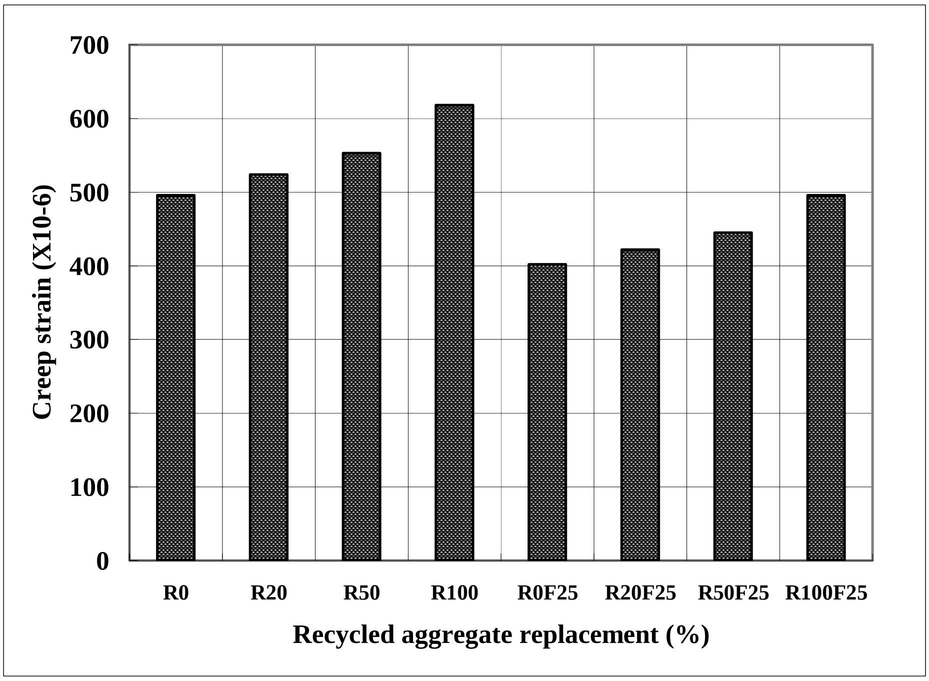


Figure 5-17 - Creep strain value at 120 days of the concrete mixtures in Series III

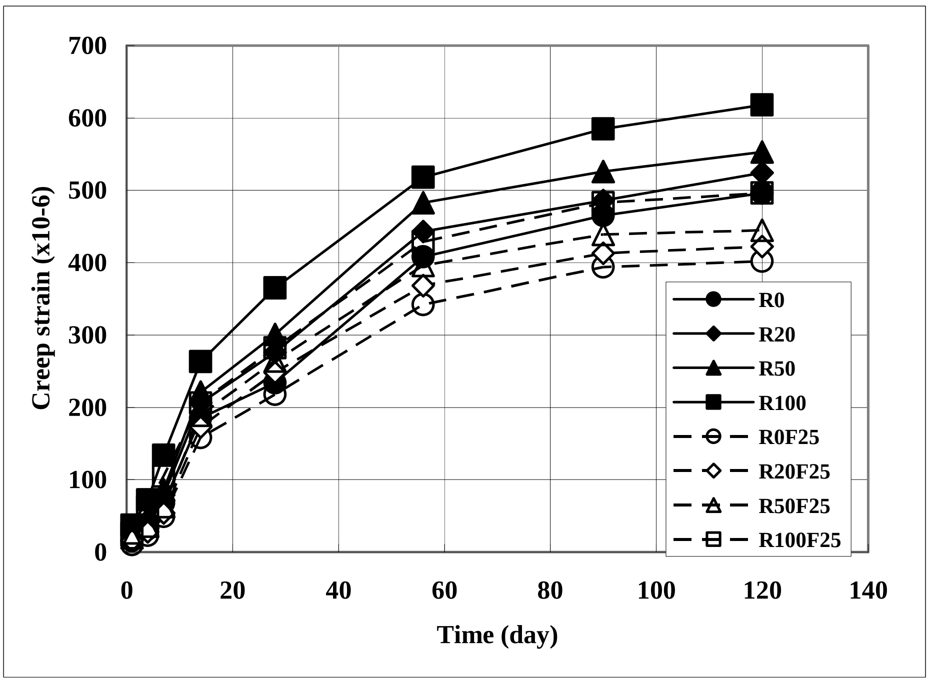


Figure 5-18 - Creep strain vs. time since loading of the concrete mixtures in Series III

5.3 SUMMARY

In this chapter, the effect of fly ash was used a substitution of cement or an additional mineral admixture on hardened properties of recycled aggregate concrete prepared with different W/C ratios and different percentages of recycled aggregate replacements has been investigated. The compressive and splitting tensile strength, static modulus of elasticity, drying shrinkage, creep strain and resistance to chloride-ion penetration of concrete made with recycled aggregate with or without fly ash were determined and discussed. Based on the results of this investigation and discussions, the following conclusions can be drawn:

- 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 aggregate with 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.

- The resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, the resistance was improved by incorporating fly ash in the concrete mixtures. A decrease in the W/B ratio improved the resistance to chloride ion penetration. Furthermore, it was found that the resistance increased as the curing age increased from 28 to 90 days.

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

CHAPTER 6 INFLUENCE OF STEAM CURING ON HARDENED PROPERTIES OF RECYCLED AGGREGATE CONCRETE

6.1 INTRODUCTION

In this chapter, the results of steam curing on the hardened properties of recycled aggregate concrete; recycled aggregate fly ash concrete, which are fly ash was used as a replacement of cement in Series I and II concrete mixture and as an additional mineral admixture in Series III, IV, V and VI concrete mixtures were presented and discussed.

6.2 TEST RESULT AND DISCUSSIONS

6.2.1 Effect of steam curing on hardened properties of recycled aggregate concrete

In this section, the results of steam curing on hardened properties, such as compressive and splitting tensile strength, static modulus of elasticity, drying shrinkage, creep and resistance to chloride-ion penetration of the conventional and recycled aggregate concrete without fly ash in Series III, IV, V, and VI were presented and discussed.

Compressive strength development

The results of compressive strengths of the concrete are presented in Table 6-1 for the concrete mixtures in Series III and IV, and Table 6-2 for the concrete mixtures in Series V and VI, respectively. Each presented value is the average of three measurements. It can be seen from Table 6-1 and Table 6-2 that the compressive strengths of concrete at all curing ages in four series decreased with an increase in the recycled aggregate content. The results showed that the steam cured recycled aggregate concrete gained strength rapidly in the first 3 days and the corresponding strength was much higher than that of water cured recycled aggregate concrete. However, the situation was reversed at late ages (beyond 28 days), and the strength of water cured recycled aggregate concrete had a higher compressive strength compared to that of steam cured recycled aggregate concrete. On the first day the strengths of steam cured recycled aggregate concrete in Series III (w/c=0.55) were 79, 79, 80 and 88 % respectively higher than those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20 , 50 and 100 %. On the other hand, the strengths of steam cured recycled aggregate concrete in Series V (w/c=0.45) were 62, 78, 80 and 81 % respectively higher than those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20 , 50 and 100 %. Results revealed that steam curing was most beneficial to concrete containing 100 % recycled aggregate. At 1 day, the concrete mixture R100 with 100% recycled aggregate and with standard water curing in Series III, IV, V and VI mixtures achieved compressive strength of 10.2, 13.9, 15.5 and 21.5 MPa, whereas the corresponding concrete mixtures with steam curing achieved compressive strength of 19.2, 30.0, 28.1 and 40.5 MPa, respectively; an increase of 88.2, 115.8, 81.3 and 88.4%, respectively, in comparison with the strength of the corresponding concrete mixtures with standard water curing.

On the 7th day, the strengths of steam cured recycled aggregate concrete in Series I (w/c=0.55) were 20, 18, 21 and 28 % respectively higher than those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20 , 50 and 100 %. On the other hand, the strengths of steam cured recycled aggregate concrete in Series II (w/c=0.45) were similar to those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20, 50 and 100 %. It was clearly that the beneficial effect of steam curing at 7th day on the compressive strength shrank compared to that on the first day. For concrete mixtures with w/c= 0.45, the strengths of steam cured concrete were even lower than those of water cured concrete at recycled aggregate replacement levels of 0, 20 and 100 %.

On the 28th day, all steam cured concrete had a lower compressive strength compared to that of water cured concrete regardless of the recycled aggregate replacement level. The strengths of steam cured recycled aggregate concrete in Series III (w/c=0.55) were 8, 6, 4 and 2 % respectively lower than those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20 , 50 and 100 %. On the other hand, the strengths of steam cured recycled aggregate concrete in Series V (w/c=0.45) were 13, 8, 1 and 1 % respectively lower than those of water cured recycled aggregate concrete at recycled aggregate contents of 0, 20 , 50 and 100 %. Nevertheless, it was noteworthy that the detrimental effect of steam curing on the 28-day compressive strength lessened with increasing recycled aggregate contents. The compressive strength of steam cured concrete with 100 % recycled aggregate was comparable to that of water cured concrete prepared with the same recycled aggregate content.

The relative compressive strength indicated in Figure 6-1 was the ratio of the compressive strength of the concrete to that of the Series III mixtures of water cured natural aggregate concrete at 28 days. Figure 6-1 indicated that the 28-day compressive strengths of the steam cured concrete were lower than that of the water cured concrete. Moreover, the rate of gain in strength of the steam cured concrete was much lower than that of the water cured concrete after 1 day. However, the detrimental effect of steam curing on the compressive strength diminished as the replacement level increased. At the recycled aggregate replacement level of 20 %, the compressive strength of the steam cured concrete was 5.1%, 6.0%, 10.0%, and 16.5% lower than that of the water cured concrete in Series III, IV, V, and VI, respectively. However, at the recycled aggregate replacement level of 100 %, the compressive strength of the steam cured concrete in four series was not significant change comparing to the water cured concrete. Also, the compressive strengths were significant increased with decrease in the water-to-cement ratio. Figure 6-1 indicated that at the test age of 28 days, the compressive strength of concrete mixture R100 with 100% recycled aggregate concrete and with water-to-cement ratio (W/C) of 0.45 was higher than that the natural aggregate concrete (R0) made with W/C ratio of 0.55. The compressive strength of concrete mixture R100 made with W/C ratio of 0.40 was increased about 20% and 10% than that natural aggregate concrete (R0) made with W/C ratios of 0.55 and 0.50, respectively.

Generally, the compressive strength of concrete decreased with an increase in the recycled aggregate contents. It was because recycled aggregate was more porous and weaker compared to those of natural aggregates as indicated by the results of the MIP and the ten percent fines value. The detrimental effects of steam curing on the compressive strength of concrete were attributed to 1) accelerated temperature resulted in a coarse pore structure, 2) hydration products did not have enough time to diffuse evenly before hardening, and 3) the differences in the thermal expansion coefficients of different concrete constituents (i.e. especially air) led to formation of microcracks. However, the concrete with 100 % recycled aggregate was least affected by steam curing. It was probably due to its porous structure as it could better accommodate the expansion of air during the steam curing process. As a result, fewer cracks were formed. Furthermore, a reduction in the w/c ratio increased the compressive strength of the recycled aggregate concrete. The reduction in the compressive strength can be adequately compensated by the use of a lower w/c ratio.

Table 6-1 Compressive strength of the concrete mixtures in Series III and IV

Curing	Age (day)	Compressive strength (MPa)							
		Series III (w/c = 0.55)				Series IV (w/c = 0.50)			
		R0	**R20**	**R50**	**R100**	**R0**	**R20**	**R50**	**R100**
Standard water cured	**1**	12.8	11.9	11.6	10.2	20.5	18.5	16.7	13.9
	4	23.3	22.4	21.8	18.6	36.1	35.5	31.1	23.1
	7	30.2	29.1	27.6	24.4	42.8	39.2	38.4	31.8
	28	48.6	45.3	42.5	38.1	54.1	51.7	47.1	43.4
	90	52.7	50.8	49.5	45.5	57.6	55.8	53.6	50.7
Steam cured	**1**	22.9	21.3	20.9	19.2	37.8	35.2	30.5	30.0
	4	31.1	29.1	28.6	27.8	39.5	36.5	32.9	35.1
	7	36.3	34.3	33.4	31.2	41.1	42.9	37.4	36.2
	28	44.5	42.8	40.9	37.2	47.9	48.8	44.5	46.1
	90	47.8	46.6	45.7	43.0	54.2	51.7	48.4	55.4

Table 6-2 Compressive strength of the concrete mixtures in Series V and VI

Curing	Age (day)	Compressive strength (MPa)							
		Series V (w/c = 0.45)				Series VI (w/c = 0.40)			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	**1**	25.8	23.6	21.1	15.5	30.8	28.6	25.3	21.5
	4	45.8	43.2	40.3	26.8	49.4	47.6	45.1	36.4
	7	53.8	51.2	49.8	36.2	57.1	55.2	53.3	45.4
	28	66.8	62.4	56.8	52.1	72.3	69.6	65.3	58.5
	90	72.3	68.0	61.5	57.2	78.1	75.2	71.6	64.5
Steam cured	**1**	41.8	41.9	38.0	28.1	50.5	47.2	44.6	40.5
	4	49.6	47.9	41.9	32.1	51.3	49.6	46.5	43.8
	7	53.2	50.3	46.7	35.7	58.2	55.2	48.0	46.8
	28	58.1	57.4	55.1	51.4	62.5	61.6	59.3	58.4
	90	63.9	65.9	62.2	58.4	68.5	66.2	64.9	62.7

Splitting tensile strength

The splitting tensile strengths of the concrete in four series are given in Table 6-3 and Table 6-4. Each presented value is the average of three specimens. The results showed that an increase in the recycled aggregate content decreased the tensile splitting strength of the concrete. Similarly, steam curing increased the 1-day tensile splitting strength compared to that of water cured concrete. However, steam curing did not have a noticeable adverse effect on the tensile splitting strength at late curing ages as opposed to the effect on the compressive strength. It can be obtained from Table 6-3 and Table 6-4 that at 1 day, the concrete mixture R100 with 100% recycled aggregate and with standard water curing in Series III, IV, V and VI mixtures achieved splitting tensile strength of 1.21, 1.24, 1.41 and 2.14 MPa, whereas the corresponding concrete mixtures with steam curing achieved splitting tensile strength of 1.70, 2.17, 2.13 and 2.64 MPa, respectively; an increase of 40.5, 75.0, 51.1 and 23.4%, respectively, in comparison with the strength of the concrete with standard water curing. The relative splitting tensile strength indicated in Figure 6-2 was the ratio of the splitting tensile strength of the concrete to that of the Series III mixtures of water cured natural aggregate concrete at 28 days. Figure 6-2 indicated that similarly, steam curing increased the 1-day tensile strength. However, after 1 day, the strength gain of the steam cured concrete was much lower than that of the water cured concrete. Furthermore, a decrease in W/C ratio from 0.55 to 0.40 increased the splitting tensile strength of concrete. Figure 6-2 showed that at the test age of 28 days, the splitting tensile strength of 100% recycled aggregate concrete made with W/C ratio of 0.45 was higher than that natural aggregate concrete made with W/C ratio of 0.55. The splitting tensile strength of 100% recycled aggregate made with W/C ratio of 0.40 was increased about 8% than that natural aggregate concrete made with W/C ratio of 0.55.

Also, the incorporation of recycled aggregate did not cause a significant decrease in the 28-day tensile splitting strength. In Series III, the increase in the recycled aggregate content from 0 to 100 % decreased the 28-day tensile splitting strength by 8.0 and 15.0 % for water cured and steam cured concretes respectively. The decrease was 17.0 and 16.0 % for water and steam cured concretes respectively in Series V. Since the tensile splitting strength is influenced by the properties of the interfacial transition zone (ITZ) (Mindess et al 2003), the results revealed that the use of recycled aggregate did not have a deleterious impact on the properties of the ITZ. Furthermore, the use of a lower w/c ratio increased the tensile splitting strength of concrete. Because a lower w/c reduced the bleeding on the underside of the aggregates, a higher tensile strength was resulted due to the reduction in porosity at the ITZ (RILEM Report 11, 1996).

Table 6-3 Splitting tensile strength of the concrete mixtures in Series III and IV

Curing	**Age (day)**	**Splitting tensile strength (MPa)**							
		Series III (w/c = 0.55)				**Series IV (w/c = 0.50)**			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	**1**	1.30	1.27	1.25	1.21	1.81	1.37	1.51	1.24
	4	2.32	2.30	2.28	2.20	2.57	2.21	2.24	1.78
	7	2.62	2.53	2.51	2.38	2.70	2.56	2.46	2.35
	28	3.32	3.21	3.16	3.06	3.47	3.39	3.28	3.19
	90	3.68	3.56	3.43	3.25	3.79	3.64	3.58	3.41
Steam cured	**1**	2.08	2.04	1.84	1.70	2.45	2.30	2.09	2.17
	4	2.57	2.50	2.40	2.28	2.57	2.50	2.20	2.42
	7	2.84	2.78	2.70	2.52	2.69	2.78	2.39	2.56
	28	3.30	3.24	2.97	2.80	3.41	3.34	3.25	2.96
	90	3.62	3.41	3.25	3.12	3.74	3.52	3.43	3.34

Table 6-4 Splitting tensile strength of the concrete mixtures in Series V and VI

Curing	Age (day)	Splitting tensile strength (MPa)							
		Series V (w/c = 0.45)				Series VI (w/c = 0.40)			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	**1**	2.15	1.91	1.64	1.41	2.62	2.42	2.36	2.14
	4	2.89	2.28	2.19	2.15	3.25	3.04	2.96	2.84
	7	2.92	2.85	2.66	2.59	3.39	3.25	3.14	3.09
	28	3.73	3.56	3.37	3.34	4.07	3.86	3.69	3.59
	90	3.84	3.72	3.67	3.49	4.16	4.12	3.97	3.76
Steam cured	**1**	2.28	2.37	2.35	2.13	2.96	2.65	2.48	2.64
	4	2.77	2.65	2.47	2.31	3.34	3.23	3.17	2.96
	7	2.80	2.76	2.67	2.47	3.38	3.31	3.24	3.19
	28	3.66	3.58	3.34	3.18	3.96	3.82	3.61	3.48
	90	3.82	3.76	3.62	3.54	3.95	3.89	3.78	3.63

Static modulus of elasticity

The static modulus of elasticity values of the concrete in four series are presented in Table 6-5 and Table 6-6. Similarly, each presented value is the average of three specimens. It can be seen from Table 6-5 and Table 6-6 that the static modulus of elasticity of concrete decreased with an increase in the recycled aggregate content. The relative static modulus of elasticity indicated in Figure 6-3 was the ratio of the static modulus of elasticity of concrete to that of the series III mixtures of water cured natural aggregate concrete at 28 days. The static modulus of elasticity of concrete prepared with 100% recycled aggregate was about 20% lower than that of the natural aggregate concrete at the curing ages of 28 days. The results also showed that the static modulus of elasticity of the steam cured concrete was lower than that of the water cured concrete. However, the detrimental effect of steam curing on the static modulus of elasticity diminished as the replacement level increased (Figure6-3). At the recycled aggregate replacement level of 20 %, the static modulus of elasticity of the steam cured concrete was 6.7 %, 8.3%, 6.6%, and 9.0% lower than that of the water cured concrete in Series III, IV, V, and VI, respectively. However, at the recycled aggregate replacement level of 100 %, the static modulus of elasticity of the steam cured concrete in four series was only 1 % lower than that of the water cured concrete.

The results at age of 90 days indicated that there was continuous improvement in elastic modulus beyond the age of 28 day. At 90 days, the concrete mixture R100 with 100% recycled aggregate and with standard water curing in Series III, IV, V and VI achieved in the static modulus elasticity of 25.7, 27.1, 28.5 and 29.1 GPa, whereas at the age of 28 days, the corresponding concrete achieved in the static modulus elasticity of 24.2, 25.8, 26.6 and 27.9 GPa, respectively; a reduction of 18.3, 32.2, 17.2 and 30.6 %, respectively, in comparison with the static modulus of elasticity of the corresponding concrete mixture. The increase in the static modulus elasticity is, of course, due to the cement that continued to hydrate. Similar results were obtained for all concrete mixtures in four series with standard water curing and steam curing.

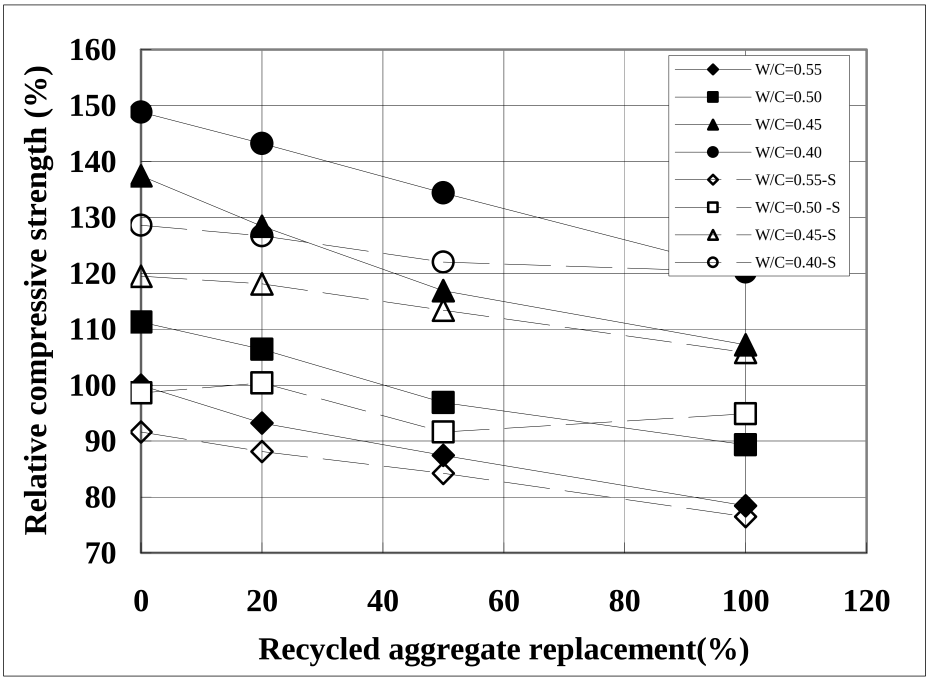


Figure 6-1-Relative compressive strength of four series concrete mixtures at 28 days

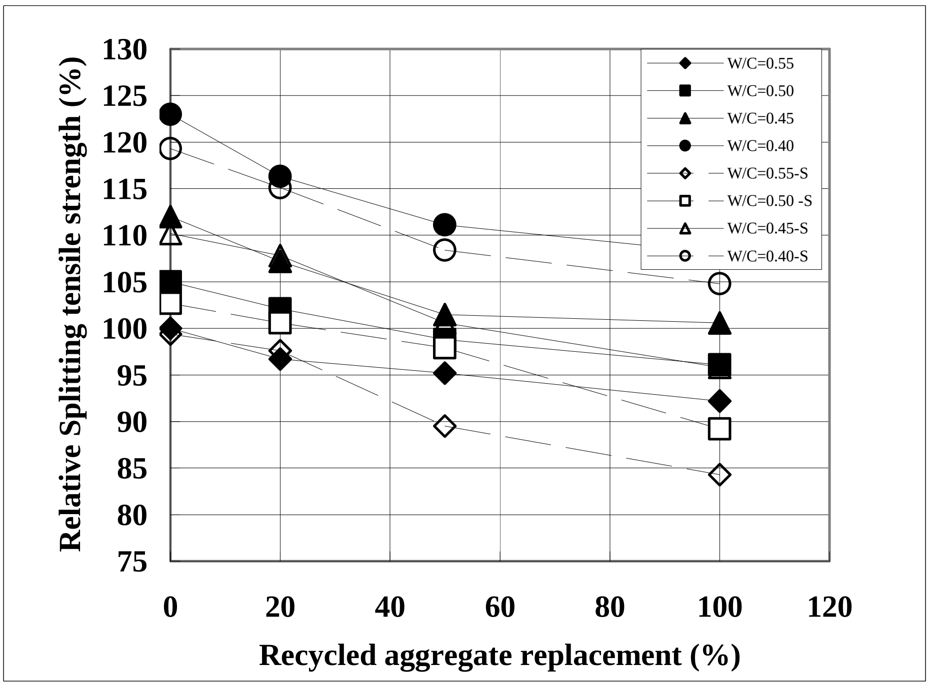


Figure 6-2 Relative splitting tensile strength of four series concrete mixtures at 28 days

Table 6-5 Static modulus of elasticity of concrete mixtures in Series III and IV at 28 and 90 days

Curing	Age (day)	Static modulus of elasticity (GPa)							
		Series III (w/c = 0.55)				Series IV (w/c = 0.50)			
Standard water cured		R0	R20	R50	R100	R0	R20	R50	R100
	28	30.1	28.8	26.3	24.2	31.1	29.7	27.6	25.8
	90	31.2	29.7	27.2	25.7	32.5	30.9	28.9	27.1
Steam cured	**28**	27.7	26.8	25.3	23.9	28.6	27.2	26.9	25.6
	90	29.9	28.8	26.6	24.7	30.8	29.9	27.8	26.8

Table 6-6 Static modulus of elasticity of the concrete mixtures in Series V and VI at 28 and 90 days

Curing	Age (day)	Static modulus of elasticity (GPa)							
		Series V (w/c = 0.45)				Series VI (w/c = 0.40)			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	**28**	32.3	30.4	28.8	26.6	33.5	31.6	29.3	27.9
	90	34.5	32.5	30.2	28.5	35.2	33.4	31.9	29.1
Steam cured	**28**	29.3	28.4	27.6	26.2	30.6	28.9	28.2	27.6
	90	31.4	30.3	29.0	28.6	32.8	31.5	30.6	29.8

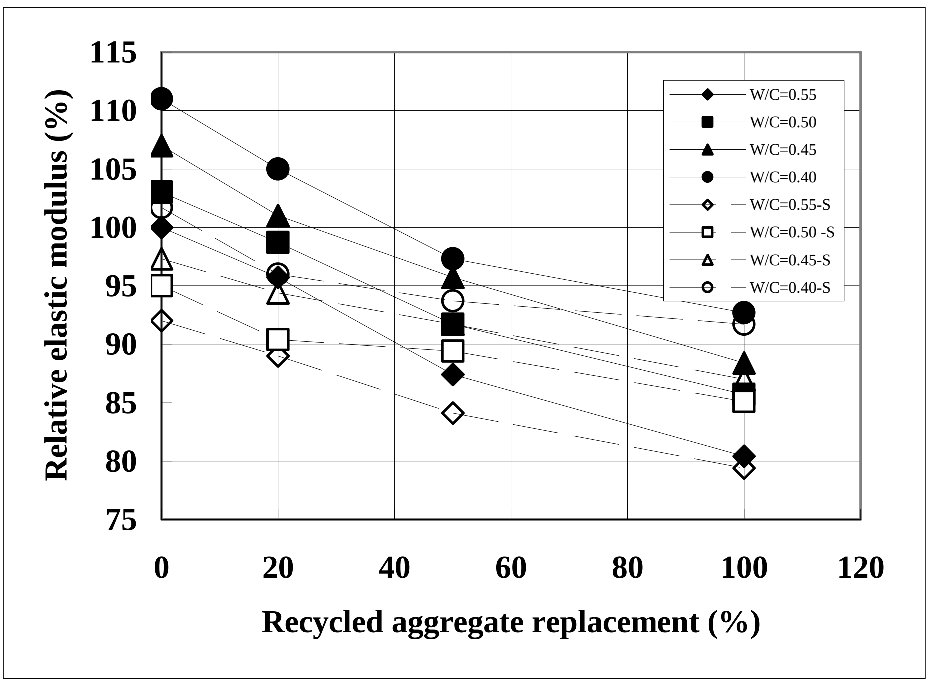


Figure 6-3 Relative static modulus of elasticity of four series concrete mixtures at 28 days

Drying shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures in four series are shown in Table 6-7 and Table 6-8. It can be seen from Table 6-7 and 6-8 that the drying shrinkage values increased with an increase in recycled aggregate content. The relative drying shrinkage indicated in Figure 6-4 was the ratio of the drying shrinkage value of concrete to that of the concrete mixtures in Series III with water cured concrete. Figure 6-4 indicated that steam curing reduced the drying shrinkage of the concrete. At the age of 112 days, the concrete mixtures R100 with 100% recycled aggregate and with standard water curing in Series III, IV, V and VI achieved in shrinkage value of 540, 503, 470 and 416 microstrain, whereas the corresponding concrete with steam curing achieved in shrinkage value of 466, 436, 401 and 375 microstrain, respectively; a reduction of 13.7, 13.3, 14.7 and 10.0 %, respectively, in comparison with the shrinkage of the corresponding concrete mixture with standard water curing. These results are similar to those reported for natural aggregate concrete by Brooks et al (1996). Furthermore, the drying shrinkage of concrete in Series IV, V, and VI was lower than that of concrete in Series III which indicated that a decrease in the W/C ratio reduced the drying shrinkage.

Table 6-7 Ultimate drying shrinkage of the concrete mixtures in Series III and IV at 112 days

Notation	Recycled aggregate (%)	Drying shrinkage (10^{-6})			
		Series III (w/c =0.55)		Series IV (w/c =0.50)	
		Standard water cured	Steam cured	Standard water cured	Steam cured
R0	0	405	350	396	324
R20	20	447	382	429	358
R50	50	476	410	462	385
R100	100	540	466	503	436

Table 6-8 Ultimate drying shrinkage of the concrete mixtures in Series V and VI at 112 days

Notation	Recycled aggregate (%)	Drying shrinkage (10^{-6})			
		Series V (w/c =0.45)		Series VI (w/c =0.40)	
		Standard water cured	Steam cured	Standard water cured	Steam cured
R0	0	379	301	325	279
R20	20	412	322	354	298
R50	50	435	365	387	343
R100	100	470	401	416	375

Creep strain

Figure 6-6 and Figure 6-7 show the creep strain measured at 120 days and the creep development of the concrete mixtures in Series III, respectively. Each presented value is the average of three measurements. In the creep test, the applied load was equivalent to 35 % of the 28-day compressive strength of the concrete. 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. The concrete with 100% recycled aggregate has largest creep value. This was attributed to the increased volume of mortar in the recycled aggregate concrete compared to that in the conventional concrete. It was found from Figure 6-6 and Figure 6-7 that the use of initial steam curing regimes reduced the creep strain of the recycled aggregate concrete and conventional concrete. At 120 days, the concrete mixture R100 with 100% recycled aggregate and with standard water curing in Series III mixture achieved in shrinkage value of 618 microstrain, whereas the corresponding concrete with steam curing achieved in shrinkage value of 524 microstrain, respectively; a reduction of 15.2 %, in comparison with the strain of the corresponding concrete mixture with standard water curing. These results are similar to those reported for natural aggregate concrete by Brooks et al (1996). In according with Brooks et al (1996) Steam curing reduces the long-term shrinkage and creep strain of conventional and recycled aggregate concrete probably because of lower hardened cement paste content due to the acceleration of hydration at a higher temperature.

Chloride penetrability

The resistances against chloride-ion penetration of concrete in four series are given in Table 6-9 and Table 6-10. The results indicated that the resistance to chloride-ion penetration of concrete mixture in Series III, IV, V and VI decreased with an increase in the recycled aggregate content. The relative total charge passed in coulombs indicated in Figure 6-5 was the ratio of the total charge passed coulombs of concrete to that of the concrete mixtures in Series III of water cured natural aggregate concrete at 28 days. Figure 6-5 showed that steam curing decreased the resistance against chloride-ion penetration of concrete. However, the detrimental effect of steam curing on the resistance against chloride-ion penetration diminished as the replacement level increased (Figure 6-5). At the recycled aggregate replacement level of 20 %, the total charge passed in coulombs of the steam cured concrete was 4.8 %, 3.3%, 2.2%, and 1.5% higher than that of the water cured concrete in Series III, IV, V, and VI, respectively. However, at the recycled aggregate replacement level of 100 %, the total charge passed in coulombs of the steam cured concrete in four series was only 1.8%, 1.1%, 1.4% and 1.2% higher than that of the water cured concrete in Series III, IV, V, and VI, respectively. A comparison among the results of Series III, IV, V and VI revealed that a decrease in the W/C ratio also significantly increased the resistance against chloride-ion penetration. At the same recycled aggregate replacement level, the concrete made with water-to-cement ratio of 0.40 had highest resistance to chloride-ion penetration.

The results at 90 days indicated that there was continuous and significant improvement in the resistance to chloride-ion penetration of the conventional and recycled aggregate concrete beyond the age of 28 days. At the age of 90 days, the concrete made with 100% recycled aggregate and with standard water curing in Series III, IV, V and VI achieved in total charge passed in coulombs of 5835, 3958, 3632 and 2239, whereas at the age of 28 days, the corresponding concrete achieved in total charge passed in coulombs of 6905, 5231, 4257 and 3225, respectively; a reduction of 18.3, 32.2, 17.2 and 30.6 %, respectively, in comparison with the total charge passed in coulombs of the corresponding concrete mixture. The increase in the resistance to chloride-ion penetration is, of course, due to the cement that continued to hydrate. Similar results were obtained for all concrete mixtures in four series with standard water curing and steam curing.

Table 6-9 Chloride-ion penetrations of the concrete mixtures in Series III and IV

Curing	Age (day)	Total charge passed (Coulombs)							
		Series III (w/c =0.55)				Series IV (w/c = 0.50)			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	28	6291	6572	6687	6905	4539	4721	4962	5231
	90	4940	5194	5425	5835	3254	3478	3697	3958
Steam cured	28	6694	6876	6892	7015	4839	4924	5073	5306
	90	5321	5432	5660	5921	3624	3762	3856	4027

Table 6-10 Chloride-ion penetrations of the concrete mixtures in Series V and VI

Curing	Age (day)	Total charge passed (Coulombs)							
		Series V (w/c =0.45)				Series IV (w/c = 0.40)			
		R0	R20	R50	R100	R0	R20	R50	R100
Standard water cured	28	3239	3543	3880	4257	2584	2786	2997	3225
	90	2427	2528	2609	3362	1583	1832	2051	2239
Steam cured	28	3442	3680	3925	4366	2688	2879	3033	3280
	90	2685	2700	2740	3707	1698	1901	2132	2293

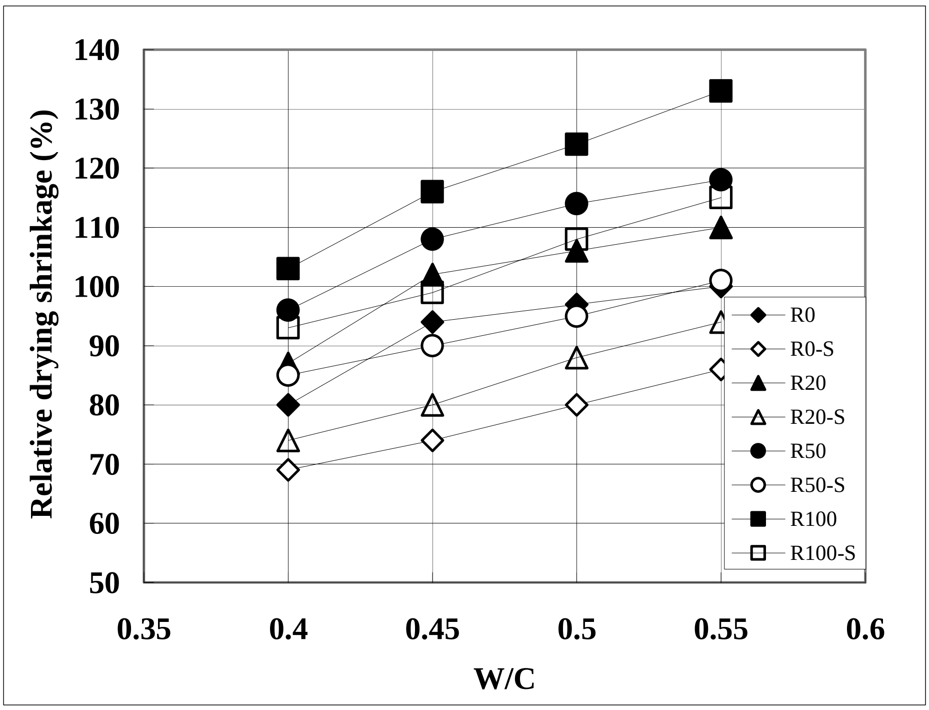


Figure 6-4 Relation between of relative drying shrinkage and water-to-cement ratio

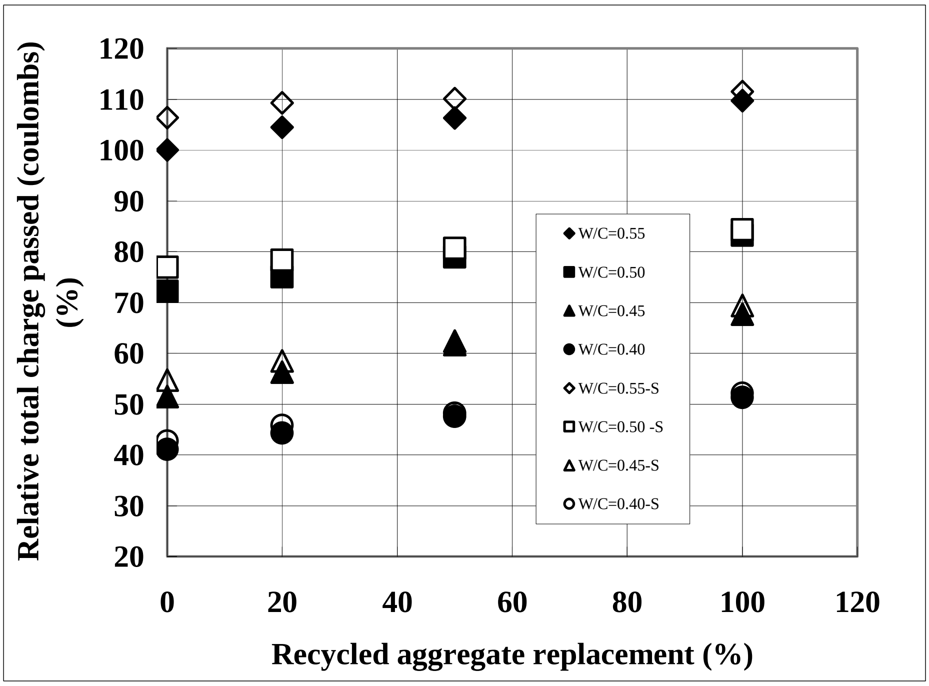


Figure 6-5 Relative chloride ion penetration of four series concrete mixtures at 28 days

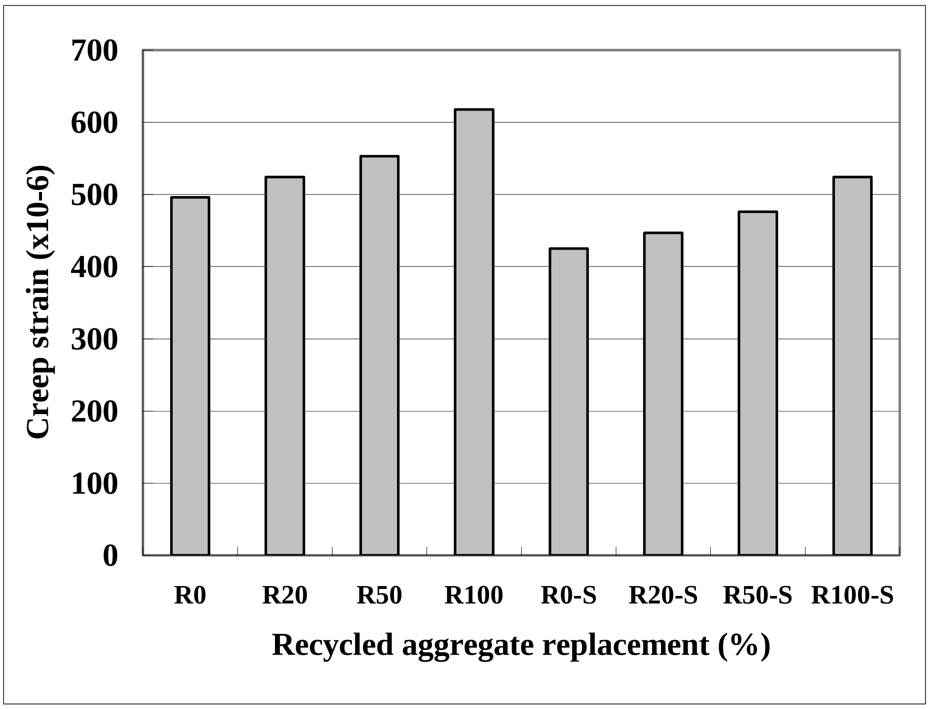


Figure 6-6 Creep strain at 120 days of the concrete mixtures in Series III

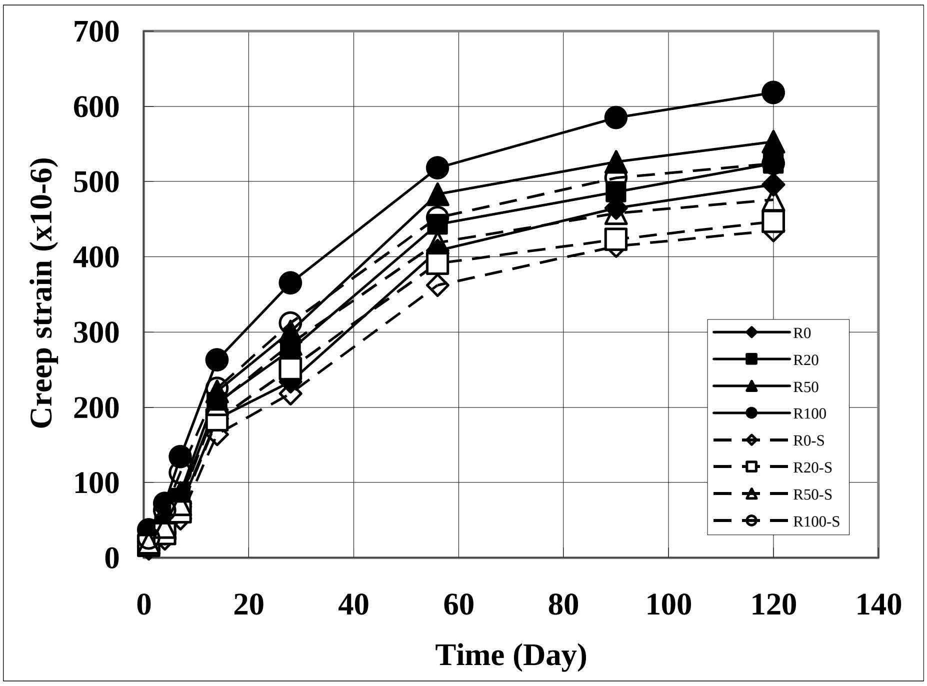


Figure 6-7 Creep strain vs. time since loading of the concrete mixtures in Series III

6.2.2 Effect of steam curing on properties of fly ash recycled aggregate concrete

6.2.2.1 Use of fly ash as a substitution of cement

In this section, the results of steam curing on the hardened properties of recycled aggregate concrete prepared with fly ash as a partial replacement of cement in Series I and II were presented and discussed.

Compressive Strength

The compressive strengths of the concrete mixtures in Series I and II with standard water cured are shown in Table 5-1 and Table 5-2, respectively. The test results of the corresponding concrete with steam cured are shown in Table 6-11 and Table 6-12. Each presented value is the average of three measurements. It can be obtained from Tables 5-1, 5-2 that at the same recycled aggregate replacement level, the early day (1, 4 and 7-day) compressive strengths of concrete were significantly reduced as the fly ash content increased. At 1 day, the concrete mixture R100 with 100% recycled aggregate in Series I achieved compressive strength of 10.2 MPa, whereas mixtures R100F25 (25% fly ash), R100F35 (35% fly ash) achieved compressive strength of 9.4 and 4.8 MPa, respectively; a reduction of 7.8 and 52.9%, respectively, in comparison with the strength of the corresponding concrete mixture without fly ash. The 90-day compressive strengths (regardless of the curing methods) of concrete containing fly ash as a 25 % replacement of cement were comparable to or higher than those of the concrete prepared with no fly ash. However, the results (Tables 5-1, 5-2, 6-11 and 6-12) showed that the 1-day compressive strengths of the steam cured concrete were higher than those of the water cured concrete. At 1 day, the concrete mixture r-R100F25 with 100% recycled aggregate, 25% fly ash and with standard water curing in Series I and II mixtures achieved compressive strength of 9.4 and 11.1 MPa, whereas the corresponding concrete mixtures with steam curing achieved compressive strength of 18.5 and 26.8 MPa, respectively; an increase of 96.8 and 141.4%, respectively, in comparison with the strength of the concrete with standard water curing. However, the corresponding 28 and 90-day compressive strengths of the steam cured concrete were lower than those of water cured concrete. However, at 90 days, the beneficial effects of the incorporation of fly ash became evident.

The detrimental effect of steam curing on the compressive strength diminished as the replacement level increased. At 28 days, the conventional aggregate concrete mixture r-R0F25 with fly ash replacement level of 25%, the compressive strength of the steam cured concrete was 11.8% and 8.5% lower than that of the water cured concrete in Series I and II, respectively. However, at the recycled aggregate replacement level of 100 %, (R100F25) the compressive strength of the steam cured concrete in two series was not significant change comparing to the water cured concrete. At 90 days, the conventional aggregate concrete mixture r-R0F25 with fly ash replacement level of 25%, the compressive strength of the steam cured concrete was 12.4% and 9.6% lower than that of the water cured concrete in Series I and II, respectively. However, at the recycled aggregate replacement level of 100 %, the concrete mixture r-R100F25 with steam curing in Series I and II achieved compressive strength of 50.3 and 52.0 MPa, respectively, whereas the corresponding concrete mixtures with standard water curing achieved compressive strength 50.1 and 52.3 MPa, respectively. The compressive strength of concrete in two series was not significant change comparing to the water cured concrete.

Splitting Tensile Strength

The splitting tensile strengths of the concrete mixtures in Series I and II with standard water cured are shown in Table 5-3 and Table 5-4, respectively. The test results of the corresponding concrete with steam cured are shown in Table 6-13 and Table 6-14. Each presented value is the average of three measurements. The results showed that an increase in the recycled aggregate content decreased the splitting tensile strength of the concrete. Similarly, steam curing increased the 1-day tensile strength. At 1 day, the concrete mixture r-R100F25 with 100% recycled aggregate, 25% fly ash and with standard water curing in Series I and II mixtures achieved splitting tensile strength of 0.75 and 0.49 MPa, whereas the corresponding concrete mixtures with steam curing achieved compressive strength of 1.46 and 1.37 MPa, respectively; an increase of 94.7 and 179.6%, respectively, in comparison with the strength of the concrete with standard water curing. However, similarly to the compressive strengths, the 28 and 90-day splitting tensile strengths of steam cured concrete were comparable to or lower than those of water cured concrete. However, at the same recycled aggregate replacement level, the use of fly ash reduced the tensile splitting strengths of the concrete.

The detrimental effect of steam curing on the splitting tensile strength diminished as the replacement level increased. Similar results were obtained for both series concrete mixtures in this section.

Table 6-11 Compressive strength of the concrete mixtures in Series I with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	Compressive strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	22.9	31.1	36.3	44.5	47.8
R20	0	20	21.3	29.1	34.3	42.8	46.6
R50	0	50	20.9	28.6	33.4	40.9	45.7
R100	0	100	19.2	27.8	31.2	37.2	43.0
r-R0 F25	25	0	22.0	28.5	34.4	38.9	50.7
r-R20 F25	25	20	20.9	27.1	32.8	39.1	49.3
r-R50 F25	25	50	19.8	26.3	29.9	38.8	49.5
r-R100F25	25	100	18.5	24.9	28.8	37.6	50.3
r-R0 F35	35	0	21.0	26.3	31.2	36.4	44.8
r-R20 F35	35	20	19.6	25.1	30.3	35.8	43.2
r-R50 F35	35	50	18.4	23.8	28.6	37.4	41.5
r-R100F35	35	100	17.2	22.6	27.4	34.7	38.3

Table 6-12 Compressive strength of the concrete mixtures in Series II with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	Compressive strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	41.8	49.6	53.2	58.1	63.9
R20	0	20	41.9	47.9	50.3	57.4	65.9
R50	0	50	38.0	41.9	46.7	55.1	62.2
R100	0	100	28.1	32.1	35.7	41.4	48.4
r-R0 F25	25	0	37.0	41.9	46.2	50.3	62.4
r-R20 F25	25	20	33.3	37.1	42.2	51.6	63.1
r-R50 F25	25	50	30.0	34.5	37.6	48.3	58.0
r-R100F25	25	100	26.8	30.7	33.6	42.1	52.0
r-R0 F35	35	0	30.4	33.6	36.4	46.2	52.2
r-R20 F35	35	20	28.5	30.5	33.7	44.1	51.1
r-R50 F35	35	50	26.3	28.9	32.1	42.3	47.2
r-R100F35	35	100	22.9	29.5	30.3	39.5	44.9

Static Modulus of Elasticity

The static modulus of elasticity of concrete mixtures was determined at the age of 28 and 90 days. The results of concrete mixtures in Series I and II are presented in Tables 6-15 and 6-16, respectively. Similarly, each presented value is the average of three measurements. The results showed that the static modulus of elasticity of concrete decreased with an increase in the recycled aggregate content. The static modulus of elasticity of concrete prepared with 100% recycled aggregate was more than 20 % lower than that of natural aggregate concrete at the curing ages of 28 and 90 days. Although steam curing had a slight detrimental effect on the modulus of elasticity of the recycled aggregate concrete prepared without fly ash, it did not affect the modulus of elasticity of the fly ash recycled aggregate concrete. However, at the same recycled aggregate replacement level, the use of fly ash slightly reduced the static modulus of elasticity values of concrete at both 28 and 90 days.

Table 6-13 Splitting tensile strengths of the concrete mixtures in Series I mixture with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	Splitting tensile strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	2.08	2.57	2.84	3.20	3.45
R20	0	20	2.04	2.50	2.78	3.16	3.59
R50	0	50	1.81	2.40	2.70	2.97	3.45
R100	0	100	1.70	2.28	2.52	3.10	3.32
r-R0 F25	25	0	1.72	2.43	2.72	3.14	3.41
r-R20 F25	25	20	1.63	2.31	2.63	3.04	3.19
r-R50 F25	25	50	1.55	2.26	2.51	2.91	3.11
r-R100F25	25	100	1.46	2.12	2.42	2.71	2.84
r-R0 F35	35	0	1.66	2.30	2.56	2.81	3.97
r-R20 F35	35	20	1.53	2.26	2.43	2.69	3.02
r-R50 F35	35	50	1.48	2.13	2.38	2.52	2.80
r-R100F35	35	100	1.37	2.01	2.26	2.55	2.74

Table 6-14 Splitting tensile strengths of the concrete mixtures in Series II mixtures with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	Splitting tensile strength (MPa)				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	2.28	2.77	2.80	3.06	3.72
R20	0	20	2.37	2.65	2.76	3.58	3.96
R50	0	50	2.35	2.47	2.67	3.24	3.62
R100	0	100	2.13	2.31	2.47	3.08	3.22
R0 F25	25	0	1.83	2.59	2.82	3.65	4.06
R20 F25	25	20	2.18	2.37	2.80	3.35	3.60
R50 F25	25	50	2.11	2.14	2.51	3.05	3.84
R100F25	25	100	1.72	1.88	2.16	2.89	3.29
R0 F35	35	0	1.79	1.96	2.37	2.71	3.24
R20 F35	35	20	1.76	1.92	2.24	2.56	3.12
R50 F35	35	50	1.73	1.87	2.21	2.46	3.09
R100F35	35	100	1.67	1.85	2.36	2.46	2.99

Drying Shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures in Series I and II are shown in Table 6-17. It can be shown that the drying shrinkage values increased with an increase in recycled aggregate content. However, an initial steam curing regime reduced the drying shrinkage of conventional and recycled aggregate concrete with and without fly ash. Also, the incorporation of fly ash as a partial replacement of cement decreased the drying shrinkage value of the concrete. Steam cured reduced by 11.0% and 15.3% of drying shrinkage value of concrete mixture r-R100F25 in Series I and II, respectively.

Chloride Penetrability

The resistances against chloride-ion penetration of concrete in Series I and II with and without steam curing are given in Tables 6-18 and 6-19, respectively. It was found Tables 6-18 and 6-19 that the use of fly ash as a partial replacement of cement increased the resistance against chloride ion penetration. The resistance to chloride-ion penetration of steam cured conventional and recycled aggregate concrete mixtures with fly ash in Series I and II were increased at both test ages of 28 and 90 days. At 28 days, the concrete mixture r-R100F25 with 100% recycled aggregates, 25% fly ash and with standard water curing in Series I and II achieved the total charge passed in coulombs of 4729 and 3818, respectively, whereas the corresponding concrete mixtures with steam curing achieved the total charge passed in coulombs of 2347 and 2047, respectively; a reduction of 50.4 and 46.4%, respectively; in comparison with the total charge passed in coulombs of the concrete mixtures with standard water curing. The improvement was significant at 90 days for both curing methods.

Furthermore, it was found that steam curing increased the resistance against chloride-ion penetration of recycled aggregate concrete with fly ash. At the age of 28 days, concrete mixture r-R0F25 in Series I with standard water curing achieved the total charge passed in coulombs of 3430, whereas the corresponding concrete mixture with steam curing achieved the total charge passed in coulombs of 1756, a reduction of 48.9% in comparison with the total charge passed in coulombs of the concrete with standard water curing. However, the total charge passed charge in coulombs of the concrete made with 100% recycled aggregate and 25% fly ash (r-R100F25) with steam curing was lower 56.7% than that the corresponding concrete with standard water curing. This could be attributed to the pozzolanic action and spherical particles due to fly ash.

Table 6-15 Static elasticity modulus values of concrete in series I mixtures

Notation	Fly ash (%)	Recycled aggregate (%)	Elasticity modulus (GPa)			
			Standard water cured		Steam cured	
			28-day	90-day	28-day	90-day
R0	0	0	27.7	29.9	27.7	29.9
R20	0	20	26.8	28.8	26.4	28.8
R50	0	50	25.3	26.6	24.9	26.6
R100	0	100	23.9	24.7	23.8	23.7
r-R0F25	25	0	29.0	31.7	27.6	29.8
r-R20F25	25	20	28.9	29.9	26.9	28.8
r-R50F25	25	50	28.7	29.1	26.4	26.5
r-R100F25	25	100	23.2	24.4	24.9	25.2
r-R0F35	35	0	28.5	29.8	25.5	27.6
r-R20F35	35	20	26.3	28.3	23.5	25.4
r-R50F35	35	50	24.9	26.4	22.9	24.3
r-R100F35	35	100	22.6	24.8	22.2	23.9

Table 6-16 Static elastic modulus values of concrete in series II mixtures

Notation	Fly ash (%)	Recycled aggregate (%)	Elastic modulus (GPa)			
			Standard water cured		Steam cured	
			28-day	90-day	28-day	90-day
R0	0	0	38.7	39.5	32.3	34.3
R20	0	20	29.1	36.5	30.4	34.3
R50	0	50	26.0	33.2	26.6	31.0
R100	0	100	23.4	28.5	22.8	27.6
r-R0F25	25	0	36.3	34.6	32.0	33.6
r-R20F25	25	20	29.3	31.6	28.5	31.9
r-R50F25	25	50	27.1	29.1	30.2	30.6
r-R100F25	25	100	23.2	26.2	25.5	26.5
r-R0F35	35	0	31.3	33.9	29.6	32.3
r-R20F35	35	20	26.3	30.5	29.8	31.0
r-R50F35	35	50	23.2	25.9	23.8	31.6
r-R100F35	35	100	23.2	28.9	27.4	29.2

Table 6-17 Drying shrinkage values of concrete in series I and II mixtures at 112 days

Notation	Fly ash (%)	Recycled aggregate (%)	Drying shrinkage ($x10^{-6}$)			
			Standard water cured		Steam cured	
			Series I	Series II	Series I	Series II
R0	0	0	405	389	350	334
R20	0	20	447	412	382	352
R50	0	50	476	435	410	370
R100	0	100	540	470	466	401
r-R0F25	25	0	364	350	321	298
r-R20F25	25	20	386	371	339	315
r-R50F25	25	50	412	392	358	333
r-R100F25	25	100	435	425	387	360
r-R0F35	35	0	353	335	302	281
r-R20F35	35	20	379	360	319	302
r-R50F35	35	50	391	374	336	315
r-R100F35	35	100	424	403	358	339

Table 6-18 Chloride-ion penetrations of in series I concrete mixtures

Notation	Fly ash (%)	Recycled aggregate (%)	Total charge passed (coulombs)			
			Standard water cured		Steam cured	
			28-day	90-day	28-day	90-day
R0	0	0	6291	4940	6694	5321
R20	0	20	6572	5194	6874	5432
R50	0	50	6687	5425	6924	5660
R100	0	100	6905	5835	7015	5921
r-R0F25	25	0	3430	2191	1756	849
r-R20F25	25	20	3903	2475	1838	1093
r-R50F25	25	50	4169	2856	1968	1223
r-R100F25	25	100	4729	3314	2047	1419
r-R0F35	35	0	3286	2356	1164	789
r-R20F35	35	20	3644	2503	1211	894
r-R50F35	35	50	3858	2619	1285	908
r-R100F35	35	100	4079	2749	1336	1049

Table 6-19 Chloride-ion penetrations of in series II concrete mixtures

Notation	Fly ash (%)	Recycled aggregate (%)	Total charge passed (coulombs)			
			Standard water cured		Steam cured	
			28-day	90-day	28-day	90-day
R0	0	0	4535	3254	4839	3624
R20	0	20	4721	3478	4924	3762
R50	0	50	4962	3697	5073	3856
R100	0	100	5231	3958	5306	4027
r-R0F25	25	0	2599	715	1552	317
r-R20F25	25	20	3038	937	1865	479
r-R50F25	25	50	3263	1275	1838	548
r-R100F25	25	100	3818	1759	2047	978
r-R0F35	35	0	2500	1109	971	510
r-R20F35	35	20	2981	1456	918	530
r-R50F35	35	50	3795	1066	1483	430
r-R100F35	35	100	3969	1789	1488	539

Creep strain

Figure 6-8 and Figure 6-9 show the creep strain measured at 120 days and the creep development of the concrete mixtures in Series I with 25% fly ash, respectively. Each presented value is the average of three measurements. In the creep test, the applied load was equivalent to 35 % of the 28-day compressive strength of the concrete. 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. The concrete made with 100% recycled aggregate has largest creep value. This result was discussed in chapter 5. It was found from Figure 6-8 and Figure 6-9 that the use of initial steam curing regimes reduced the creep strain of the recycled aggregate concrete and conventional concrete incorporating fly ash. At the age of 120 days, the concrete mixture r-R100F25 made with 100% recycled aggregate, 25% fly ash and with standard water curing in Series I mixtures achieved in creep value of 514 microstrain, whereas the corresponding concrete with steam curing achieved creep strain value of 408 microstrain, respectively; a reduction of 20.6 %, in comparison with the creep strain of the corresponding concrete mixture with standard water curing. These results are similar to those reported for natural aggregate concrete with GGBFS by Brooks et al (1996). In according with Brooks et al (1996) Steam curing reduces the long-term shrinkage and creep strain of conventional and recycled aggregate concrete probably because of lower hardened cement paste content due to the acceleration of hydration at a higher temperature and fly ash replaced cement.

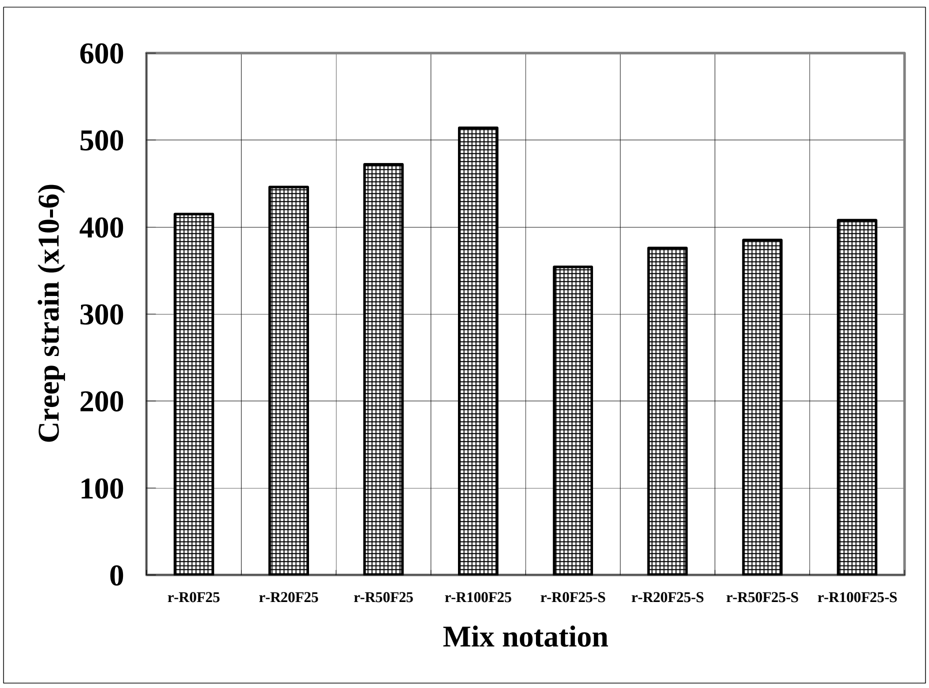


Figure 6-8 – Creep strain at 120 days of the concrete mixture in Series I

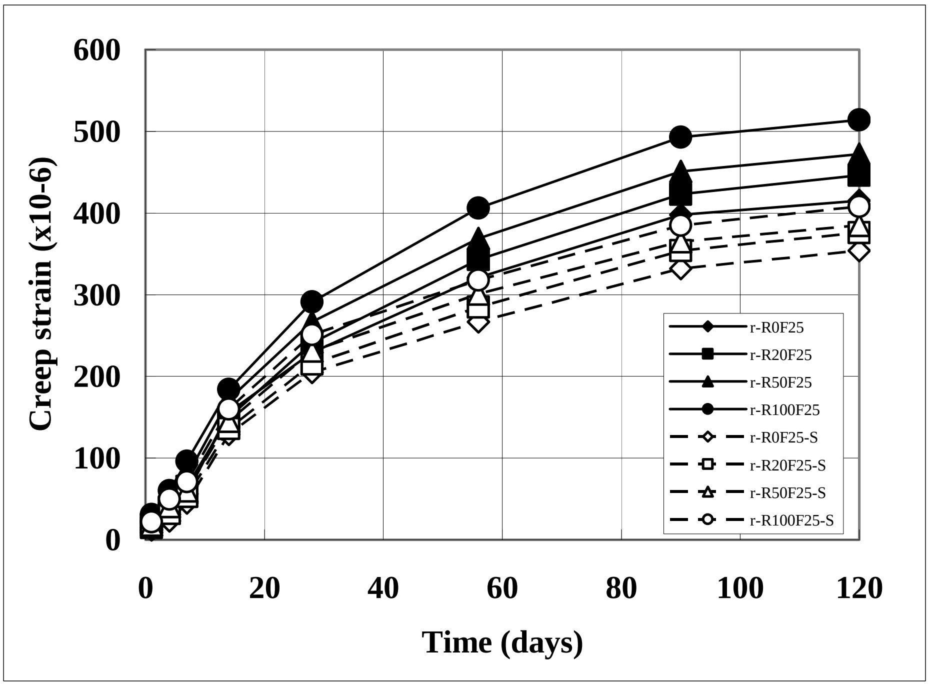


Figure 6-9 – Creep strain vs. time since loading of the concrete mixtures in Series I

6.2.2.2 Use of fly ash as an additional mineral admixture

In this section, the results of steam curing on the hardened properties of recycled aggregate concrete prepared with fly ash as additional mineral admixture in Series III, IV, V, and VI were presented and discussed.

Compressive Strength

The compressive strength of concrete mixtures made with fly ash was determined at the curing age of 1, 4, 7, 28 and 90 days. The test results of concrete with 25% fly ash in Series III, IV, V and VI with standard water curing are given in Table 5-5, 5-6, 5-7 and 5-8, respectively, and the test results of the corresponding concrete with steam curing are presented in Table 6-20 and Table 6-21. It can be seen from Table 6-1 and Table 6-2 that the compressive strengths of concrete at all curing ages in four series decreased with an increase in the recycled aggregate content. These results have been discussed in chapter 5 and above section (6.2.1) in this chapter. The results showed that the early ages (1, 4, and 7days) compressive strengths of the steam cured concrete with 25% fly ash in four series were higher than those of the water cured concrete. At 1 day, the concrete mixture a-R100F25 with 100% recycled aggregate, 25% fly ash and with standard water curing in Series III, IV, V and VI achieved compressive strength of 16.3, 17.5, 21.5 and 20.9 MPa, whereas the corresponding concrete mixtures with steam curing achieved compressive strength of 31.8, 40.4, 50.3 and 55.5 MPa, respectively; an increase of 92.7, 130.9, 134.0 and 165.6%, respectively, in comparison with the strength of the corresponding concrete mixtures with standard water curing. The relative compressive strength indicated in Figure 6-10 was the ratio of the compressive strength of the concrete to that of the series III mixtures of water cured natural aggregate concrete at 28 days. Figure 6-10 indicated that the 28-day compressive strengths of the steam cured concrete were lower than that of the water cured concrete. Moreover, the rate of gain in strength of the steam cured concrete was much lower than that of the water cured concrete after 28 day. However, the detrimental effect of steam curing on the compressive strength diminished as the replacement level increased. At the age of 28 days, the recycled aggregate replacement level of 20 % and addition of fly ash 25%, the compressive strength of the steam cured concrete mixtures a-R20F25-s was 1.8%, 5.7%, 3.2%, and 7.6% lower than that of the water cured concrete mixtures a-R20F25 in Series III, IV, V, and VI, respectively. However, at the recycled aggregate replacement level of 100 % and addition of fly ash 25%, the compressive strength of the steam cured concrete mixtures a-R100F25-s in four series was not significant change comparing to the water cured concrete mixtures a-R100F25. Also, the compressive strengths were significant increased with decrease in the water-to-cement ratio. Figure 6-10 also indicated that at 28 days, the compressive strength of 100% recycled aggregate and addition of 25% fly ash concrete mixtures a-R100F25-s made with water-to-cement ratio (W/C) of 0.45 was higher than that the natural aggregate concrete mixture a-R0F25-s made with W/C ratio of 0.55. The compressive strength of 100% recycled aggregate and addition of fly ash 25% (a-R100F25-s) made with W/C ratio of 0.40 was increased by 37.6% and 27.6% than that the natural aggregate concrete mixtures a-R0F25-s made with W/C ratios of 0.55 and 0.50, respectively.

It can be obtained from Table 6-20 that at the all test ages, the compressive strength of steam cured concrete was increased with an increase the fly ash content. At 1 day, the concrete mixture a-R100F25-s achieved compressive strength of 31.8 MPa, whereas concrete mixture a-R100F35-s achieved compressive strength of 37.6; an increase of

18.2% in comparison with the strength of the concrete mixture a-R100F25-s. Similar results were obtained for the concrete mixtures with steam curing.

Table 6-20 – compressive strength of the concrete mixtures in Series III with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
a-R0 F25	25	0	0.44	34.5	39.3	43.1	49.8	65.0
a-R20F25	25	20	0.44	33.2	36.9	40.4	51.0	64.2
a-R50F25	25	50	0.44	32.4	34.7	38.8	50.9	63.3
a-R100F25	25	100	0.44	31.8	33.7	37.6	49.9	64.2
a-R0F35	35	0	0.41	43.2	45.3	48.9	61.6	72.9
a-R20F35	35	20	0.41	41.6	44.2	46.9	59.3	71.8
a-R50F35	35	50	0.41	39.5	42.5	45.1	57.9	69.3
a-R100F35	35	100	0.41	37.6	39.5	42.1	56.9	68.2

Table 6-21 – Compressive strength of the concrete mixtures in Series IV, V, and VI with steam curing

Notation	Fly ash (%)	Recycled aggregate (%)	W/B	Compressive strength (MPa)				
				1-day	4-day	7-day	28-day	90-day
Series IV								
a-R0 F25	25	0	0.40	40.4	44.4	47.2	53.4	66.4
a-R20F25	25	20	0.40	38.7	42.5	44.2	52.8	66.3
a-R50F25	25	50	0.40	38.2	41.6	42.2	50.7	69.9
a-R100F25	25	100	0.40	37.3	40.4	41.6	50.9	69.6
Series V								
a-R0 F25	25	0	0.36	49.5	53.9	58.1	67.3	79.8
a-R20F25	25	20	0.36	50.1	53.2	57.6	65.2	77.5
a-R50F25	25	50	0.36	49.3	53.5	55.7	64.3	76.4
a-R100F25	25	100	0.36	46.9	50.3	53.2	63.7	73.2
Series VI								
a-R0 F25	25	0	0.32	51.8	59.3	61.1	71.3	76.9
a-R20F25	25	20	0.32	50.3	58.4	60.2	68.7	76.1
a-R50F25	25	50	0.32	50.1	57.9	60.9	69.2	77.9
a-R100F25	25	100	0.32	48.6	55.5	59.1	68.0	78.8

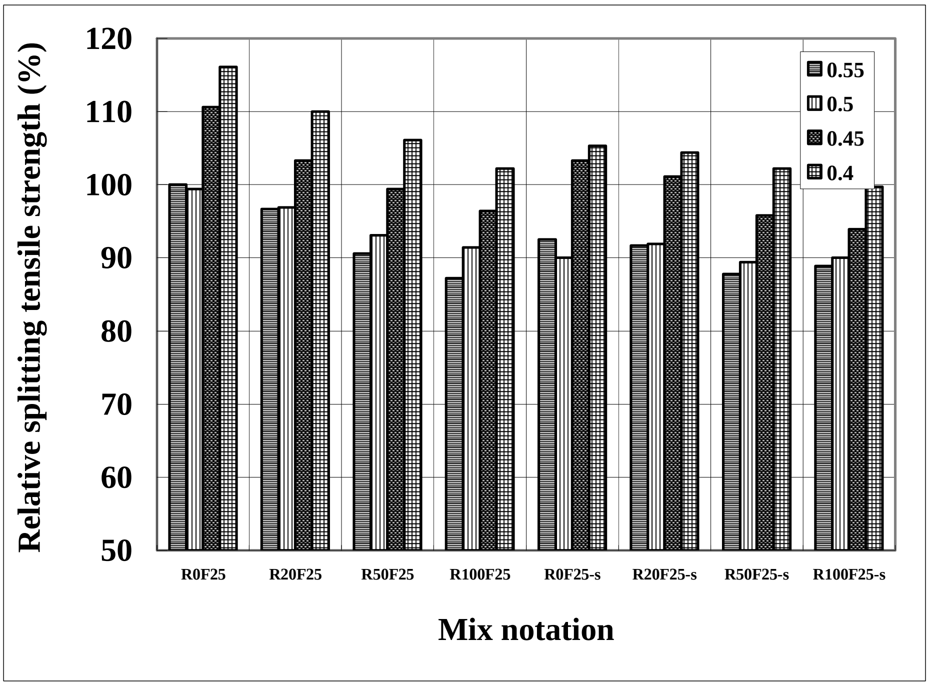


Figure 6-10 – Relative compressive strength of the concrete in four series mixtures with and without steam curing at 28 days

Splitting Tensile Strength

The splitting tensile strength of concrete mixtures made with fly ash was determined at curing age of 1, 4, 7, 28 and 90 days. The test results of concrete with 25% fly ash in Series III, IV, V and VI with standard water curing are given in Table 5-9, 5-10, 5-11 and 5-12, respectively, and the test results of the corresponding concrete with steam curing are presented in Table 6-22 and Table 6-23. The results showed that at the all test ages, an increase in the recycled aggregate content decreased the splitting tensile strength of the steam cured concrete. At the early ages (1, 4 and 7 days), the splitting tensile strengths of the steam cured concrete with fly ash in four series were higher than those of the water cured concrete. It can be obtained from Tables 5-9 to 5-12, 6-22 and 6-23 that at 1 day, the concrete mixtures a-R100F25 with 100% recycled aggregate, addition of 25% fly ash and with standard water curing in Series III, IV, V and VI achieved splitting tensile strength of 1.33, 1.42, 1.75 and 2.03 MPa, whereas the corresponding concrete mixtures a-R100F25-s with steam curing achieved splitting tensile strength of 2.24, 2.35, 2.44 and 2.73 MPa, respectively; an increase of 40.6, 39.5, 29.3 and 25.6%, respectively, in comparison with the strength of the concrete mixtures a-R100F25 with standard water curing. The relative splitting tensile strength indicated in Figure 6-11 was the ratio of the splitting tensile strength of the concrete to that of the series III mixtures of water cured natural aggregate concrete at 28 days. Figure 6-11 indicated that like compressive strength results, splitting tensile strength of concrete mixtures with fly ash and steam curing also increased with a decrease in W/C ratio from 0.55 to 0.40. Figure 6-11 showed that at the test age of 28 days, the splitting tensile strength of concrete mixture a-R100F25-s with 100% recycled aggregate, addition of 25% fly ash and made with W/C ratio of 0.45 was higher than that the natural aggregate concrete a-R0F25-s made with W/C ratio of 0.55. The splitting tensile strength of concrete mixture a-R100F25-s made with W/C ratio of 0.40 was increased by 35% compared with the natural aggregate concrete mixture a-R0F25-s made with W/C ratio of 0.55.

It can be also obtained from Table 6-22 that like compressive strength results, at the all test ages, the splitting strength of steam cured concrete was increased with an increase the fly ash content. At the 1 day, the concrete mixture a-R100F25-s achieved splitting tensile strength of 2.24 MPa, whereas concrete mixture a-R100F35-s achieved splitting tensile strength of 2.85; an increase of 27.2% in comparison with the strength of the concrete mixture a-R100F25-s. Similar results were obtained for the concrete mixtures with steam curing at the ages of 4, 7, 28 and 90 days.

Table 6-22 – Splitting tensile strength of the concrete mixtures in Series III with steam curing

Notation	**Fly ash** (%)	**Recycled aggregate** (%)	W/B	**Compressive strength (MPa)**				
				1-day	4-day	7-day	28-day	90-day
a-R0 F25	25	0	0.44	2.42	2.60	2.99	3.33	3.26
a-R20F25	25	20	0.44	2.38	2.56	2.89	3.30	3.31
a-R50F25	25	50	0.44	2.32	2.44	2.71	3.22	3.36
a-R100F25	25	100	0.44	2.24	2.31	2.59	3.20	3.90
a-R0F35	35	0	0.41	3.24	3.45	3.55	3.64	4.26
a-R20F35	35	20	0.41	3.14	3.21	3.46	3.53	3.96
a-R50F35	35	50	0.41	2.96	3.19	3.40	3.49	3.74
a-R100F35	35	100	0.41	2.85	3.06	3.32	3.41	3.66

Table 6-23 – Splitting tensile strength of the concrete mixtures in Series IV, V, and VI with steam curing

Notation	**Fly ash (%)**	**Recycled aggregate (%)**	**W/B**	**Compressive strength (MPa)**				
				1-day	**4-day**	**7-day**	**28-day**	**90-day**
Series IV								
a-R0 F25	25	0	0.40	2.58	2.70	2.91	3.24	3.85
a-R20F25	25	20	0.40	2.47	2.61	2.94	3.31	3.82
a-R50F25	25	50	0.40	2.37	2.57	2.81	3.22	3.71
a-R100F25	25	100	0.40	2.35	2.28	2.73	3.24	3.60
Series V								
a-R0 F25	25	0	0.36	2.62	3.25	3.65	3.72	4.12
a-R20F25	25	20	0.36	2.55	3.21	3.46	3.64	3.99
a-R50F25	25	50	0.36	2.48	3.14	3.25	3.45	3.86
a-R100F25	25	100	0.36	2.44	3.06	3.16	3.38	3.81
Series VI								
a-R0 F25	25	0	0.32	3.04	3.32	3.62	3.79	4.39
a-R20F25	25	20	0.32	3.00	3.26	3.36	3.76	4.18
a-R50F25	25	50	0.32	2.87	3.17	3.18	3.68	4.03
a-R100F25	25	100	0.32	2.73	2.95	3.11	3.59	4.04

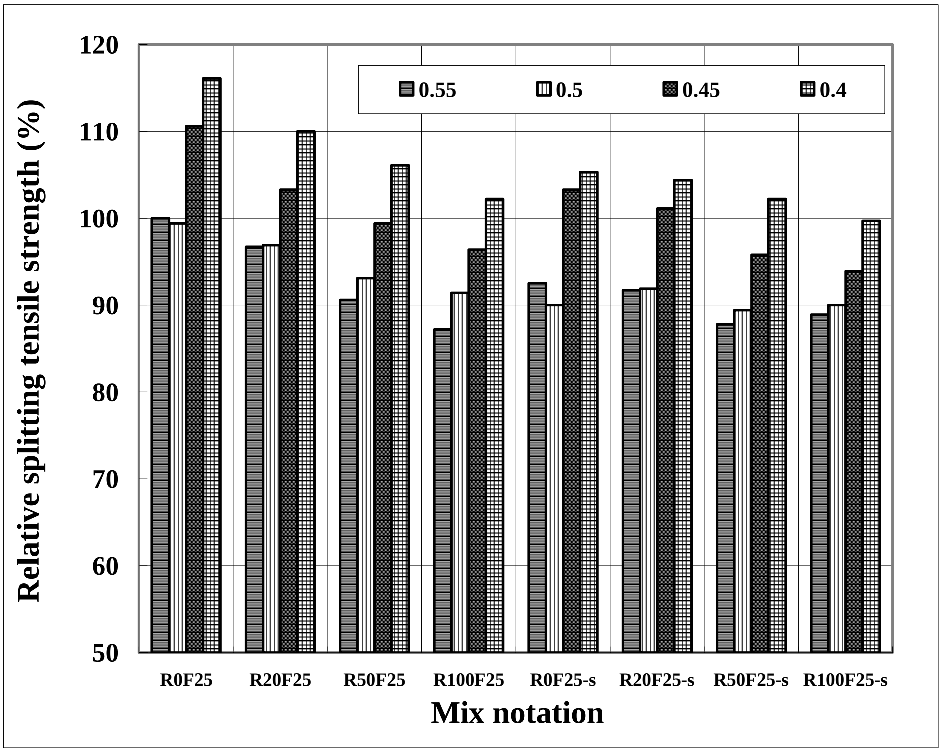


Figure 6-11- Relative splitting tensile strength of concrete in four series with and without steam curing at 28 days

Static Modulus of Elasticity

The static modulus of elasticity of concrete mixtures was determined at the ages of 28 and 90 days. Results of the concrete in four series at the ages of 28 and 90 days are presented in Figure 6-12 and Figure 6-13, respectively. Similarly, each presented value is the average of three specimens. It can be seen from Figure 6-12 and Figure 6-13 that at the same fly ash content, the static modulus of elasticity of steam cured recycle aggregate concrete decreased with an increase in the recycled aggregate content. At 28 days. The static modulus of elasticity of concrete mixtures a-R100F25-s prepared with 100% recycled aggregate, addition of 25% fly ash and with steam curing in Series III, IV, V and VI was about 13.0, 9.0, 8.0 and 8.0% lower than that of the natural aggregate concrete mixtures a-R0F25-s with steam curing, respectively. However, the detrimental effect of steam curing on the static modulus of elasticity diminished as the recycled aggregate replacement level increased (Figures 6-12 and 6-13). At the recycled aggregate replacement level of 20 % and addition of fly ash 25% (a-R20F25-s), the static modulus of elasticity of the steam cured concrete was 6.9 %, 6.3%, 2.5%, and 3.5% lower than that of the water cured concrete in Series III, IV, V, and VI, respectively. However, at the recycled aggregate replacement level of 100 % and addition of 25% fly ash (a-R100F25-s), the static modulus of elasticity of the steam cured concrete in four series was only 1 % lower than that of the corresponding concrete mixtures a-R100F25 with water curing. The results at age of 90 days indicated that there was continuous improvement in elastic modulus of the steam cured recycled and conventional aggregate concrete with fly ash beyond the age of 28 day. At the age of 90 days, the concrete mixture a-R100F25-s made with 100% recycled aggregate, addition of 25% fly ash and with steam curing in Series III, IV, V and VI achieved in the static modulus elasticity of 28.2, 30.2, 30.9 and 32.8 GPa, whereas at the age of 28 days, the corresponding concrete achieved in the static modulus elasticity of 25.9, 27.6, 29.9 and 30.5 GPa, respectively; an increase of 8.9, 9.4, 3.3 and 7.5%, respectively, in comparison with the static modulus of elasticity of the corresponding concrete mixture a-R100F25-s at 28 days. The increase in the static modulus elasticity is, of course, due to the cement and fly ash that continued to hydrate. Similar results were obtained for all concrete mixtures in four series with standard water curing and steam curing.

Figure 6-14 shows the relationship between the 28 days compressive strength and the 28 days static modulus of elasticity. The equation suggested by ACI for predicting the modulus of elasticity is also plotted in the graph. It is shown that the ACI equation over-estimates the modulus of elasticity of steam cured and standard water cured fly ash recycled aggregate concrete. In other words, the predicted deformation of a structural concrete member prepared with recycled aggregate and fly ash would be smaller than the actual value.

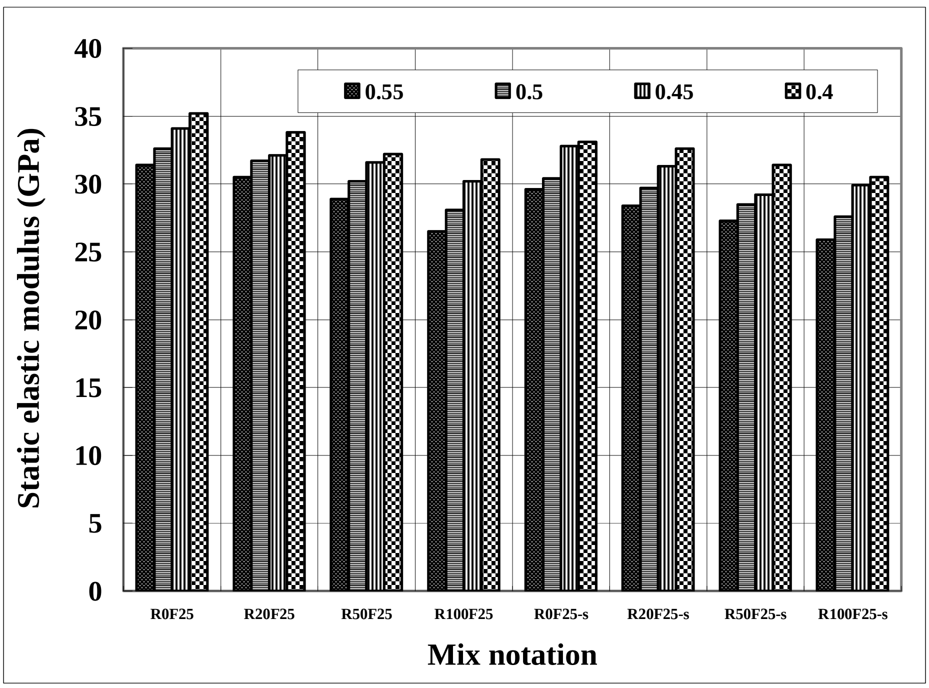


Figure 6-12- Static elastic modulus of concrete in four series mixture with and without steam curing at 28 days

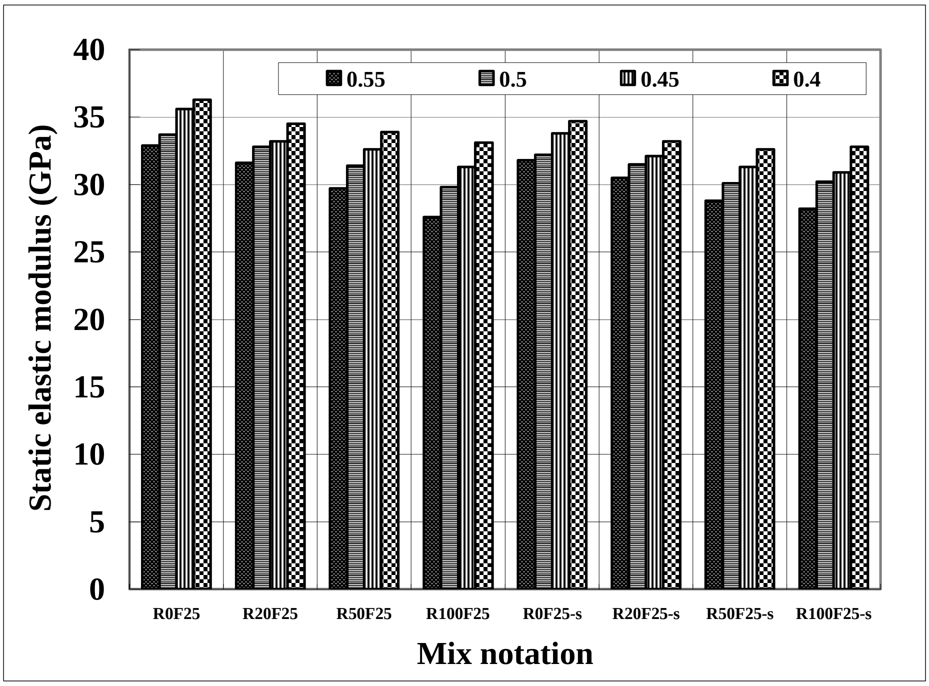


Figure 6-13 - Static elastic modulus of concrete in four series mixture with and without steam curing at 90 days

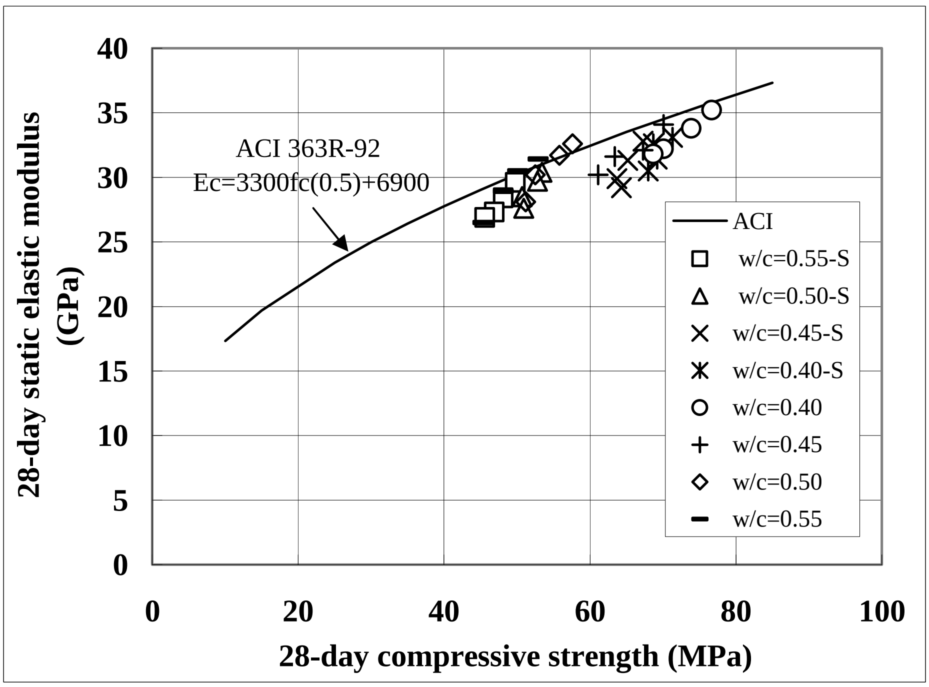


Figure 6-14 – Relationship between 28-day compressive strength and 28-day elastic modulus

Drying Shrinkage

The drying shrinkage values (tested at 112 days) of the concrete mixtures in four series are shown in Figure 6-15 that at the same fly ash content, the drying shrinkage values increased with an increase in recycled aggregate content. Figure 6-15 also indicated that steam curing reduced the drying shrinkage of the fly ash conventional and recycled aggregate concrete. At 112 days, the concrete mixture a-R100F25 made with 100% recycled aggregate, addition of 25% fly ash and with standard water curing in Series III, IV, V and VI achieved in shrinkage value of 501, 466, 458 and 410 microstrain, whereas the corresponding concrete mixture a-R100F25-s with steam curing achieved in shrinkage value of 415, 361, 347 and 329 microstrain, respectively; a reduction of 17.2, 12.5, 24.2 and 19.8 %, respectively, in comparison with the shrinkage of the corresponding concrete mixture a-R100F25 with standard water curing.

Furthermore, the drying shrinkage of steam cured conventional and recycled aggregate concrete with fly ash in Series IV, V, and VI was lower than that of the corresponding concrete in Series III which indicated that a decrease in the W/C ratio reduced the drying shrinkage.

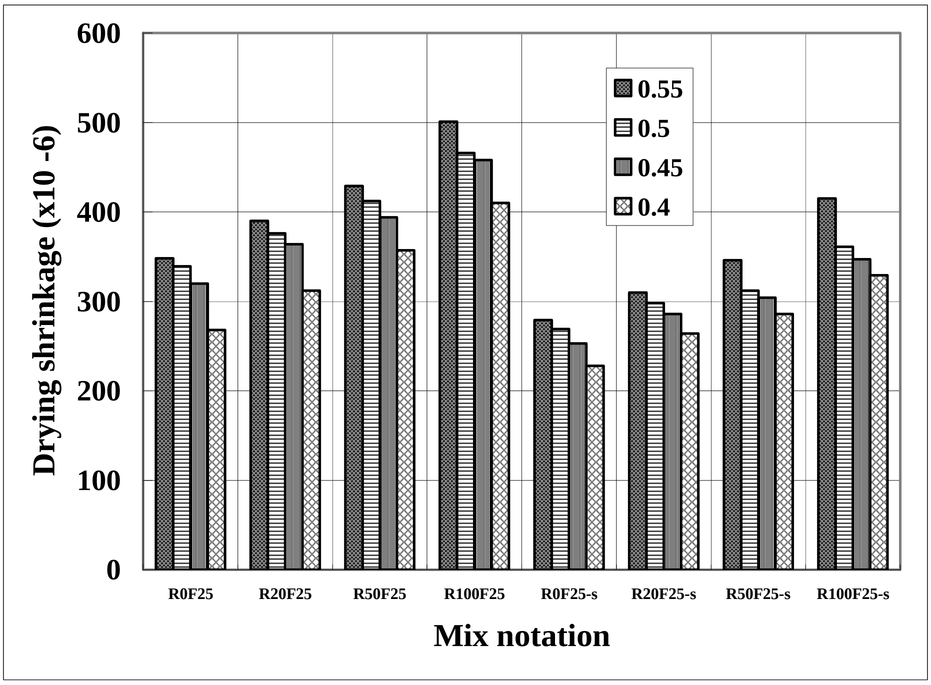


Figure 6-15 - Dying shrinkage of concrete mixtures with 25% fly ash in Series III, IV, V and VI with and without steam curing at 112 days

Creep strain

Figure 6-16 and Figure 6-17 show the creep strain measured at 120 days and the creep development of the concrete mixtures in Series III, respectively. Each presented value is the average of three measurements. Similar to above section in chapter 5 and this chapter, 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 can be fined from Figure 6-16 and 6-17 that the deformation of the concrete specimens increased with an increase in the recycled aggregate content. The concrete mixture a-R100F25 with 100% recycled aggregate and 25% fly ash has largest creep value. This was attributed to the increased volume of mortar in the recycled aggregate concrete compared to that in the conventional concrete. It was also found from Figure 6-16 and

Figure 6-17 that the use of initial steam curing regimes reduced the creep strain of the fly ash recycled aggregate concrete and conventional concrete. At 120 days, the concrete mixture a-R100F25 with 100% recycled aggregate, addition of 25% fly ash and with standard water curing in Series III achieved in shrinkage value of 496 microstrain, whereas the corresponding concrete mixture a-R100F25-s with steam curing achieved in shrinkage value of 423 microstrain, respectively; a reduction of 14.7 %, in comparison with the shrinkage of the corresponding concrete mixture a-R100F25 with standard water curing. Steam curing reduces the long-term shrinkage and creep strain of conventional and recycled aggregate concrete probably because of lower hardened cement paste content due to the acceleration of hydration at a higher temperature.

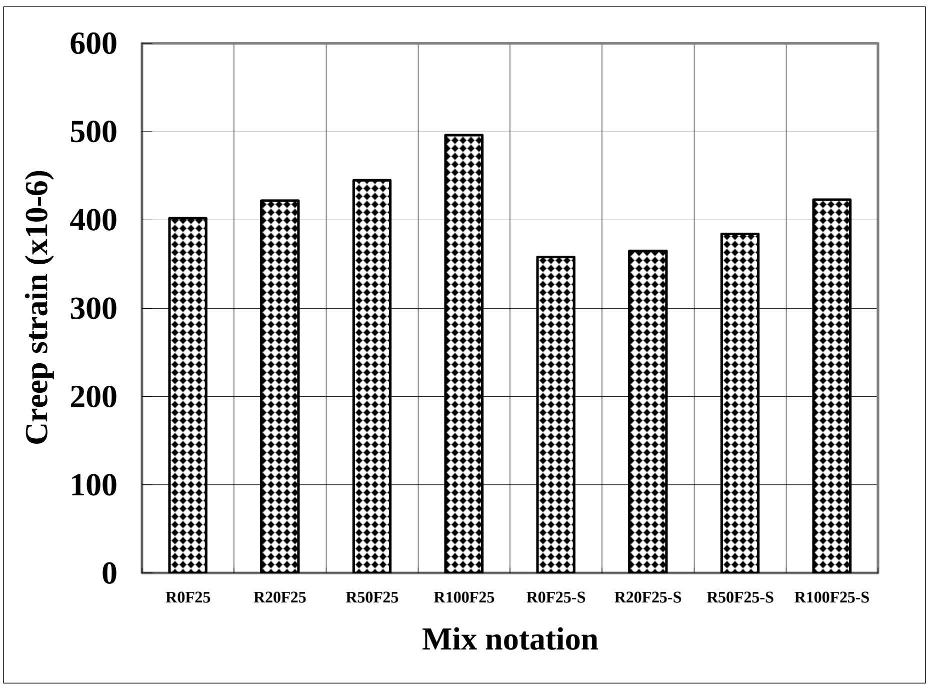


Figure 6-16 – Creep strain at 120 days of concrete mixtures in Series III

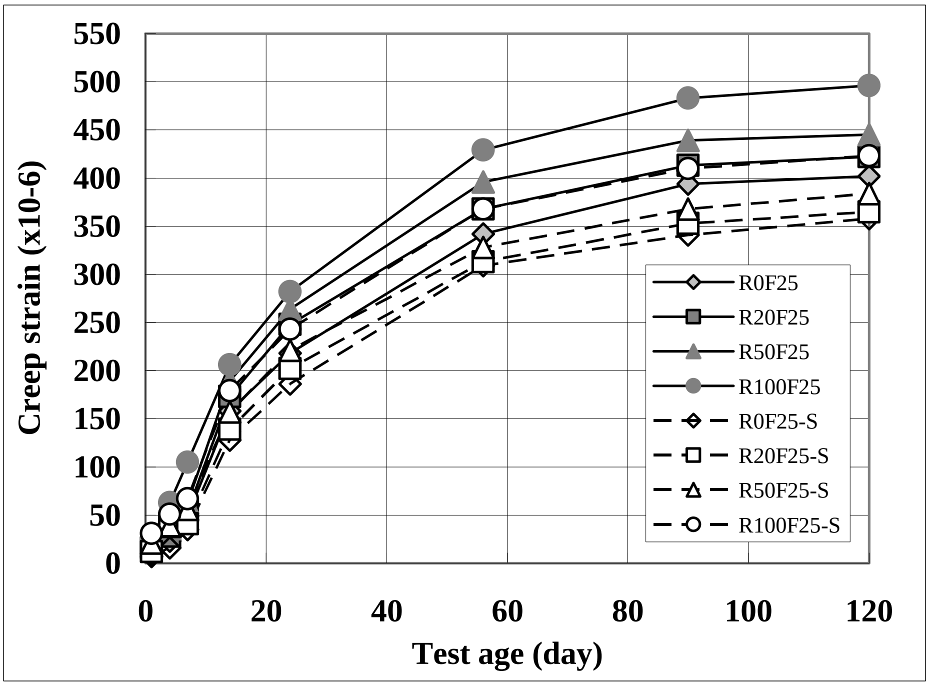


Figure 6-17- Creep strain vs. time since loading of concrete mixtures in Series III

Resistance to Chloride-Ion Penetration

The resistances against chloride-ion penetration of fly ash conventional and recycled aggregate concrete in all four series at the ages of 28 and 90 days are given in figure 6-18 and figure 6-19, respectively. The results indicated that the resistance to chloride-ion penetration of concrete mixture with fly ash in Series III, IV, V and VI decreased with an increase in the recycled aggregate content. It can be obtained from figure 6-18 and figure 6-19 that at the both test ages of 28 and 90 days, steam curing increased the resistance against chloride-ion penetration of fly ash conventional and recycled aggregate concrete. At the age of 28 days, concrete mixture a-R100F25 with 100% recycled aggregate, addition of 25% fly ash and with standard water curing achieved the total charge passed in coulombs of 4236, 3012, 1882, and 1305, whereas the concrete mixture a-R100F25-s with steam cuing achieved the total charge passed in coulombs of 2614, 1925, 1132 and 569, in Series III, IV, V, and VI, respectively; a reduction of 38.3, 36.1, 39.8 and 45%, respectively, in comparison with the total charge passed in coulombs of the concrete mixture a-R100F25 with standard water curing. Similar results were obtained for all four series concrete mixtures at 90 days.

A comparison among the results of Series III, IV, V and VI revealed that a decrease in the W/C ratio also significantly increased the resistance against chloride-ion penetration of steam cured fly ash recycled and conventional concrete. At the same recycled aggregate replacement level and fly ash content, the concrete made with water-to-cement ratio of 0.40 had highest resistance to chloride-ion penetration.

The results at 90 days indicated that there was continuous and significant improvement in the resistance to chloride-ion penetration of the fly ash conventional and recycled aggregate beyond the age of 28 days. At the age of 90 days, the concrete mixtures a-R100F25-s made with 100% recycled aggregate, addition of 25% fly ash and with steam curing in Series III, IV, V and VI achieved in total charge passed in coulombs of 1902, 1421, 846 and 469, whereas at the age of 28 days, the corresponding concrete mixtures achieved in total charge passed in coulombs of 2614, 1925, 1132 and 569, respectively; a reduction of 28.2, 26.2, 26.3 and 17.6 %, respectively, in comparison with the total charge passed in coulombs of the corresponding concrete mixture at 28 days. The increase in the resistance to chloride-ion penetration is, of course, due to the cement that continued to hydrate and higher C-S-H gel due to the acceleration of hydrated fly ash and cement at a higher temperature. Similar results were obtained for all concrete mixtures in four series with standard water curing and steam curing.

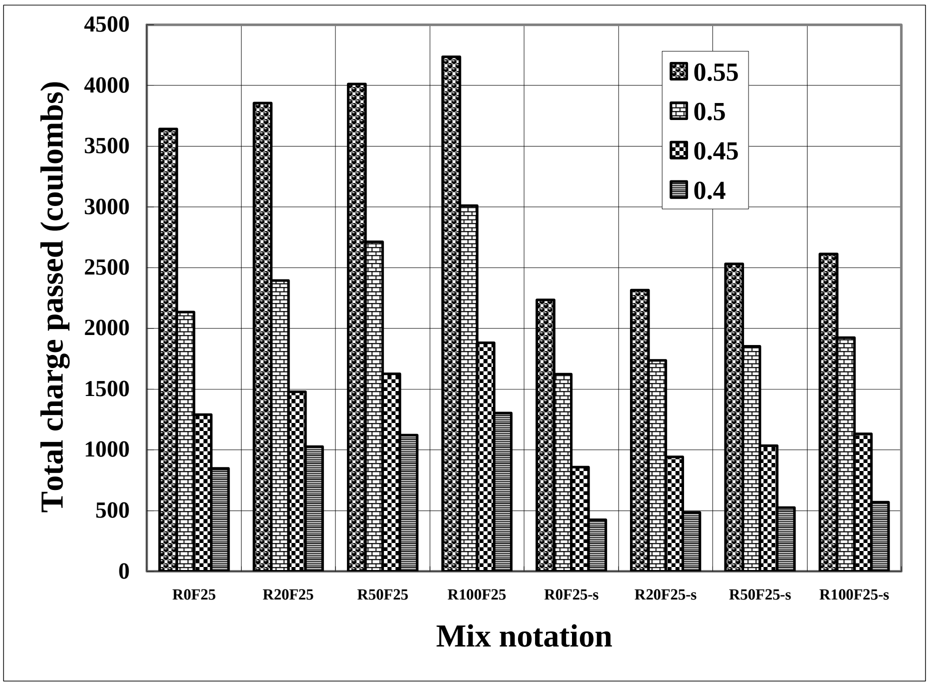


Figure 6-18 - Total charge passed in coulombs of the concrete with 25% fly ash in Series III, IV, V and VI with and without steam curing at 28 days

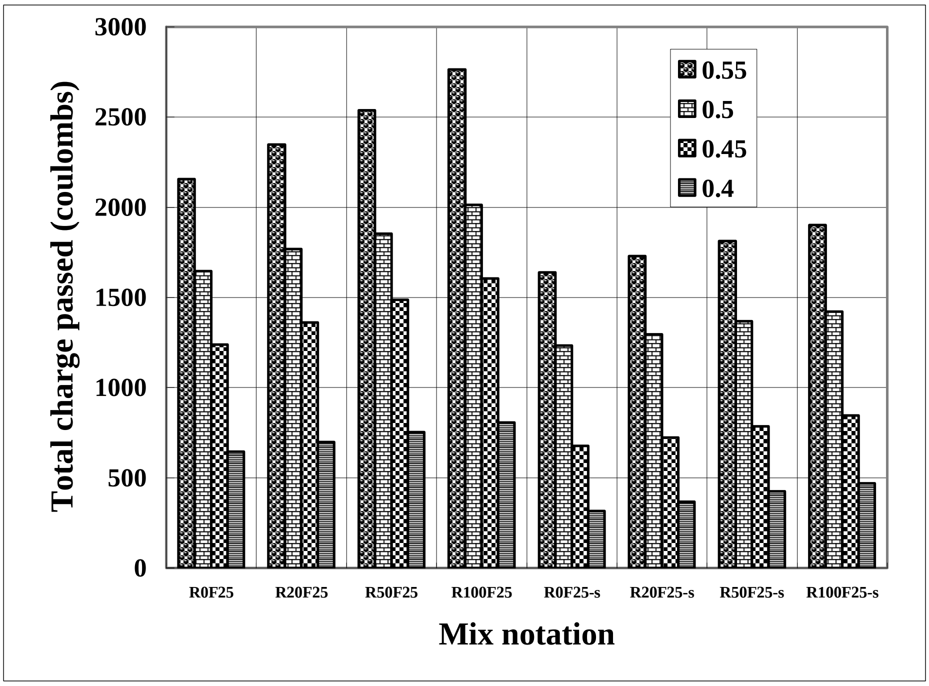


Figure 6- 19- Total charge passed in coulombs of the concrete with 25% fly ash in Series III, IV, V and VI with and without steam curing at 90 days

6.3 SUMMARY

In this chapter, influences of steam curing on hardened properties of recycled aggregate concrete and fly ash was used as a substitution of cement and as an additive admixture in conventional and recycled aggregate were investigated. The compressive and splitting tensile strength, static modulus of elasticity, drying shrinkage, chloride-ion penetration and creep strain of the concrete with or without fly ash and with steam curing were determined and discussed. Based on the results of this investigation and discussions, the following summaries can be drawn from the above test results:

- Steam curing at 65 ºC increased the early ages (1, 4, and 7-day) strength of all concrete mixtures compared to that of the water cured concrete. However the 28 and 90-day strengths of the steam cured concrete were lower than those of the water cured concrete.

- Since recycled aggregates are generally more porous than natural aggregates, the detrimental effect of steam curing on the long-term hardened properties of natural aggregate concrete are reduced in the recycled aggregate concrete and fly ash recycled aggregate concrete.

- Steam cuing regime decreased the static modulus of elasticity values of recycled and conventional aggregate. However, the detrimental effect of steam curing on the concrete against chloride-ion penetration of recycled aggregate concrete are reduced as an increase recycled aggregate.

- The drying shrinkage of concrete increased with an increase in the recycled aggregate replacement level. The drying shrinkage value of concrete prepared with 100% recycled aggregate was about 30 % higher than that of natural aggregate concrete. Nevertheless, steam curing reduced the drying shrinkage. The reduction was about 15 % for the steam cured concrete prepared with 100 % recycled aggregate.

- Steam curing reduced the drying shrinkage of fly ash recycled aggregate concrete. When fly ash was used a substitution 25% of cement and addition of 25% fly ash, the reduction was about 10-15% and 20-25% for the steam cured concrete prepared with 100% recycled aggregate, respectively.

- Steam curing reduced the creep strain of recycled aggregate and fly ash recycled aggregate concrete. When fly ash was used a substitution 25% of cement and addition of 25% fly ash, the reduction was about 27% and 17% for the steam cured concrete prepared with 100% recycled aggregate, respectively.

- The resistance against chloride-ion penetration of the concrete decreased with an increasing recycled aggregate content where concrete prepared with 100% recycled aggregate had the highest charge passed. An initial steam curing regime decreased the resistance of the concrete against chloride-ion penetration. However, the detrimental effect of steam curing on the concrete against chloride-ion penetration of recycled aggregate concrete are reduced as an increase recycled aggregate.

- An initial steam curing regime significantly increased the resistance of the fly ash conventional and recycled aggregate concrete against chloride-ion penetration at both ages of 28 and 90 days.

- 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.

CHAPTER 7 MICROSTRUCTURE OF RECYCLED AGGREGATE CONCRETE MADE WITH FLY ASH AT DIFFERENT CURING CONDITIONS

7.1 INTRODUCTION

In this chapter, SEM and EDX examination of concrete mixture in Series I and pore size distribution of concrete mixtures in Series I and II with standard water curing and steam curing were carried out in order to analyse any possible hardened properties problem. For SEM and EDX-map examination, the test age of the concretes were 28 days and for pore size distribution test, the age of the concretes were 28 and 90 days when they where analyzed.

7.2 VISUAL INSPECTION OF SAMPLES

The visual inspection was useful to determine the homogeneity of the concrete with respect to the distribution of the aggregate in concrete, and the density of the concretes.

7.2.1 Aggregates distribution and composition

The recycled aggregate concretes (R0, R20, R50 and R100) had a homogeneous density, and a regular distribution of aggregates. The porosity of the new paste appeared to be similar in all concretes, although the recycled aggregates appeared to be far more porous than conventional aggregate, due to the attached mortar, see Figure 7.1.

The old cement paste was not as dense as the new one, however this did not affect the interfacial transition zone between the old and new paste, see Figure 7-1. These observations were consistent with result of Larranaga et al (2004).

7.2.2 Composition of recycled aggregates

As stated in Chapter 3, 50% of the recycled aggregates were original aggregates with the attached mortar. In order to analysis the existing interface transition zone, it was considered imperative to determine the class of the original coarse aggregates. A representative sample of coarse original aggregates (from recycled aggregates) was taken and was classified mainly as granite.

The mineralogy composition of the fine recycled aggregates was detected employing a SEM and EDX-map, see Section 7-3.

Figure 7-1 Recycled aggregate in the concrete

7.2.3 The new interfacial transition zone

It is convenient to differentiate the intrinsic interfaces that are formed between the paste and the aggregates. The interface is considered to have a fundamental effect on the strength of concrete.

The nature of the interface is controlled by the properties of both the aggregate and the cement paste. Aggregates used in concrete as well as the possibilities of adherent dust and dirt have varying degrees of porosity, shape and surface roughness.

Physical contact and degree of separation of the paste from the aggregate will be largely dependent on the amount of water concentrated at the interface and the amount of plastic settlement that takes place before setting.

Both these factors, which are closely interrelated, create space at the interface in which crystallization from pore solution can occur.

In recycled aggregate concrete, two interfaces exist. One is the new paste with old aggregate and the other one, old paste with old aggregate. When the old aggregate does not have any old paste adhered to its surface or in its pores, the interface develops in much the same way as with natural aggregate.

7.3 CONCRETE AND INTERFACIAL TRANSITION ZONE EXAMINED BY SEM AND EDX-MAPS

7.3.1 Original Aggregates

The fracture surface R100 was examined. Figure 7-2 shows that silica is the principal element of the original fine aggregates of the recycled aggregates.

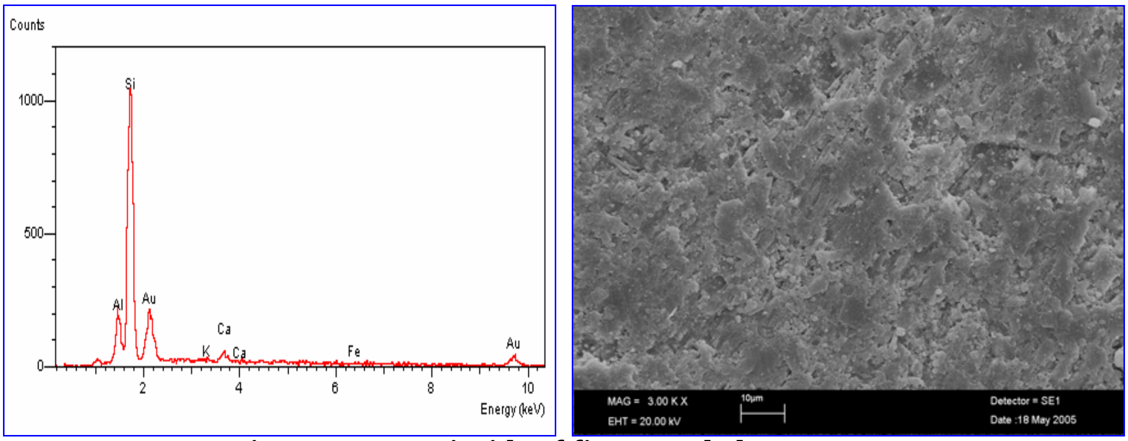


Figure 7-2 Spot inside of fine recycled aggregates

The cement paste around the original fine aggregates has the composition C-S-H of Portland cement, see figure 7-3

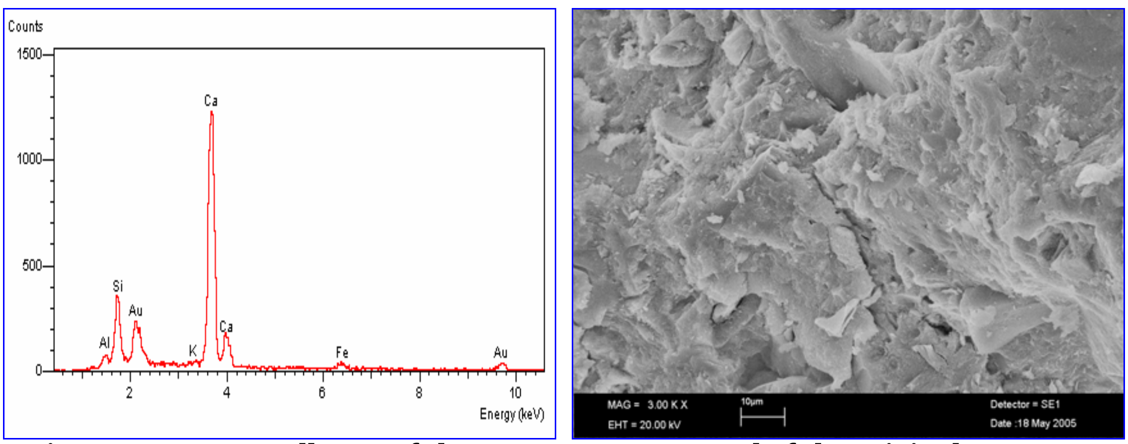


Figure 7-3 very small area of the cement paste around of the original aggregate

The cement paste of the recycled aggregates was more porous than the new paste. These aggregates were sometimes cracked due to the stress experienced during the manufacturing phases and their life span. The cracks always started in the 'Silica' original aggregates found in the recycled aggregates, they crossed the original cement paste of recycled aggregates and they ended in the interfacial with the new cement paste. The cracks were empty, no reaction product was detected.

7.3.2 Original cement paste

The cracks were clear and were not filled with any reaction product consequently they were thought to be produced in the crushing processes of the recycling operation. Figure 7-4 depicts the analysis of the recycled aggregate's cement paste composition.

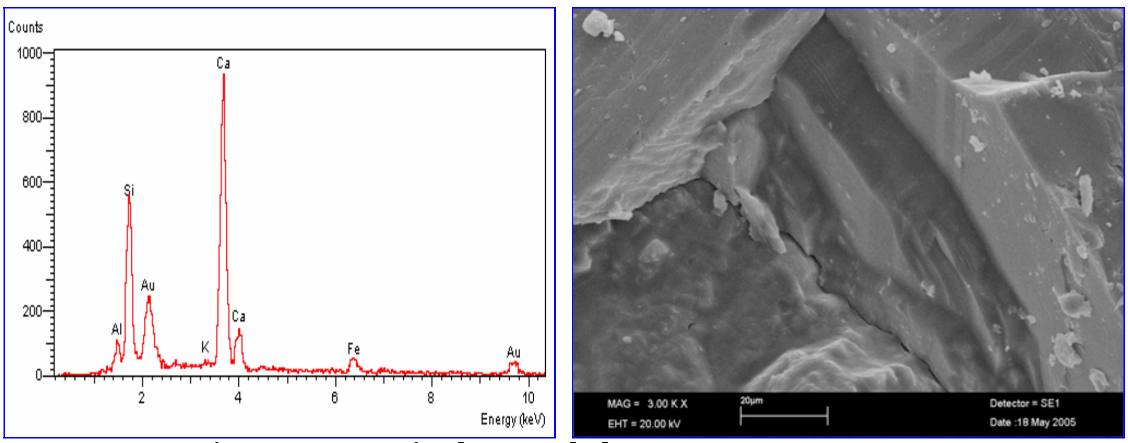


Figure 7-4 Spot in the recycled aggregate cement paste

The composition of the cement paste of the recycled aggregates was found to be a common one. The original paste was a conventional C-S-H gel and almost all of the fine aggregates had Si as a main component.

7.3.3 Interfacial transition zone

Interfacial Transition Zone between Cement Paste and Aggregate

A SEM was employed to analyze "the interfacial transition zone" of the samples of the fracture surface of the conventional and recycled aggregate concrete with and without fly ash at different curing condition where the interfaces was detected. The images of the interfacial transition zone are shown as a continuous material; see Figures 7- 5 to 7-12.

Figures 7-5 and 7-6 show a view of the interfacial transition zone between conventional aggregates and the new paste (no fly ash) with standard water curing and steam curing, respectively, at age of 28 days. It can be seen that the boundary between the cement paste and the granite aggregate was very clear (Fig. 7-5). When compared to the standard water cured concrete specimens, the interfacial transition zone of the steam cured conventional aggregate concrete was more porous. The cracks were very clear in the interfacial transition zone of steam cured conventional aggregate concrete (Fig. 7-6).

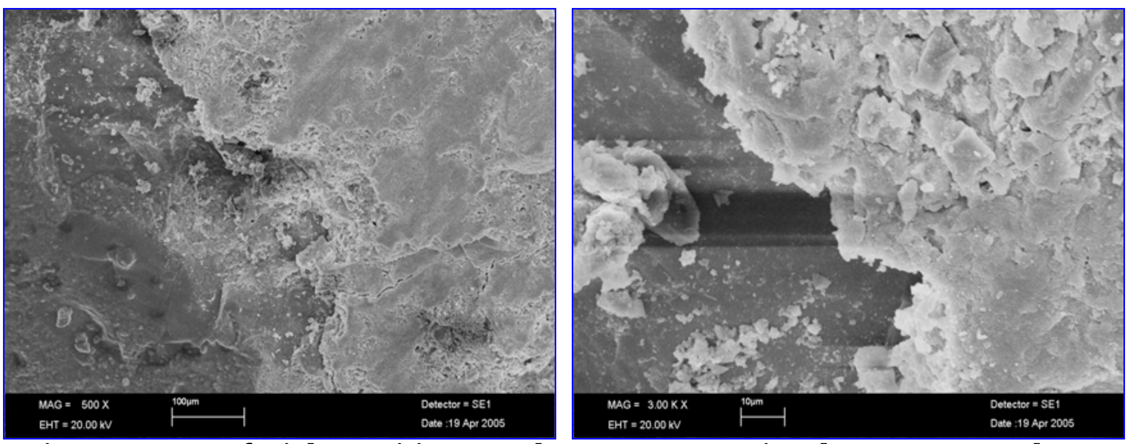


Figure 7-5 Interfacial transition zone between conventional aggregates and new paste no fly ash with standard water curing

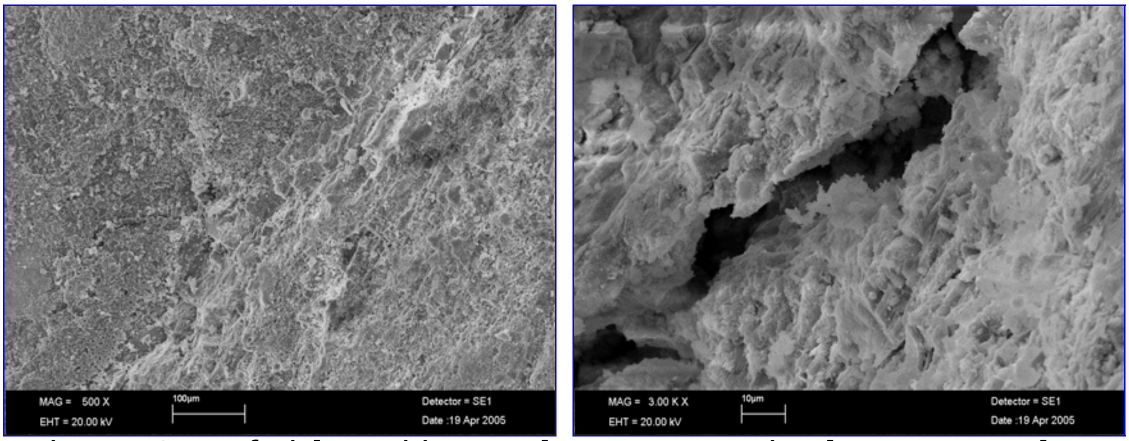


Figure 7-6 Interfacial transition zone between conventional aggregates and new paste no fly ash with steam curing

The interfacial transition zone between the recycled aggregates and the new paste (no fly ash) with standard water curing and steam curing are shown in Figure 7-7 and Figure 7-8, respectively. It can be seen that when compared to the standard water cured recycled aggregate concrete specimens, the interfacial transition zone of the steam cured recycled aggregate concrete was not significantly changed. Since recycled aggregates are generally more porous than natural aggregates, the detrimental effect of steam curing on the interfacial transition zone of natural aggregate concrete are reduced in the recycled aggregate concrete.

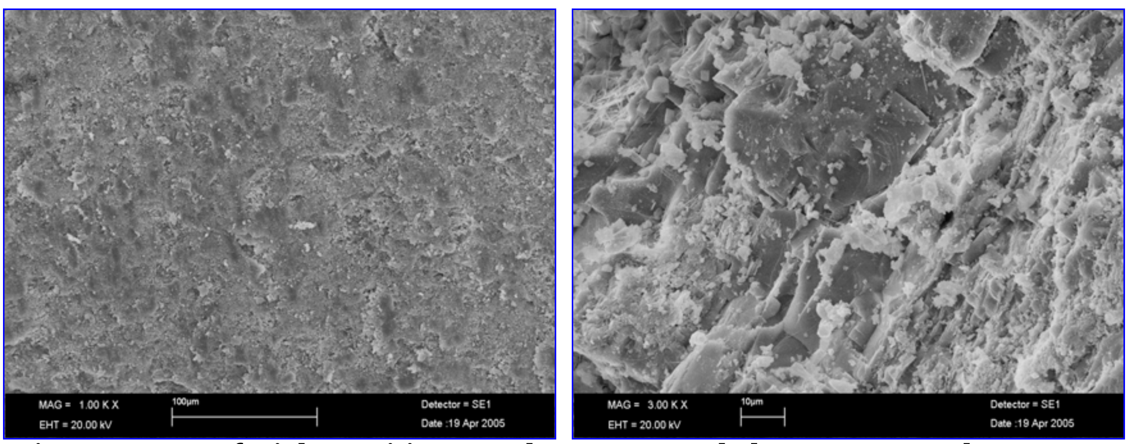


Figure 7-7 Interfacial transition zone between recycled aggregates and new paste no fly ash with standard water curing

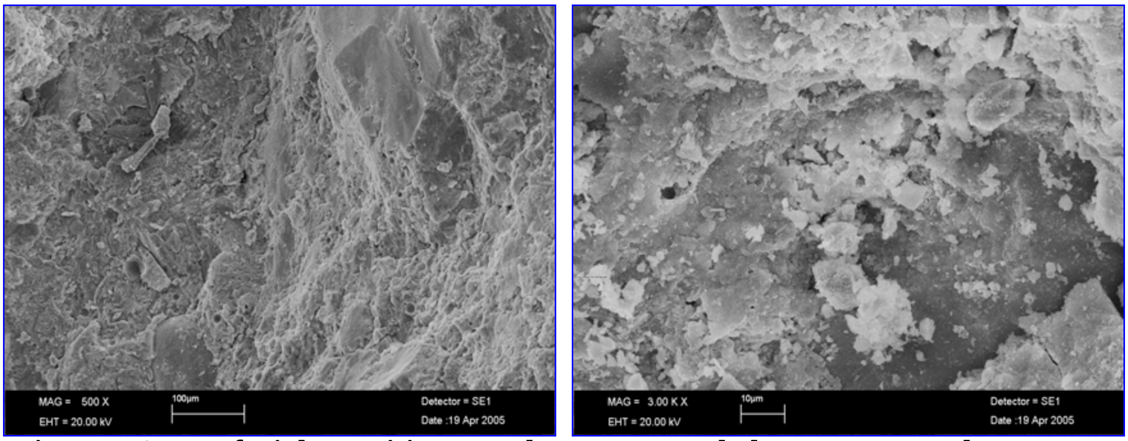


Figure 7-8 Interfacial transition zone between recycled aggregates and new paste no fly ash with steam curing

Figures 7-9 and 7-10 show the views of the ITZ between conventional aggregates and the new paste (with 25% fly ash), with standard water curing and steam curing, respectively, at age of 28 days. Comparing to the standard water cured concrete specimens the interfacial transition zone of the steam cured conventional aggregate fly ash concrete was also more porous. The cracks were very clear between the interfacial transition zone and the new paste of the steam cured conventional aggregate concrete (Fig. 7-10).

Figures 7-11 and 7-12 show the views of the ITZ between recycled aggregates and the new paste (with 25% fly ash), with standard water curing and steam curing, respectively, at age of 28 days. Comparing to the standard water cured concrete specimens the ITZ of steam cured recycled aggregate fly ash concrete was not significantly changed. The steam curing regime increased the reaction between fly ash and $Ca(OH)_2$. The C-S-H gel were very clear on fly ash surfaces in the interfacial transition zone of steam cured recycled aggregate fly ash concrete (Fig. 7-12).

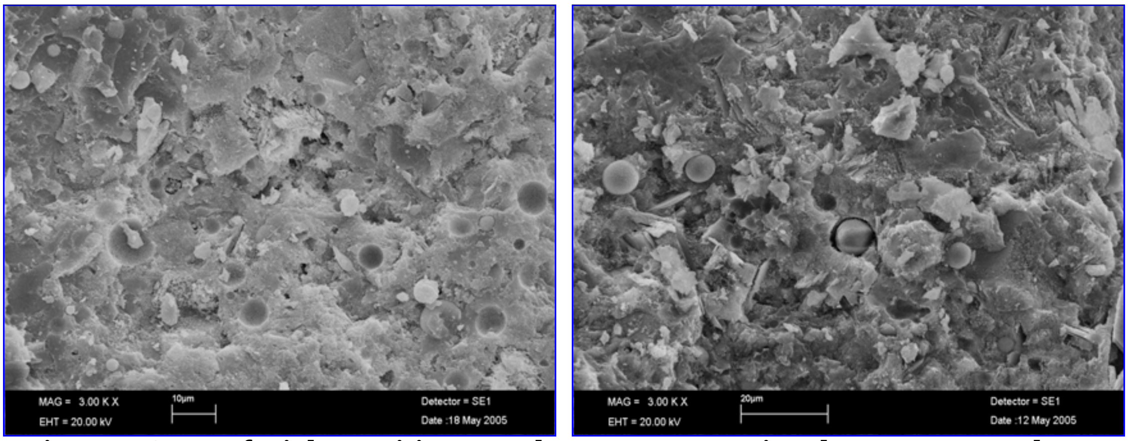


Figure 7-9 Interfacial transition zone between conventional aggregates and new paste with 25% fly ash and with standard water curing

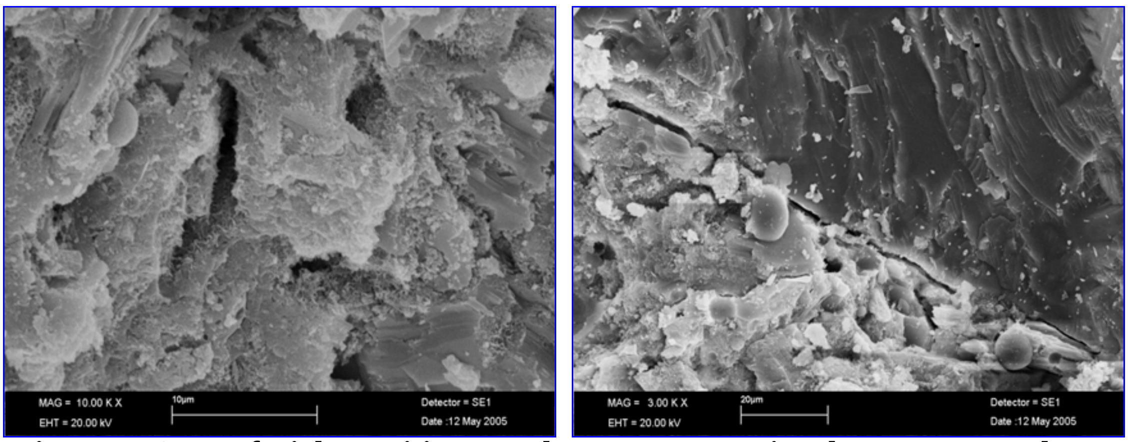


Figure 7-10 Interfacial transition zone between conventional aggregates and new paste with 25% fly ash and with steam curing

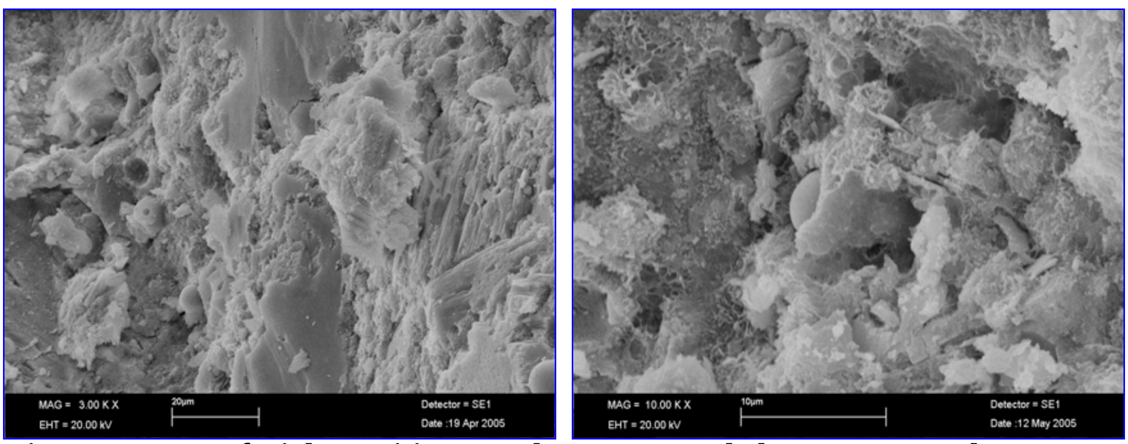


Figure 7-11 Interfacial transition zone between recycled aggregates and new paste with 25% fly ash and with standard water curing

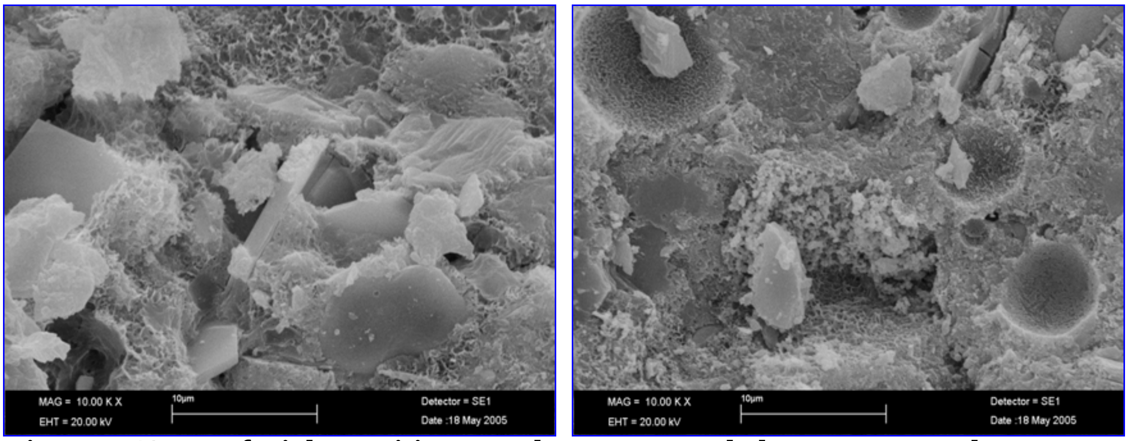
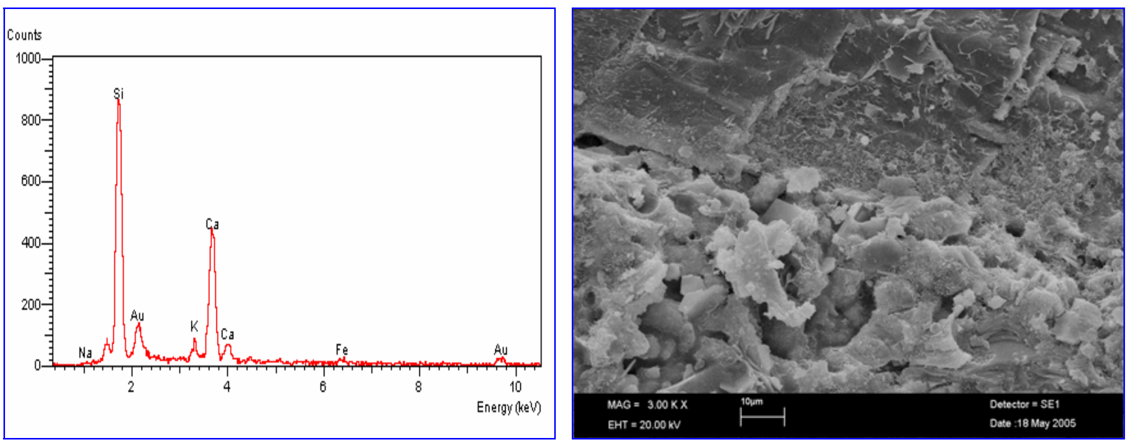


Figure 7-12 Interfacial transition zone between recycled aggregates and new paste with fly ash and with steam curing

EDX-MAPS of the Interfacial Transition Zone between Cement Paste and Aggregate

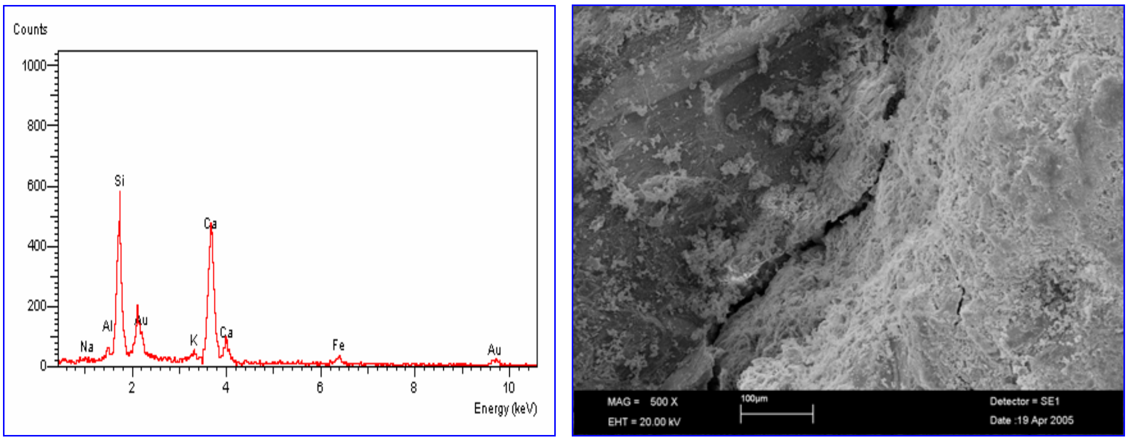
Figures 7-13 and 7-14 show the EDX-map and the views of the ITZ between conventional aggregates and the new paste (no fly ash) with standard water curing and steam curing, respectively, at age of 28 days. Since the granite was very clear in the picture, in the EDX-map of standard water cured and steam cured concrete specimens, the amount of Si was higher than Ca.



(a) (b)

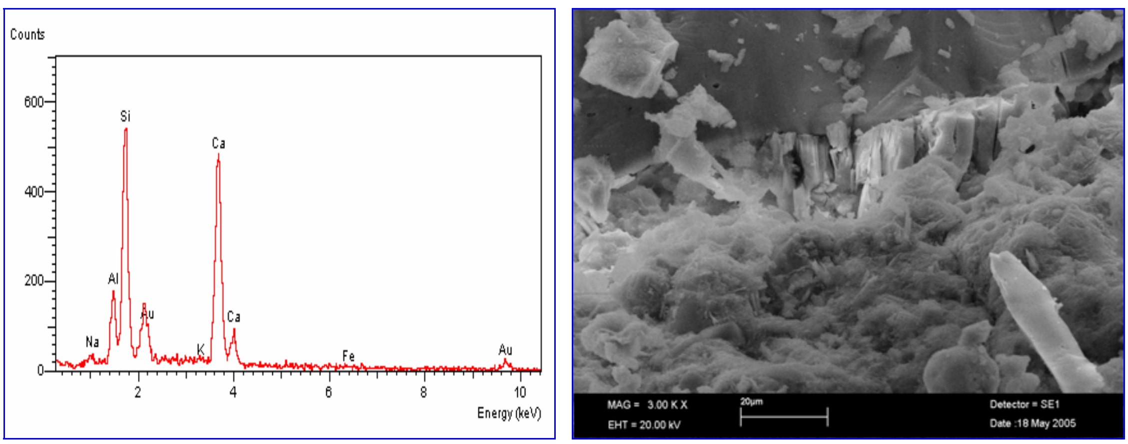
Figure 7-13 Interfacial transition zone between conventional aggregates and new paste no fly ash with standard water curing. EDX map of the total are of the picture

Similar results can be seen from Figures 7-15 and 7-16 that in the EDX-map of ITZ of the conventional aggregate concrete (with 25% fly ash), with standard water curing and steam curing, the amount of Si was higher than Ca. A layer of $Ca(OH)_2$ was in direct contact with the aggregate surface followed by a layer of cement hydration products (Figure 7-15 b). The interfacial zone of the steam cured concrete specimens was more porous and cracks could be clearly observed (Figure 7-16 b).



(a) (b)

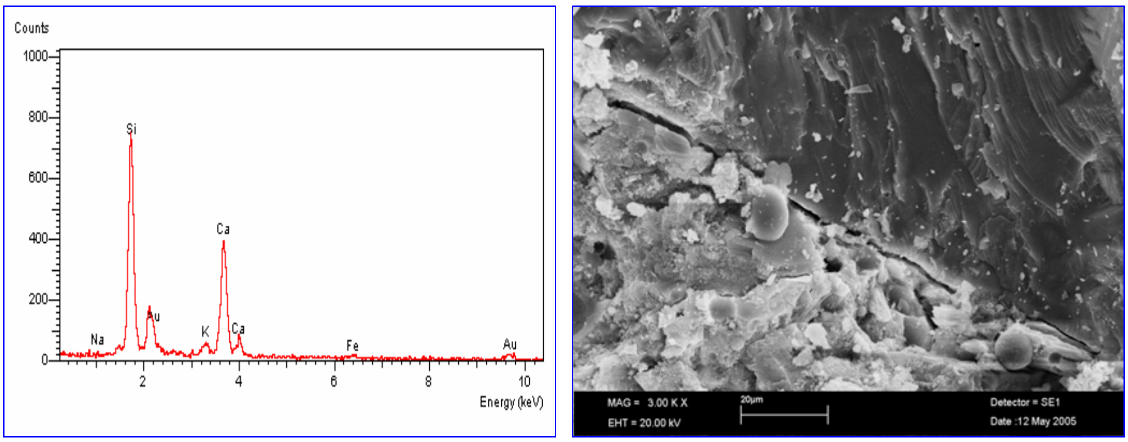
Figure 7-14 Interfacial transition zone between conventional aggregates and new paste no fly ash with steam curing. EDX map of the total are of the picture



(a) **(b)**

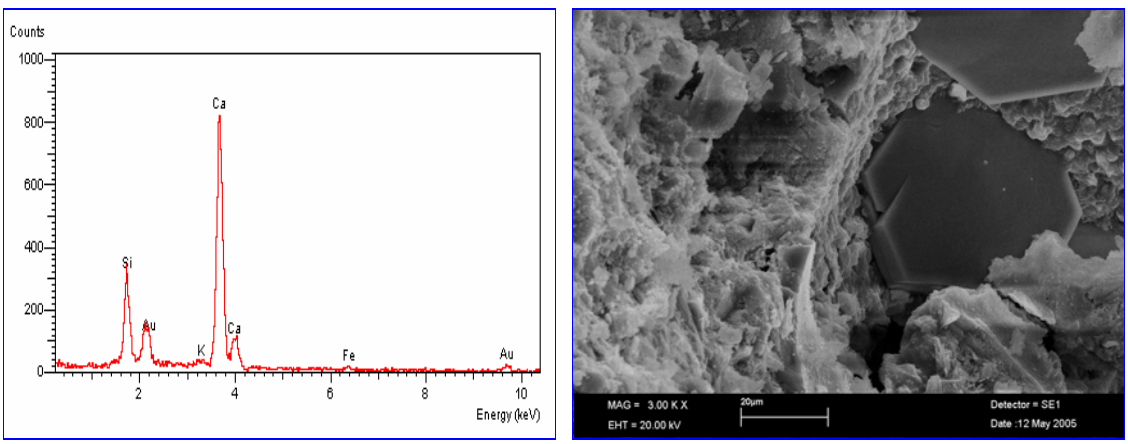
Figure 7-15 Interfacial transition zone between conventional aggregates and new paste with 25% fly ash with standard water curing. EDX map of the total are of the picture

Figures 7-17 to 7-20 show the EDX-maps and the views of the ITZ in standard water cured and steam cured recycled aggregate concrete (with and without fly ash). Although the element composition was similar, the Ca quantity was higher, and this was similar to the C-S-H composition of hydrated Portland cement. Steam curing regime increased the reaction of fly ash and $Ca(OH)_2$. The C-S-H gel was very clear on the fly ash surface in the interface zone seen in Figure 7-21 (b). There are few cracks between recycled aggregates and the new paste of the concretes with steam curing.



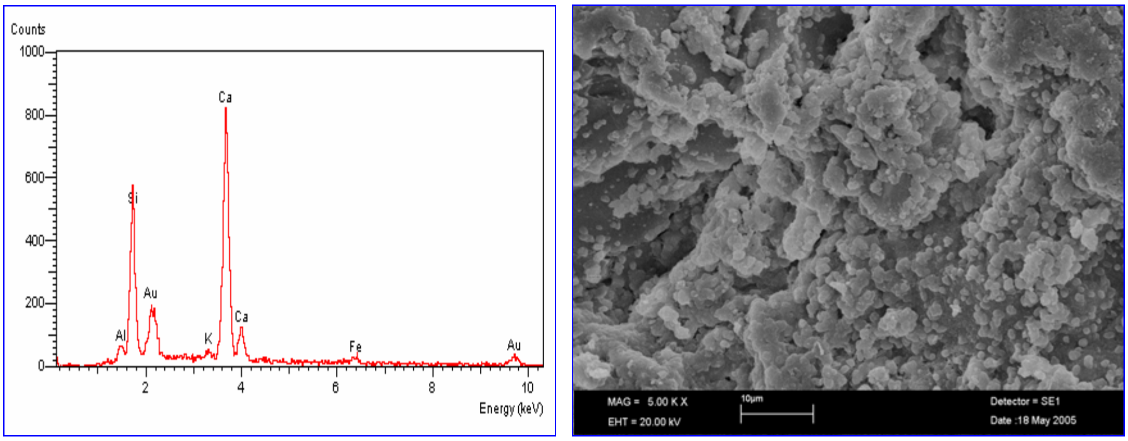
(a) (b)

Figure 7-16 Interfacial transition zone between conventional aggregates and new paste with 25% fly ash with steam curing. EDX map of the total are of the picture



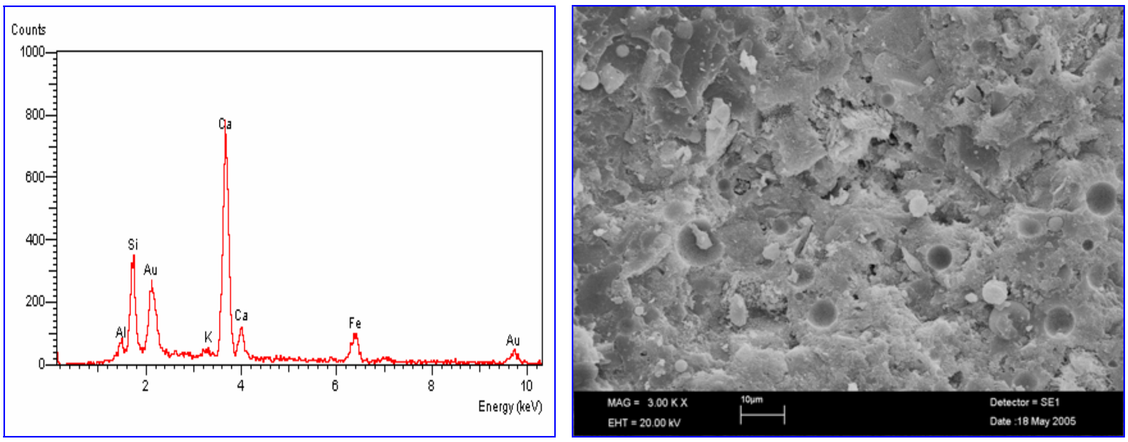
(a) (b)

Figure 7-17 Interfacial transition zone between recycled aggregate and new paste no fly ash with standard water curing. EDX map of the total are of the picture



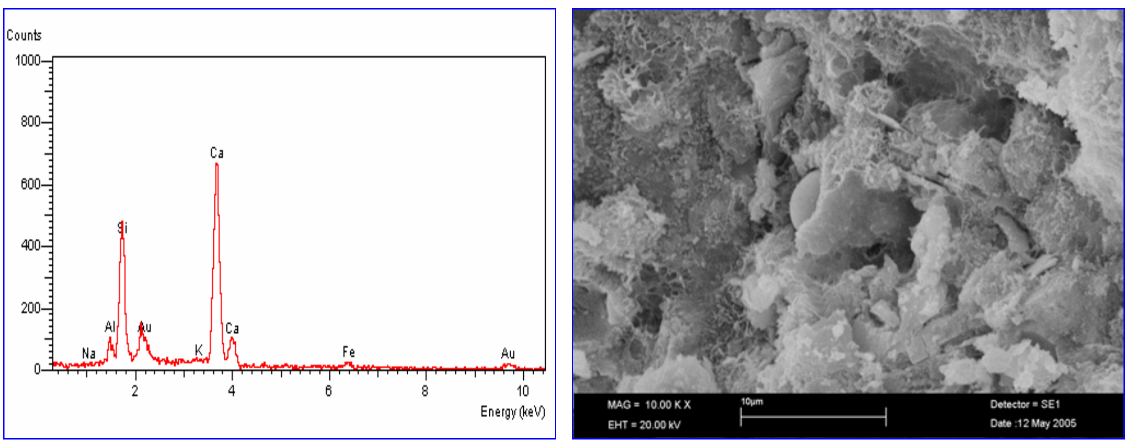
(a) **(b)**

Figure 7-18 Interfacial transition zone between recycled aggregate and new paste no fly ash with steam curing. EDX map of the total are of the picture



(a) **(b)**

Figure 7-19 Interfacial transition zone between recycled aggregate and new paste with 25% fly ash and with standard water curing.



(a) **(b)**

Figure 7-20 Interfacial transition zone between recycled aggregate and new paste with 25% fly ash and with steam curing. EDX map of the total are of the picture

7.4 PORE SIZE DISTRIBUTION OF RECYCLED AGGREGATE CONCRETE

Only limited amount of research results on the pore size distribution of recycled aggregate concrete are available. Gomez-Soberon (2002) presented the pore size distribution, theoretical pore diameters, critical pore ratio and the surface area of recycled aggregate concrete with varying replacement levels of natural aggregate by recycled coarse and fine aggregates (55% coarse recycled gravel + 45% recycled fine gravel). He indicated that porosity increased considerably when natural aggregate was replaced by recycled aggregate. Additionally, a reduction in the mechanical properties of the recycled aggregate concrete was seen.

In this study, the mercury intrusion test was carried out at 28 days and 90 days in Series I and II concrete mixtures. The results are summarized in Tables 7-1 and 7-2 for standard water cured specimens and Tables 7-3 and 7-4 for steam cured concrete specimens. The data presented in Tables 7-1, 7-2, 7-3 and 7-4 are average values of two tests. For most of the measured porosity values, the relative differences of two measurements were less than 3%, while for the measured average pore diameter values, the differences were negligible. The pore size distribution curves of concrete mixtures without fly ash in Series I and II at the ages of 28 and 90 days are shown in Figures 7-21 and 7-22, respectively. The pore size distribution curves of concrete mixtures with

25% fly ash in Series I and II at the ages of 28 and 90 days are shown in Figures 7-23 and 7-24, respectively. The pore size distribution curves of concrete mixtures with 25% and 35% fly ash in Series I and II at the age of 28 days are shown in Figures 7-25. The pore size distribution curves of steam cured concrete mixtures without fly ash in Series I and II at age of 28 days are shown in Figures 7-26 and Figure 7-28, respectively. The pore size distribution curves of steam cured concrete mixtures with 25% fly ash in Series I and II at the age 28 days are shown in Figures 7-27 and Figure 7-29, respectively.

7.4.1. Pore size distribution of standard water cured concrete

In Tables 7-1 and 7-2, it can be seen that in both of the Series I and II concrete mixtures, the total porosity and average pore diameter increased as the recycled aggregate content increased. At the age of 28 days, concrete mixture R0 with 100% natural aggregate in Series I and II achieved total porosity of 10.0% and 8.9%, respectively, whereas concrete mixture R100 with 100% recycled aggregate achieved total porosity of 12.9% and 11.3%, respectively, an increase of 22.6% and 21.0%, respectively; in comparison with the porosity of the concrete mixture R0. The concrete mixture R0 in Series I and II had average pore diameter of 0.0299 μm and 0.0278 μm, respectively, whereas concrete mixture R100 in Series I and series II had average pore diameter of 0.0345 μm and 0.0329 μm, respectively; an increase of 13.3% and 15.5%, respectively, in comparison with the average pore diameter of the concrete mixture R0. This is attributed to the recycled aggregates have some adhered mortar which is extremely porous and having suffered from “manufacturing” the quality of the original aggregates has been reduced. The results at 90 days indicated that there was continuous and significant decrease in total porosity and average pore diameter beyond the age of 28 days. The decrease in total porosity and average pore diameter of concrete mixture R100 with 100% recycled aggregate in Series I from 28 to 90 days was 10.4% and 7.5%, respectively.

In Figure 7-21and Figure 7-22 it can be seen that the pore size distribution of the concretes made with recycled aggregates was shifted to the bigger pore size range demonstrating the pore coarsening effect of the recycled aggregates. All the recycled aggregate concrete specimens recorded higher intrusion volumes in pores of sizes larger that 0.01 μm in comparison with the conventional aggregate concrete.

It can also be seen from Tables 7-1 and 7-2 that in both of Series I and II concrete mixtures, the replacement of cement by 25% fly ash resulted in lower MIP porosities of recycled and conventional aggregate concrete at the ages of 28 days and 90 days. However, the replacement of cement by 35% fly ash resulted in higher MIP porosities of the concretes. At 28 days, concrete mixtures R100 with 100% recycled aggregate and no fly ash in Series I and II had the total porosity of 12.9% and 11.3%, respectively, whereas concrete mixture r-R100F25 with 100% recycled aggregate and 25% fly ash in Series I and II had the total porosity of 11.5% and 10.4%, respectively, a reduction of 10.6% and 7.6%, respectively; in comparison with the total porosity of concrete mixture R100 without fly ash. Concrete mixture r-R100F35 with 100% recycled aggregate and 35% fly ash in Series I and II have the total porosity of 13.3% and 11.5%, respectively, an increase of 3.3% and 2.1%, respectively, in comparison with the total porosity of concrete mixture R100.

In both of Series I and II concrete mixtures, the average pore diameter of the recycled and conventional aggregate concrete was decreased with an increase in fly ash content. At 28 days. The concrete mixtures R100 in Series I had the average pore diameter of 0.0345 μm, whereas the concrete mixtures r-R100F25 and r-R100F35 had the average pore diameter of 0.0319 μm and 0.0306 μm, respectively; a reduction of 7.5% and 11.3%, respectively, in comparison with the average pore diameter of the concrete mixture R100 without fly ash. The decrease in average pore diameter is, of course, due to fly ash particles are predominantly amorphous and spherical in nature, and it is smaller than that the cement. The results at 90 days indicated that there was continuous and significant decrease in total porosity and average pore diameter of recycled and conventional concrete with fly ash beyond the age of 28 days. The decrease in total porosity and average pore diameter of concrete mixture r-R100F25 with 100% recycled aggregate and 25% fly ash in Series I from 28 to 90 days was 15.5% and 10.0%, respectively. This decrease was higher than that corresponding concrete mixture without fly ash (10.4% and 7.5%). The significant decrease in total porosity and average pore diameter of fly ash concrete is due to pozzolanic reaction of fly ash.

Table 7-1 Average pore diameter and total porosity of concrete mixtures in Series I with standard water curing

Mix notation	Recycled aggregate (%)	Fly ash (%)	Average Pore diameter (μm)		Total porosity (%)	
			28 days	90 days	28 days	90 days
R0	0	0	0.0299	0.0259	9.98	8.91
R20	20	0	0.0312	0.0277	10.74	9.39
R50	50	0	0.0322	0.0296	11.80	10.70
R100	100	0	0.0345	0.0319	12.89	11.37
r-R0F25	0	25	0.0278	0.0229	8.65	6.60
r-R20F25	20	25	0.0297	0.0243	9.62	7.90
r-R50F25	50	25	0.0302	0.0265	10.36	9.35
r-R100F25	100	25	0.0319	0.0287	11.52	9.74
r-R0F35	0	35	0.0259	0.0209	10.27	8.56
r-R20F35	20	35	0.0275	0.0221	11.35	9.68
r-R50F35	50	35	0.0293	0.0239	12.48	11.26
r-R100F35	100	35	0.0306	0.0296	13.33	11.81

In Figure 7-23 and Figure 7-24 it can be seen that the pore size distribution of the recycled and conventional aggregate concretes made with fly ash was shifted to the smaller pore size range demonstrating the pore refining effect of the fly ash. All the fly ash concretes specimens recorded lower intrusion volumes in pores of sizes larger than 0.01 μm in comparison with the concrete mixtures without fly ash.

Figure 7-25 shows at 28 days, the pore size distributions of concrete mixture R100 with varying percentage of fly ash in Series I and II, respectively. It can be seen that in both of Series I and II concrete mixtures, among the concrete mixtures R100 (0% fly ash), r-R100F25 (25% fly ash) and r-R100F35 (35% fly ash), the concrete mixture r-R100F25 had the lowest intrusion volume in pores of sizes larger than 0.01 μm.

The pore size distributions were also determined for concrete mixtures prepared with the water-to-binder (W/B) ratios of 0.55 and 0.45. The total porosity and the average pore diameter of conventional and recycled aggregate concrete decreased with a decrease in water-to-binder ratio. At the age of 28 days, the concrete mixture R100 (100% recycled aggregate and no fly ash) with W/B ratio of 0.55 had total porosity and average pore diameter of 12.89% and 0.0345 μm, respectively, whereas the corresponding concrete mixture with W/B ratio of 0.45 had total porosity and average pore size of 11.3% and 0.0329 μm, respectively, a reduction of 11.3% and 4.6%, respectively, in comparison with the porosity and the pore diameter of concrete mixture R100 with W/B ratio of 0.55. Lowering W/B ratio also resulted in lower total porosity and average pore diameter of fly ash conventional and recycled aggregate concrete. At 28 days, the concrete mixture r-R100F25 with W/B ratio of 0.55 had total porosity and average pore diameter of 11.5% and 0.0319 μm, respectively, whereas the corresponding concrete mixture with W/B ratio of 0.45 had total porosity and average pore size of 10.4% and 0.0299 μm, respectively, a reduction of 9.8% and 6.3%, respectively, in comparison with the porosity and the pore diameter of concrete mixture r-R100F25 with W/B ratio of 0.55. Similar results were obtained for all concrete mixtures in Series II due to the W/B ratio was decreased from 0.55 to 0.45.

Table 7-2 Average pore diameter and total porosity of concrete mixtures in Series II with standard water curing

Mix notation	Recycled aggregate (%)	Fly ash (%)	Average Pore diameter (μm)		Total porosity (%)	
			28 days	90 days	28 days	90 days
R0	0	0	0.0278	0.0235	8.89	6.70
R20	20	0	0.0286	0.0254	9.31	7.98
R50	50	0	0.0305	0.0269	10.49	8.95
R100	100	0	0.0329	0.0289	11.25	10.05
r-R0F25	0	25	0.0255	0.0215	7.66	5.72
r-R20F25	20	25	0.0267	0.0234	8.34	6.69
r-R50F25	50	25	0.0281	0.0251	9.29	7.81
r-R100F25	100	25	0.0299	0.0267	10.39	9.23
r-R0F35	0	35	0.0228	0.0195	9.19	7.21
r-R20F35	20	35	0.0243	0.0205	10.04	8.28
r-R50F35	50	35	0.0261	0.0228	10.68	9.26
r-R100F35	100	35	0.0278	0.0249	11.09	10.37

7.4.2. Pore size distribution of steam cured concrete

In Tables 7-3 and 7-4, it can be seen that steam curing increased the total porosity and average pore diameter of conventional and recycled aggregate concrete at the test ages of 28 and 90 days. However, these increases were decreased with an increase of recycled aggregate content. At 28 days, standard water cured concrete mixture R0 with 100% conventional aggregate and no fly ash in Series I have the total porosity of 9.98% and the average pore diameter of 0.0299 μm, whereas the steam cured corresponding concrete mixture R0-s had the total porosity of 11.48% and average pore diameter of 0.0322 μm; an increase of 13.1% and 7.1%, respectively, in comparison with the porosity and pore diameter of the concrete mixture R0. However, standard water cured concrete mixture R100 with 100% recycled aggregate and no fly ash in Series I have the total porosity of 12.89% and average pore diameter of 0.0321 μm, whereas the steam cured corresponding concrete mixture R100-s had the total porosity of 13.17% and average pore diameter of 0.0332 μm; an increase of 2.1% and 3.3%, respectively, in comparison with the porosity and pore diameter of the concrete mixture R100. Similar results were obtained for the corresponding concrete mixtures in Series II. At the age of 28 days, the total porosity and the average pore diameter of steam cured concrete mixture R0-s in Series II were higher of 10.0% and 7.9% than that the corresponding concrete mixture R0. However, the total porosity and average pore diameter of steam cured concrete mixture R100-s in Series II were higher of 3.6% and 2.7%, respectively than that the corresponding concrete mixture R100 with standard water curing. In Figures 7-26 it can be seen that the pore size distribution of conventional aggregate concrete with steam curing was shifted to the bigger pore size range. The intrusion volume of steam cured recycled and conventional aggregate concretes in pores of sizes larger than 0.01μm was not significant different.

Steam curing also increased the total porosity and average pore diameter of fly ash conventional and recycled aggregate concrete in the test ages of 28 and 90 days. At 28 days, standard water cured concrete mixture r-R0F25 with 100% conventional aggregate and with 25% fly ash in Series I had the total porosity of 8.7% and the average pore diameter of 0.0278 μm, whereas the steam cured corresponding concrete mixture r-R0F25-s had the total porosity of 9.7% and average pore diameter of 0.0289 μm; an increase of 9.3% and 3.8%, respectively, in comparison with the porosity and pore diameter of the concrete mixture r-R0F25. Standard water cured concrete mixture r-R100F25 with 100% recycled aggregate and with 25% fly ash in Series I had the total porosity of 11.5% and average pore diameter of 0.0319 μm, whereas the steam cured corresponding concrete mixture r-R100F25-s had the total porosity of 11.9% and average pore diameter of 0.0328 μm; an increase of 3.4% and 2.7%, respectively, in comparison with the porosity and pore diameter of the concrete mixture R100F25. Similar results were obtained for the concrete mixtures in Series II. At 28 days, the total porosity and the average pore diameter of steam cured concrete mixture r-R0F25-s in Series II were higher of 12.2% and 4.1% than that the corresponding concrete mixture r-R0F25. However, the total porosity and average pore diameter of steam cured concrete mixture r-R100F25-s in Series II were higher of 1.6% and 1.3%, respectively than that the corresponding concrete mixture r-R100F25 with standard water curing.

Table 7-3 Average pore diameter and total porosity of concrete mixtures in Series I with steam curing

Mix notation	Recycled aggregate (%)	Fly ash (%)	Average Pore diameter (μm)		Total porosity (%)	
			28 days	90 days	28 days	90 days
R0	0	0	0.0322	0.0278	11.48	10.12
R20	20	0	0.0329	0.0287	11.88	10.79
R50	50	0	0.0335	0.0306	12.21	11.12
R100	100	0	0.0332	0.0319	13.17	11.73
r-R0F25	0	25	0.0289	0.0236	9.66	8.28
r-R20F25	20	25	0.0306	0.0251	10.25	9.15
r-R50F25	50	25	0.0312	0.0278	11.05	10.13
r-R100F25	100	25	0.0328	0.0296	11.92	10.64
r-R0F35	0	35	0.0264	0.0216	11.66	10.42
r-R20F35	20	35	0.0288	0.0232	11.94	10.82
r-R50F35	50	35	0.0307	0.0251	12.66	11.36
r-R100F35	100	35	0.0315	0.0308	13.43	12.11

Table 7-4 Average pore diameter and total porosity of concrete mixtures in Series II with steam curing

Mix notation	Recycled aggregate (%)	Fly ash (%)	Average Pore diameter (μm)		Total porosity (%)	
			28 days	90 days	28 days	90 days
R0	0	0	0.0302	0.0235	9.88	8.70
R20	20	0	0.0316	0.0254	10.10	8.98
R50	50	0	0.0324	0.0269	11.06	10.05
R100	100	0	0.0329	0.0289	11.67	10.55
r-R0F25	0	25	0.0266	0.0224	8.72	7.52
r-R20F25	20	25	0.0279	0.0246	9.37	8.21
r-R50F25	50	25	0.0292	0.0262	9.89	9.12
r-R100F25	100	25	0.0303	0.0275	10.56	10.14
r-R0F35	0	35	0.0238	0.0206	10.24	9.12
r-R20F35	20	35	0.0256	0.0214	10.84	9.58
r-R50F35	50	35	0.0275	0.0236	11.04	9.98
r-R100F35	100	35	0.0284	0.0258	11.79	10.48

The replacement of cement by 25% fly ash resulted in lower MIP porosities of steam cured recycled and conventional aggregate concrete at the ages of 28 days and 90 days. However, the replacement of cement by 35% fly ash resulted in higher MIP porosities of the concretes. At 28 days, concrete mixtures R100-s with 100% recycled aggregate and no fly ash in Series I and II had the total porosity of 13.17% and 11.67%, respectively, whereas concrete mixture r-R100F25-s with 100% recycled aggregate and 25% fly ash in Series I and II had the total porosity of 11.92% and 10.56%, respectively, a reduction of 9.5% and 9.4%, respectively; in comparison with the total porosity of concrete mixture R100-s without fly ash; Concrete mixture r-R100F35-s with 100% recycled aggregate and 35% fly ash in Series I and II had the total porosity of 13.43% and 11.79%, respectively, an increase of 1.9% and 1.02%, respectively, in comparison with the total porosity of concrete mixture R100-s.

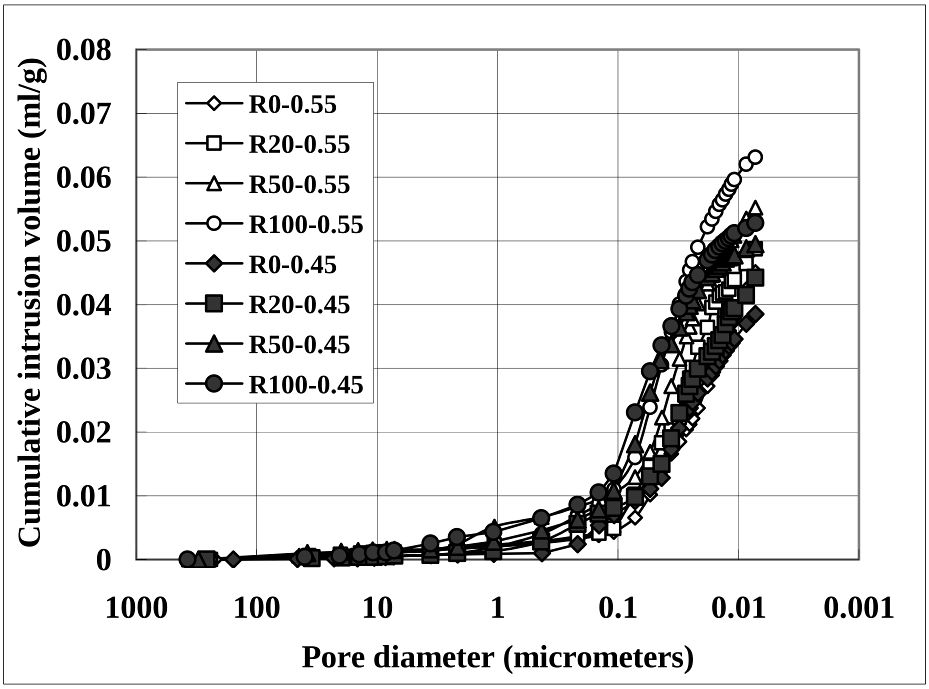


Figure 7-21 Pore size distribution of concrete mixtures without fly ash in Series I and II at 28 days

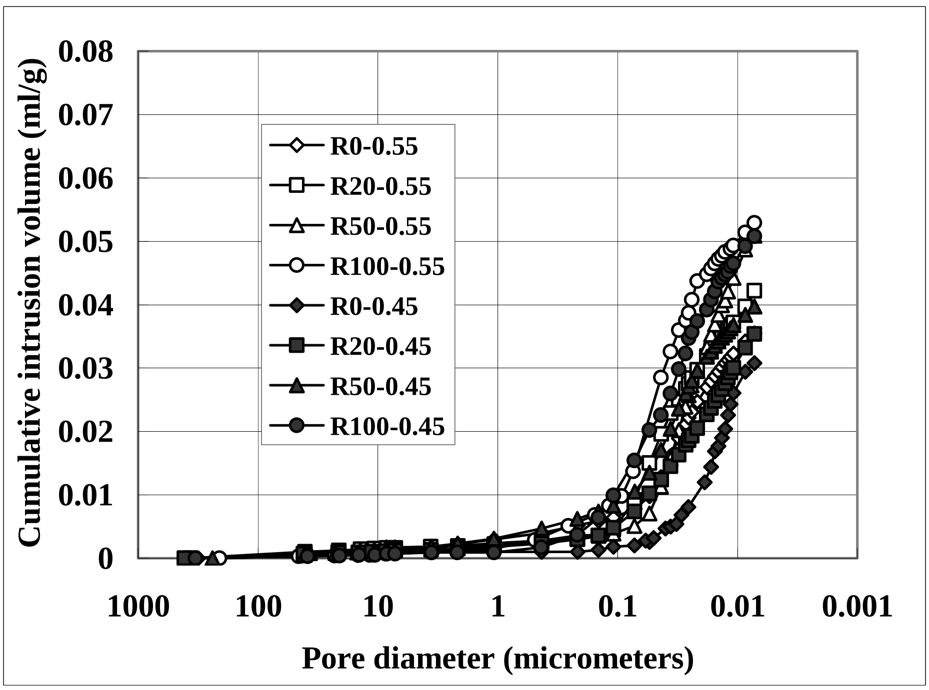


Figure 7-22 Pore size distribution of concrete mixtures without fly ash in Series I and II at 90 days

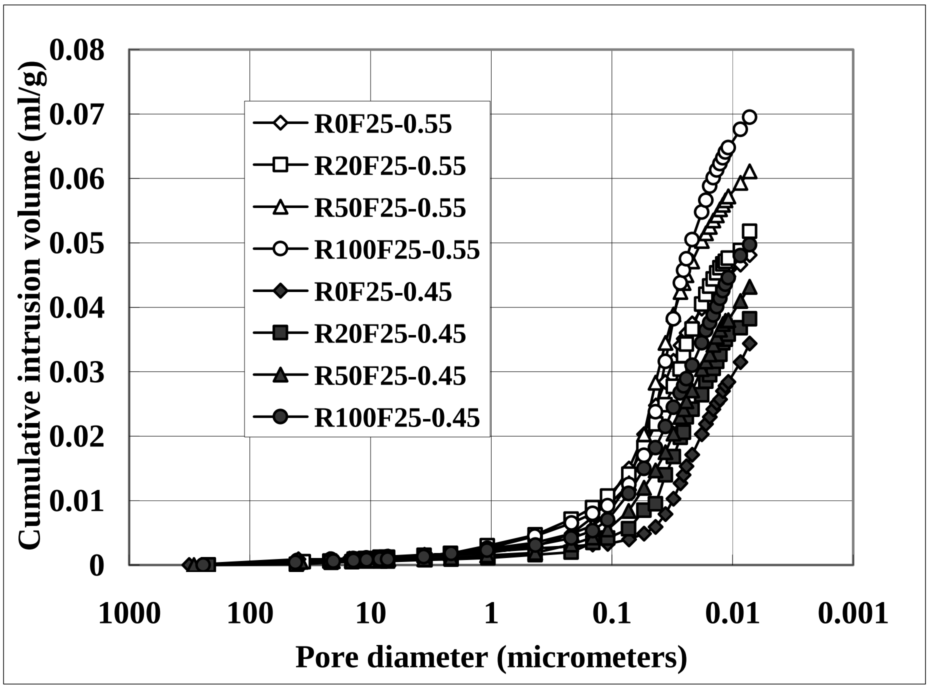


Figure 7-23 Pore size distribution of concrete mixtures with 25% fly ash in Series I and II at 28 days

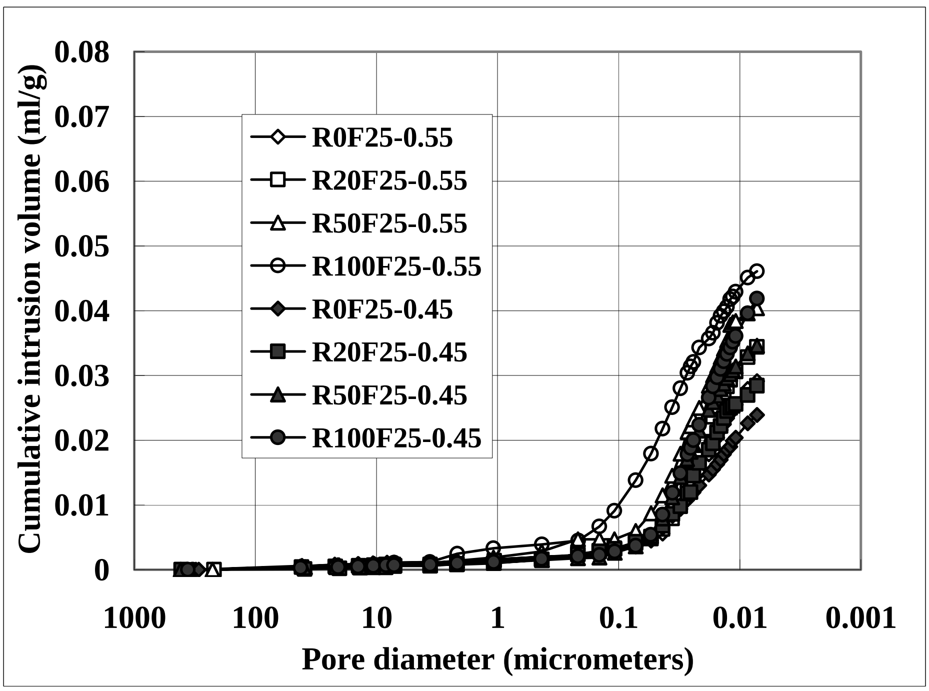


Figure 7-24 Pore size distribution of concrete mixtures with 25% fly ash in Series I and II at 90 days

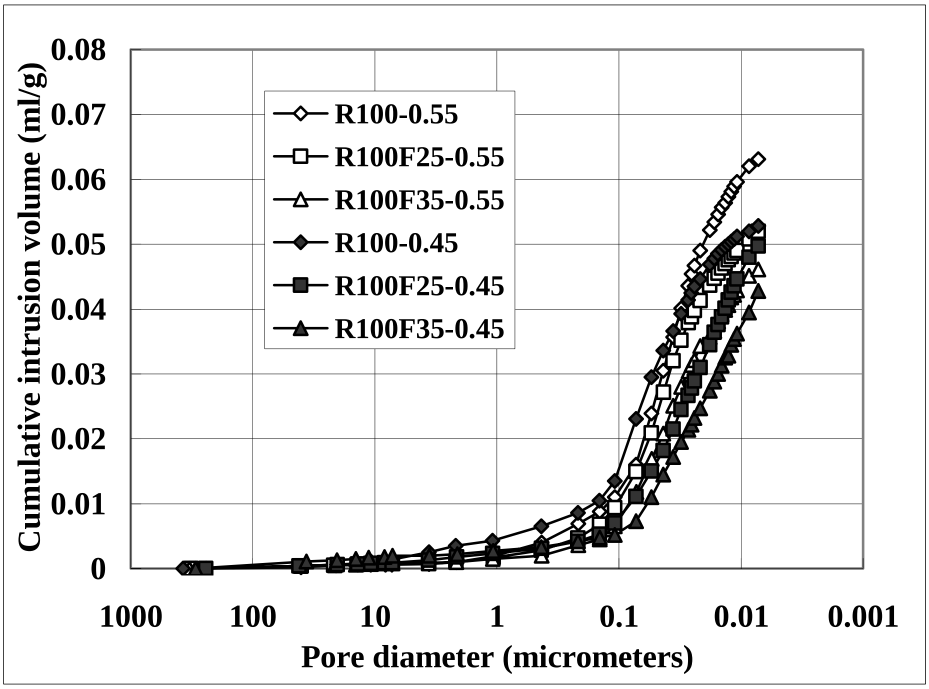


Figure 7-25 Pore size distribution of concrete mixture with varing % of fly ash in Series I and II at 28 days

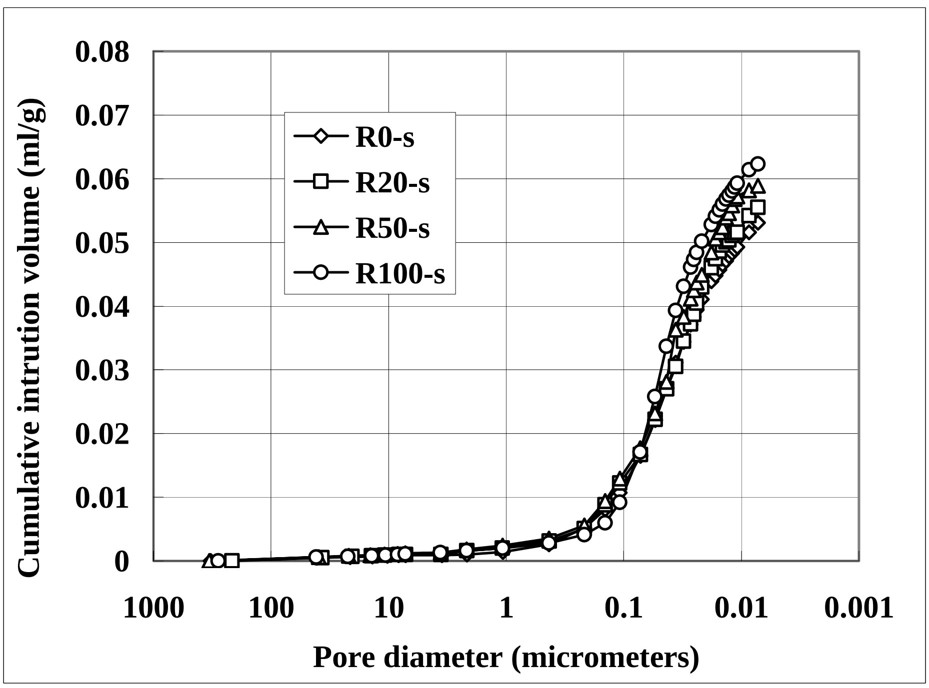


Figure 7-26 Pore size distribution of steam cured concrete mixtures without fly ash in Series I at 28 days

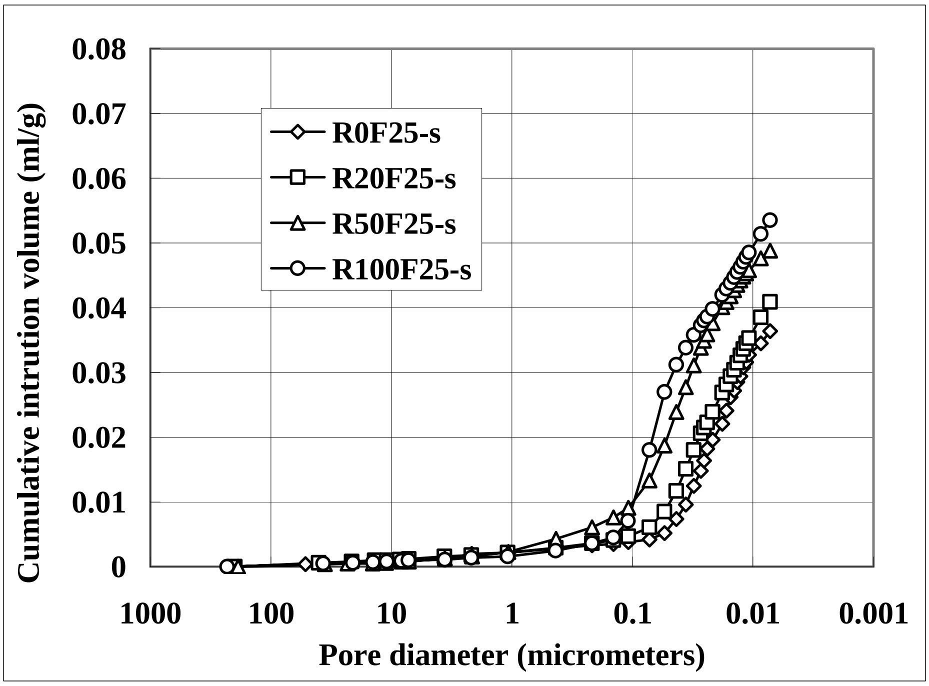


Figure 7-27 Pore size distribution of stem cured concrete mixtures with 25% fly ash in Series I at 28 days

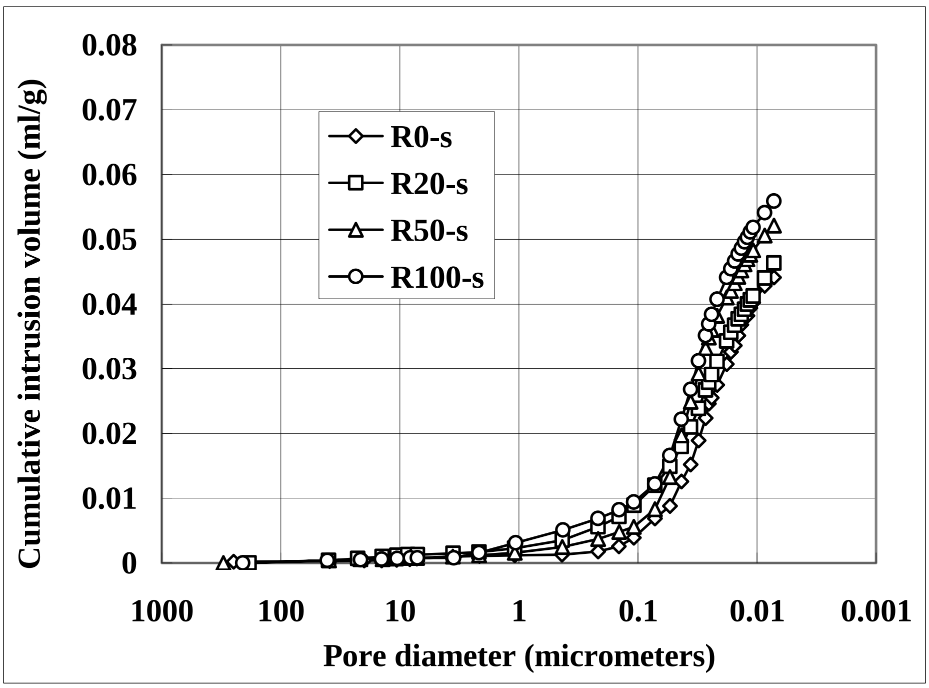


Figure 7-28 Pore size distribution of steam cured concrete mixtures without fly ash in Series II at 28 days

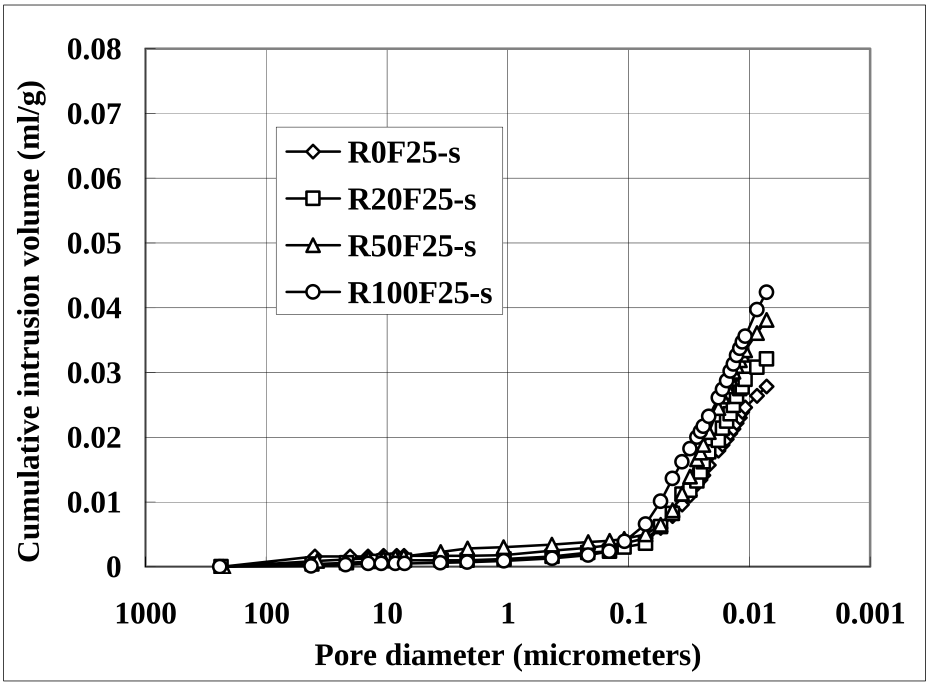


Figure 7-29 Pore size distribution of steam cured concrete mixtures with 25% fly ash in Series II at 28 days

7.5 SUMMARY

An analysis of microstructure and pore size distribution of the concrete made with conventional and recycled aggregates with and without fly ash by different curing regimes was carried out and the summary obtained is the following:

- According to microstructure analysis the distribution of aggregates was homogeneous in all concretes. All the recycled aggregates studied behave similarly from this point of view. The high porosity of original cement paste is evident.

- Interfacial transition zones between aggregates and the new paste of the steam cured conventional aggregate concrete were more porous with more cracks than the recycled aggregate concrete.

- For the concrete made with recycled aggregates, the quality of interfacial transition zone is better than that of the old paste, consequently in these concretes, the weakest point could be the adhered mortar. Therefore the adhered mortar strength will be what determines the material strength and behavior. This is one of the greatest differences with respect to conventional aggregate concrete

- Total porosity and average pore diameter increased as the recycled aggregate content increased. The pore size distribution of the concrete made with recycled aggregates was shifted to the bigger pore size range demonstrating the pore clarifying effect of the recycled aggregates.

- The replacement of cement by 25% fly ash resulted in lower MIP porosities of recycled and conventional aggregate concrete at the ages of 28 and 90 days. However, the replacement of cement by 35% fly ash resulted in slightly higher MIP porosities of the concretes.

- All the fly ash concretes specimens recorded lower intrusion volumes in pores of sizes larger than 0.01μm in comparison with the concrete mixtures without fly ash,

- Total porosity and average pore diameter of conventional and recycled aggregate concrete was decreased with a decrease water-to-binder ratio.

- Steam curing regime increased the total porosity and average pore diameter of conventional and recycled aggregate concrete with and without fly ash at the test ages of 28 and 90 days. However, these increases were decreases with an increase of recycled aggregate content.

CHAPTER 8 FRACTURE PROPERTIES AND COMPRESSIVE STRESS-STRAIN CURVE OF RECYCLED AGGREGATE CONCRETE

8.1 INTRODUCTION

The fractural energy, G_f is one of the important material properties for the design of concrete structures and is the most useful material parameter in the analysis of cracked concrete structures. It is defined as the area under the load-deflection curve per unit fractured surface area used to characterize the process of fracture. Concrete is a specific type of composite material, which consists of three phases: cement paste as matrix, interface transition zone (ITZ), and aggregates. Many studies about the ITZ characterization have been conducted. Specifically, Garboczi et al (1996 and 1997) developed analytical models based on spherical shape of aggregates for the effect of ITZ on properties of concrete. Buyukozturk et al (1993) studied the behavior of mortar-aggregate interfaces. Lee et al (1998) studied the factors influencing fracture toughness of mortar-aggregate interface. Kawakami (1993) and Kan et al (1993) conducted systematic testing for the effect of different types of aggregates on fracture properties of concrete. Issa et al. (1996) and Zollinger et al. (1993) studied the effect of the aggregate size on the fracture toughness and fracture process zone of concrete. Feng et al. (1995) investigated the effects of various parameters of the concrete mix design including water to cement ratio, size of coarse aggregate, weight ratio of coarse to fine aggregate, and the volume content of coarse aggregate. El-Sayed et al. (1998) conducted a series of tests (compression, tension, and three-point bend) to study the influences of the various aggregate shapes on the fracture behavior of concrete. Amparano et al. (2000) conducted a series of tests to study on the effect of aggregate content on the fracture behavior of concrete. However, the influence of the recycled concrete aggregate on the fracture behavior of concrete has not been clearly understood.

The aim of this chapter is to clarify the effect of recycled aggregate on the mechanical properties of the interfacial bonding between the cement matrix and the aggregate in RAC. The fracture properties of the interfacial bonding and compressive stress-strain curve of concrete mixtures in Series I and II were determined. Fracture energy was calculated according to the RILEM draft recommendation (RILEM Committee FMC 50. Determination of the fracture energy of mortar and concrete by means of the three-point bend tests on notched beams, Materials and Structures, 1985). The test method and specimens prepared were presented in Chapter 3.

8.2 TEST RESULTS AND DISCUSIONS

8.2.1 Flexural strength of concrete

Flexural strength of concrete mixtures was determined at the ages of 28 and 90 days.

Concrete beams in size 100x100x500 mm were tested and the results for concrete mixtures in Series I and II are given in Table 8-1 and Table 8-2, respectively. Flexural strength increased with the increase in recycled aggregate content in both of Series I and II concrete mixtures. At 28 days, flexural strength of concrete mixture R0 (0% recycled aggregate) in Series I was 4.42 MPa, whereas concrete mixtures R20 (20% recycled aggregate), R50 (50% recycled aggregate) and R100 (100% recycled aggregate) achieved flexural strength of 4.55, 4.74 and 4.96 MPa, respectively; an increase of 2.85%, 6.75% and 10.89%, respectively, in comparison with the strength of the mixture R0. Flexural strength of concrete mixtures also increased with age. At 28 days, concrete mixture R100 in Series I and II achieved flexural strength of 4.96 and 5.46 MPa, respectively, whereas at 90 days the corresponding concrete mixtures achieved flexural strength of 5.98 and 6.18 MPa.

The replacement of cement by 25% fly ash resulted in lower flexural strength of conventional and recycled aggregate concrete in Series I and II at 28 days. However, at 90 days, the flexural strength of the concretes with 25% fly ash was higher than the corresponding concrete mixture without fly ash. At 28 days, flexural strength of concrete mixture R100 (0% fly ash) in Series I was 4.96 MPa, whereas concrete mixture r-R100F25 (25% fly ash) achieved flexural strength of 4.76 MPa, a reduction of 4.20%, in comparison with the strength of the concrete mixture R100. At 90 days, flexural strength of concrete mixture R100 (0% fly ash) in Series I was 5.98 MPa, whereas concrete mixture r-R100F25 (25% fly ash) achieved flexural strength of 6.17 MPa, an increase of 3.08%, in comparison with the strength of the concrete mixture R100. The increase in flexural strength of fly ash concrete is due to pozzolanic reaction between fly ash and $Ca(OH)_2$ and it contributed to the interfacial properties.

Steam curing regimes resulted in higher flexural strength of recycled aggregate concrete at the test ages of 28 and 90 days. At 28 days, concrete mixtures R100 in Series I and II with standard water curing achieved flexural strength of 4.96 MPa and 5.46 MPa, respectively, whereas concrete mixtures R100-s in Series I and II had flexural strength of 5.21 MPa and 5.59 MPa, respectively, an increase of 5.04% and 2.32%, respectively; in comparison with the strength of concrete mixtures R100 with standard water curing. Similar results were obtained for all the recycled aggregate concrete mixture with fly ash.

8.2.2 Fracture energy of recycled aggregate concrete

Fracture energy was calculated according to the RILEM draft recommendation (RILEM Committee FMC 50. Determination of the fracture energy of mortar and concrete by means of the three-point bend tests on notched beams. Materials and Structures, 1985), the results of concrete mixtures in Series I and II at the age of 28 days are shown in

Table 8-1 and Table 8-2, respectively. The load-deflection curves are shown in Figures 8-1 to 8-6.

In Tables 8-1 and 8-2, it can be seen that in both of the Series I and II concrete mixtures, the fracture energy and peak-load (P_{max}) increased as the recycled aggregate content increased. At the age of 28 days, concrete mixture R0 in Series I and II achieved fracture energy of 146 N/m and 153 N/m, respectively, whereas concrete mixture R100 with 100% recycled aggregate achieved fracture energy of 175 N/m and 181 N/m, respectively, an increase of 16.6% and 15.5%, respectively; in comparison with the fracture anergy of the concrete mixture R0. Concrete mixture R0 in Series I and II achieved P_{max} of 3.04 kN and 3.35 kN, respectively, whereas concrete mixture R100 achieved P_{max} of 3.68 kN and 3.94 kN respectively; an increase of 17.4% and 15.0%, respectively. This is attributed to the recycled aggregate concrete have better adhesion between the aggregate and new paste compared to the conventional aggregates concrete. These results were given and discussed in Chapter 7. The results at 90 days indicated that there was not significant increase in fracture energy and peak-load beyond the age of 28 days. The increase in fracture energy and peak-load of concrete mixture R100 in Series I from 28 to 90 days was only 2.8% and 2.9%, respectively.

Figures 8-1 and 8-2 reveal that in both of the Series I and II concrete mixtures, the peak-load and the area surrounded by the curve are increased by increasing recycled aggregate content. When attention is paid to the residual strength at a deflection of 0.25 mm, the recycled aggregate concrete had a lower rate of caused the strength loss and the fracture because ductile in some cases. This is presumably because cracks made detours towards weak boundaries between the aggregate and the matrix.

It can also be seen from Tables 8-1 and 8-2 that in both of the Series I and II concrete mixtures, at 90 days, the replacement of cement by 25% fly ash resulted in higher fracture energy and peak-load. Concrete mixture R100 without fly ash in Series I and II had the fracture energy of 176 N/m and 185 N/m, respectively, r-R100F25 However, at the age of 28 days, the fracture energy and peak-load of the corresponding concrete mixture with 25% fly ash was not significantly changed. This is consistent with the results of conventional concrete with fly ash (Lam, et al 1999). Fly ash contributes to fracture properties mainly by the pozzolanic effect. Concretes with 25% of fly ash, a better interfacial bond requires 90 days of curing. At the early ages (before 28 days), the interfacial bond strength development falls behind the compressive strength development, but at later ages (90 days), the former surpasses the later. Strengthening of the interfaces can account for higher long-term strength and excellent durability properties for the fly ash recycled and conventional aggregate concrete.

Table 8-1 Fracture energy (G_f) and maximum load of normal and steam cured concrete in Series I

Mix notation	Curing	f_f (MPa)	G_f (N/m)	P_{max} (KN)	f_f (MPa)	G_f (N/m)	P_{max} (KN)
		28 days			90 days		
R0	Standard water cured	4.42	146	3.04	5.31	154	3.15
R20		4.55	154	3.26	5.28	160	3.31
R50		4.74	162	3.44	5.74	166	3.52
R100		4.96	171	3.68	5.98	176	3.79
R0F25		4.35	143	2.99	5.76	163	3.60
R20F25		4.42	156	3.18	5.81	171	3.73
R50F25		4.58	167	3.47	5.97	182	3.95
R100F25		4.76	178	3.72	6.17	189	4.12
R0-s	Steam cured	4.61	140	2.85	5.01	147	2.94
R20-s		4.72	152	3.05	5.46	159	3.17
R50-s		4.94	169	3.56	5.81	175	3.62
R100-s		5.21	181	4.02	6.12	191	4.14
r-R0F25-s		4.45	136	3.01	5.67	156	3.34
r-R20F25-s		4.52	159	3.12	6.06	176	3.72
r-R50F25-s		4.71	174	3.43	6.23	188	4.07
r-R100F25-s		4.90	189	3.74	6.43	201	4.34

Table 8-2 Fracture energy (G_f) and maximum load of normal and steam cured concrete in Series II

Mix notation	Curing	f_f (MPa)	G_f (N/m)	P_{max} (KN)	f_f (MPa)	G_f (N/m)	P_{max} (KN)
		28 days			90 days		
R0	Standard water cured	4.94	153	3.35	5.41	162	3.43
R50		5.13	168	3.56	5.63	166	3.58
R100		5.46	176	3.94	6.18	185	3.96
R0F25		4.79	150	3.32	5.72	161	4.02
R50F25		4.95	166	3.61	6.15	178	4.38
R100F25		5.27	183	3.89	6.36	196	4.61
R0-s	Steam cured	4.82	146	3.13	5.24	155	3.23
R50-s		5.16	163	3.68	6.09	171	3.72
R100-s		5.59	178	4.21	6.82	187	4.34
r-R0F25-s		4.76	144	3.06	5.61	152	3.82
r-R50F25-s		5.28	168	3.45	6.22	181	4.46
r-R100F25-s		5.72	181	3.83	6.65	195	4.83

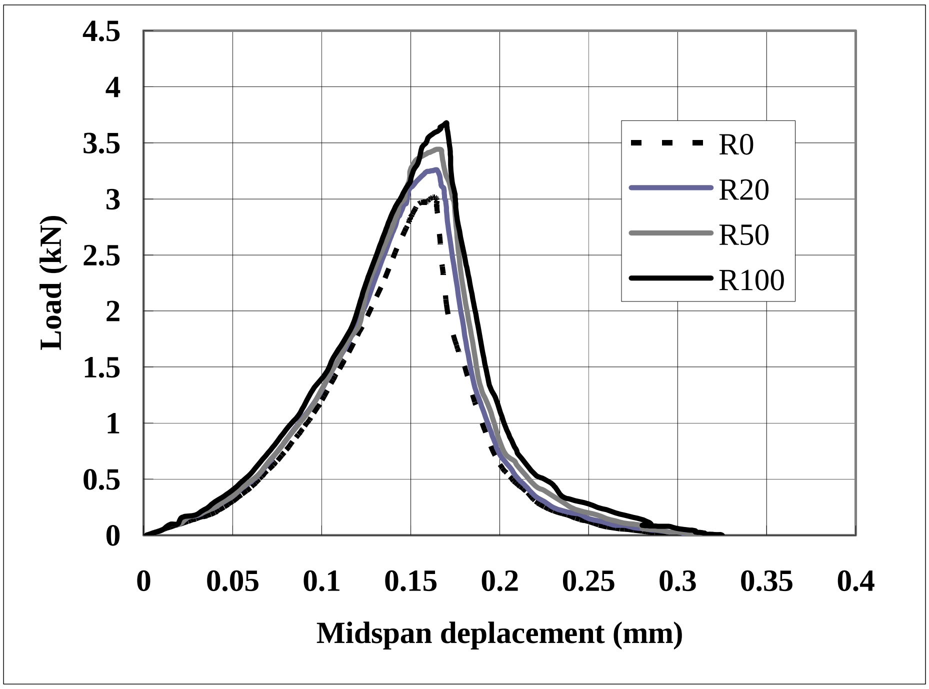


Figure 8-1 Load versus midspan deflection of concrete mixtures without fly ash in series I at 28 days

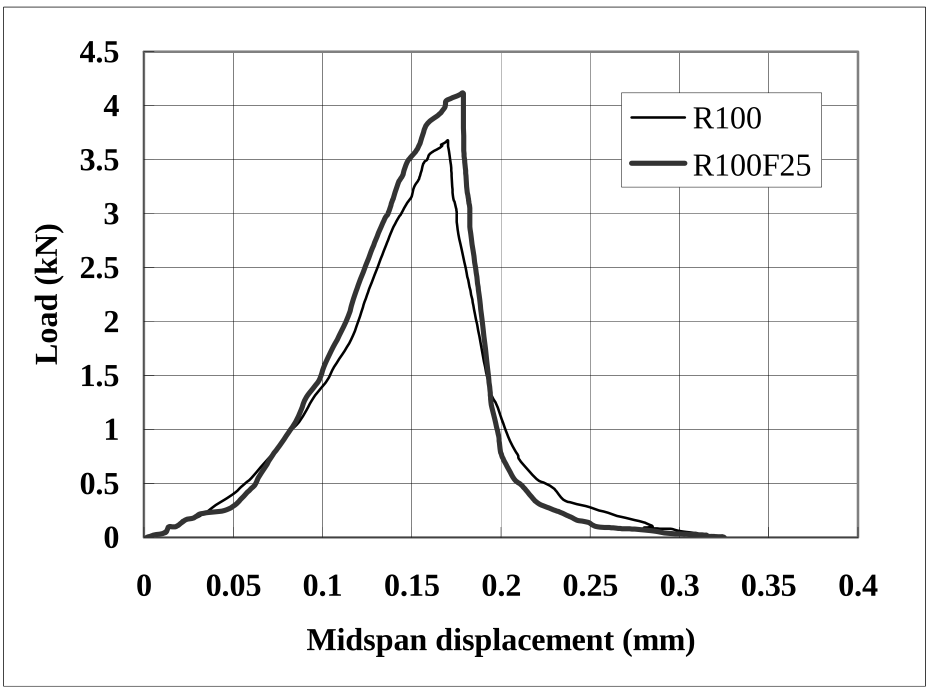


Figure 8-2 Load versus midspan deflection of concrete mixture with 100% recycled aggregate with and without fly ash in series I at 90 days

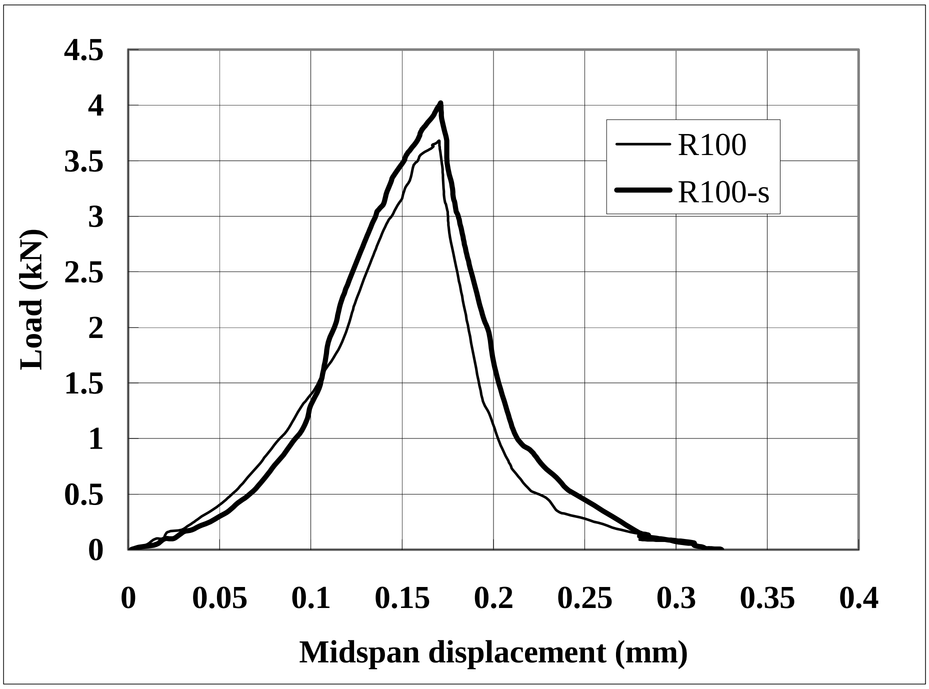


Figure 8-3 Load versus midspan deflection of concrete mixture with 100% recycled aggregate with steam curing and standard water curing in Series I at 28 days

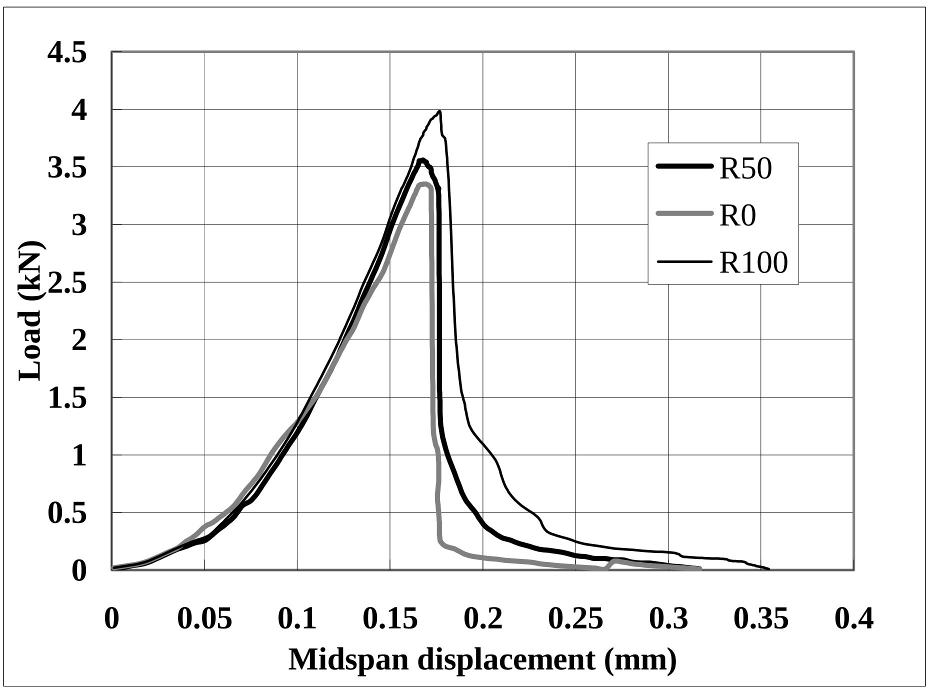


Figure 8-4 Load versus midspan deflection of concrete mixtures without fly ash in series II at 28 days

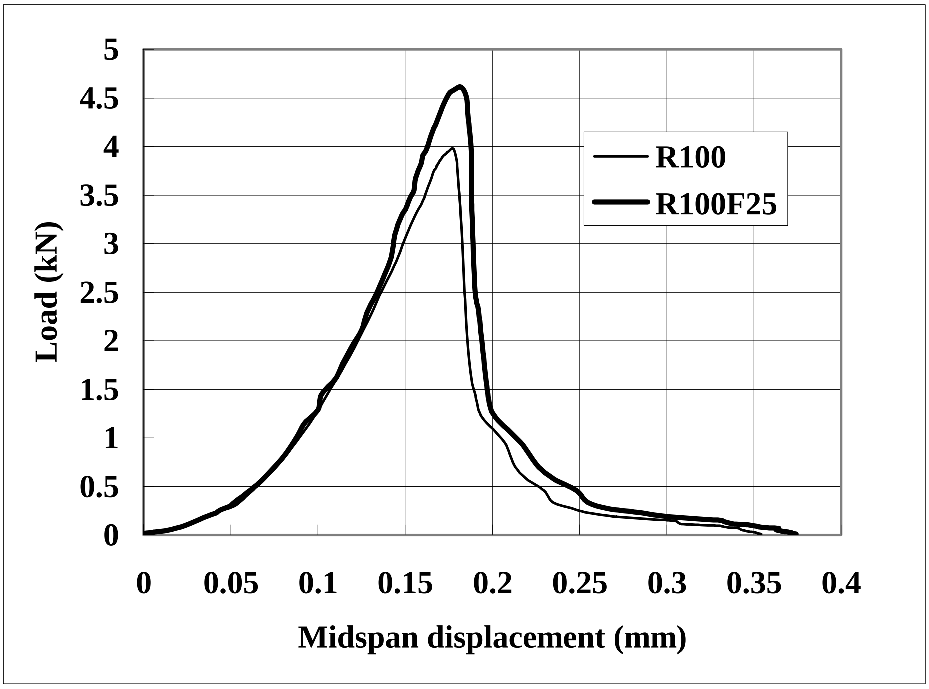


Figure 8-5 Load versus midspan deflection of concrete mixture with 100% recycled aggregate with and without fly ash in series II at 90 days

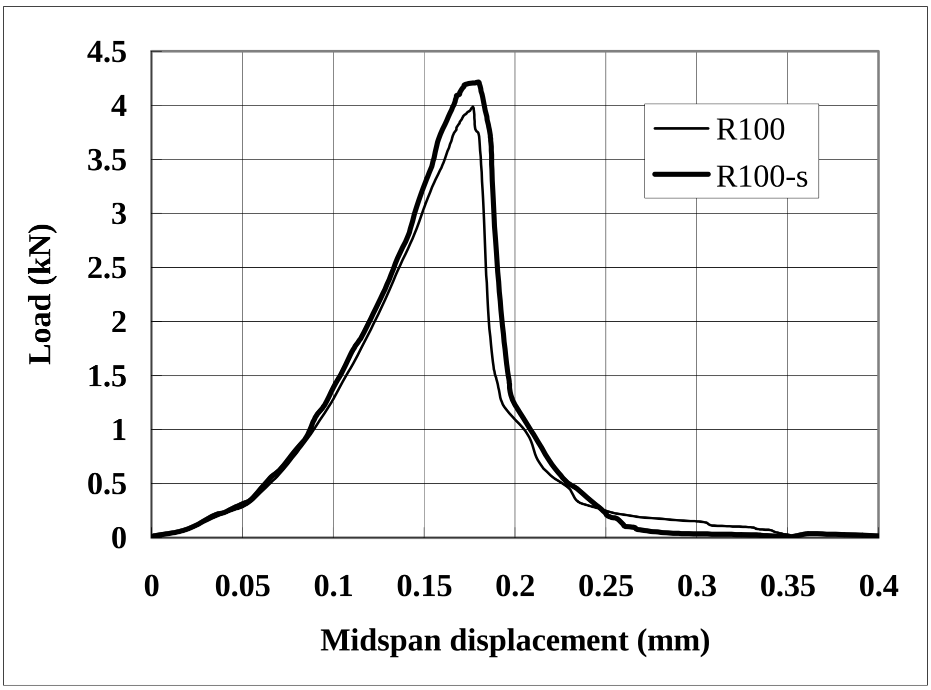


Figure 8-6 Load versus midspan deflection of concrete mixture with 100% recycled aggregate with steam curing and standard water curing in Series II at 28 days

8.2.3 Stress-strain curves of recycled aggregate concrete

8.2.3.1. Failure behavior

Normal concrete

In the early stage of the loading, the test specimens did not show any cracks. With the increase of the compression loading, small vertical micro-cracks were gradually formed in the test specimens. After reaching the peak stress, the loading decreased slowly. Several discontinuous short vertical cracks appeared, and they then coalesced into inclined macro-cracks. The inclination angle of the macrocracks with respect to the vertical loading plumb is about 62–72°.

Recycled aggregate concrete

In the early stage of the loading, nearly the same behavior as the normal concrete was observed. However, after the compression loading exceeding the peak stress, the first vertical micro-cracks appeared which were very short and thin. By continuing the test, it was very fast to form an inclined macro-crack through the specimen, and the load went down immediately. For some test specimens, a sound induced by cracking could be heard. After forming a through macro-crack, the test specimen was supported by itself and the friction between the cracks. Some vertical or slightly inclined branch cracks were observed on some samples, while the loading was stable. As the strain was controlled effectively, most of the specimens did not spall and maintained its completeness at the end of the test. All the test samples showed an inclined failure plane, with an inclination angle of about 65–83° with respect to the vertical load plumb. The inclination angle of the failure plane of recycled aggregate concrete was considerably larger than that of the normal concrete. In general, the plastic deformation of recycled aggregate concrete was less than that of the normal concrete. By carefully analyzing the failure plane, it can be concluded that fracture of the recycled and natural coarse aggregates was rarely seen. The experimental results indicated that the failure mode of recycled aggregate concrete was a shear mode, at least under the experimental conditions of this investigation. The typical failure pattern of recycled aggregate concrete is shown in Figure 8-7.

8.2.3.2 Stress–strain curves

The typical stress–strain curves of recycled aggregate concrete with different recycled aggregate contents are shown in Figures 8-8 and 8-9. Figure 8-8 illustrates that the recycled aggregate replacement percentage has marked influences on the stress-strain curve of recycled aggregate concrete. Nevertheless, the shape of the stress–strain curve for all the recycled aggregate concrete was similar to that of the natural aggregate concrete, irrespective of the recycled aggregate replacement percentages. It is worth mentioning that the strains were higher than those of the natural aggregate concrete under the same loads mainly due to the lower elastic modulus of the recycled aggregate concrete. Roughly speaking, the stress-strain curves can be divided into three characteristic parts. The first part represents the linear portion and the second represents the nonlinear portion of the ascending branch, and the third part is the descending branch. The curvature of each ascending branch of the stress-strain curves increases with the increase of the recycled aggregate content. The presence of interfaces between the new cement mortar–aggregate, old cement mortar– aggregate, and old cement mortar–new cement mortar may give rise to a progressive development of micro-cracks at these interfaces. There are a large number of such interfaces in concrete containing higher proportion of recycled coarse aggregate (Ryu, 2002, Otsuki et al, 2003). Thus, the strain increases at a faster rate than the applied stress does and so the curvature of the stress–strain curves increases with increasing recycled aggregate content. These results are similar to those reported by Xiao et al (2005).

The shape and the surface properties of recycled aggregate may also have influences on the stress–strain curves and the elastic modulus. Another notable fact of the stress-strain curve is that the slope of their descending branch decreases as the recycled aggregate content increases. In conclusion, the addition of recycled aggregate into a normal concrete leads to a substantial change in its stress–strain responses. This change is generally characterized by an increase in the peak strain (strain at peak stress) and a significant decrease in the ductility of the concrete as described by the descending portion of the stress-strain curve.

Figure 8-7 Failure pattern of recycled aggregate concrete cylinders

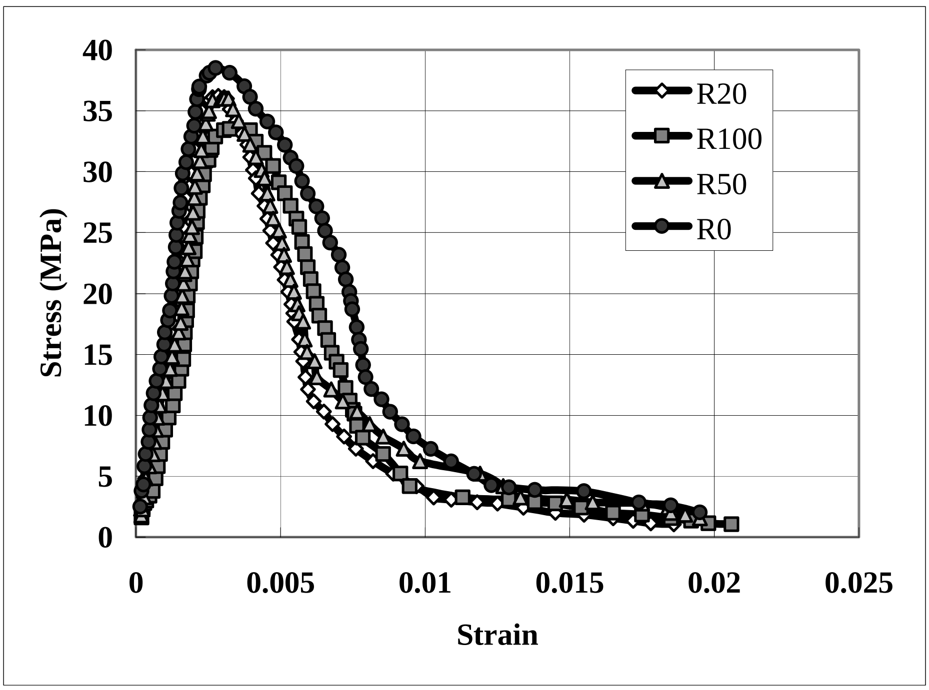


Figure 8-8 Complete compressive stress-strain curves of concrete in Series I at 28 days

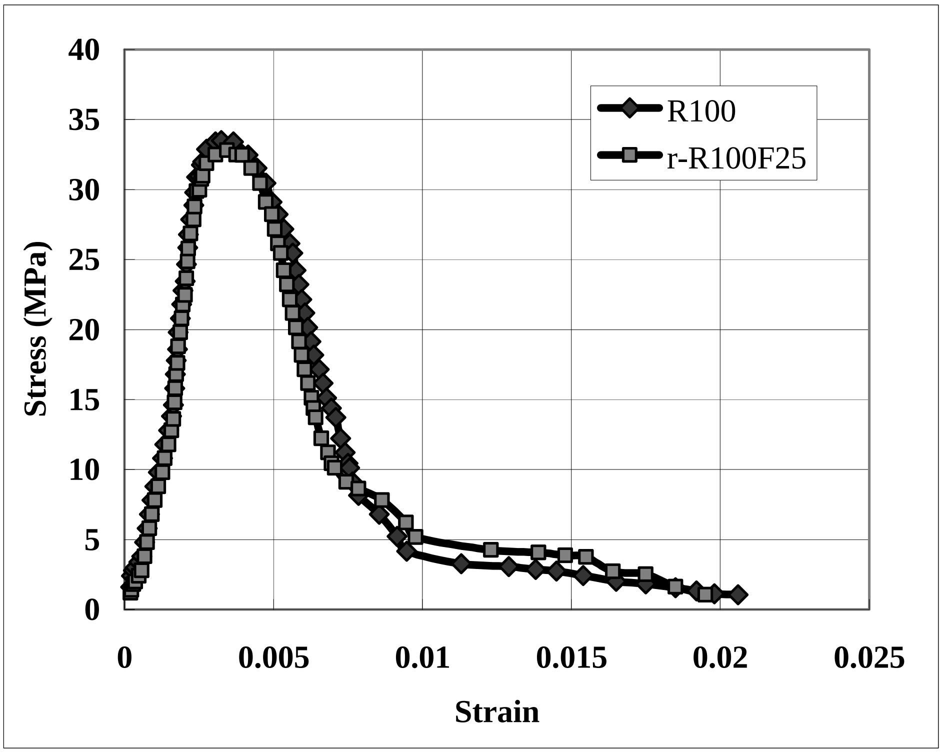


Figure 8-9 Complete compressive stress-strain curves of concrete mixtures R100 in Series I and II at 28 days

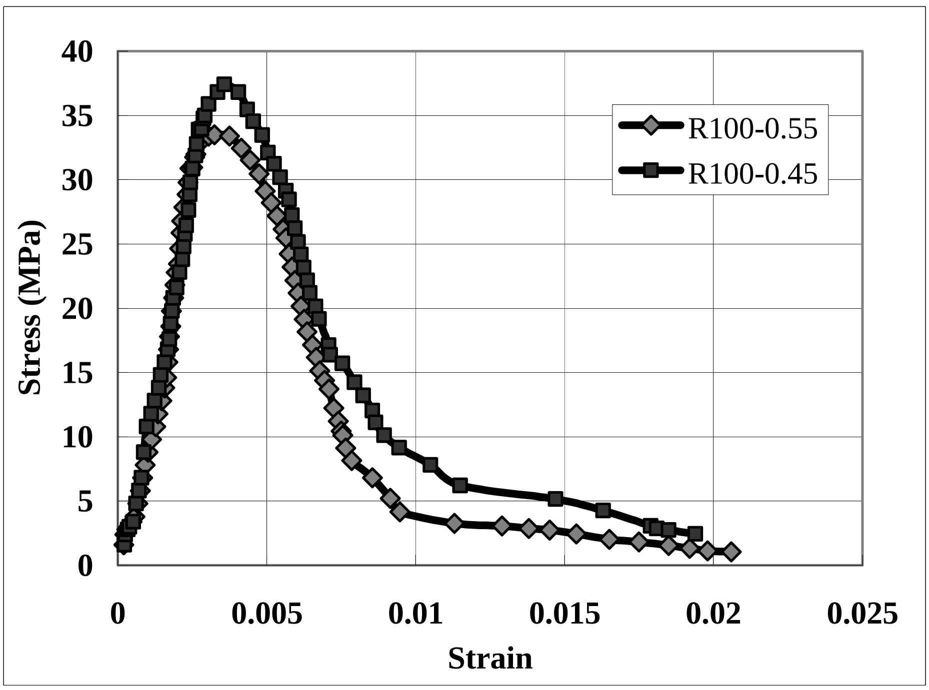


Figure 8-10 Complete compressive stress-strain curves of concrete mixture r-R100F25 in Series I at 28 days

8.2.3.3 Peak strain

The peak strain is the strain corresponding to the peak stress. The peak strain of the conventional and recycled aggregate concrete at the 28 days is present in Table 8-3. From Table 8-3, it can be seen that the value of the peak strain increases as the recycled aggregate content increases. Concrete mixture R0 with 0% recycled aggregate in Series I and II achieved peak strain of 276 and 308 microstrian, respectively, whereas concrete mixture R100 with 100% recycled aggregate achieved peak strain of 325 and 358 microstrain, respectively, an increase of 17.8% and 16.2%, respectively; in comparison with the strain of the concrete mixture R0. This is consistent with the results of Atkinson et al (1999) and Xiao et al (2005). The main reason for the increase of the peak strain of recycled aggregate concrete is due to use recycled aggregate reduced the elastic modulus of the concrete, which leads to a larger deformation.

The replacement of cement by 25% fly ash had a higher peak strain of natural and recycled aggregate concrete than that corresponding concrete mixture without fly ash. Concrete mixture R100 with 0% fly ash in Series I and II achieved peak strain of 325 and 358 microstrain, respectively, whereas concrete mixture r-R100F25 with 25% fly ash achieved peak strain of 344 and 368 microstrain, respectively, an increase of 5.85% and 2.80%, respectively; in comparison with the strain of the corresponding concrete mixture without fly ash.

Table 8-3 Experimental results of concrete cylinders under compression loading

Mix notation	*W/b*	Strain at peak stress
R0	0.55	0.00276
R50		0.00306
R100		0.00325
r-R0F25		0.00295
r-R50F25		0.00331
r-R100F25		0.00344
R0	0.45	0.00308
R50		0.00322
R100		0.00358
r-R0F25		0.00318
r-R50F25		0.00341
r-R100F25		0.00368

8.3 SUMMARY

In this chapter, the fracture properties of concrete with various recycled aggregate contents were tested by geometrically similar three-point bend concrete beams and the experimental results for the mechanical properties of recycled aggregate concrete under uniaxial compassion loading are presented and discussed. From this investigation, the following summary can be drawn:

- Flexural strength increased with the increase in recycled aggregate content in both of Series I and II concrete mixtures. The replacement of cement by 25% fly ash resulted in lower flexural strength of conventional and recycled aggregate concrete

- The fracture energy increased as the recycled aggregate content increased. The peak-load and the area surrounded by the curve are increased by increasing recycled aggregate content

- At 90 days, the replacement of cement by 25% fly ash resulted in higher fracture energy and peak-load.

- The failure mode of recycled aggregate concrete was a shear mode under the experimental conditions of this study. The failure process of recycled aggregate concrete was relatively short. The inclination angle between the failure plane and the vertical load plumb was about 65-83°.

- The recycled aggregate replacement percentage had a considerable influence on the stress-strain curves of recycled aggregate concrete. For all considered cases recycled aggregate content from 0% to 100%, the stress-strain curves showed a similar behavior. The stress-strain curves of recycled aggregate indicated an increase in the peak strain and the ductility as characterized by their descending portion.

- The peak strain of recycled aggregate concrete was higher than that of conventional concrete. It increases with the increased of recycled aggregate contents. For concrete mixture R100 with 100% recycled aggregate, the peak strain was increased by 15%.

- The replacement of cement by 25% fly ash resulted in a substantial improvement in the post peak stress-strain behavior of recycled aggregate concrete. The stress-strain curves of recycled aggregate concrete made with 25% fly ash indicate an increase in the peak strain and the ductility.

CHAPTER 9 CONCLUSION AND RECOMMENDATION

9.1 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 4.The effect of fly ash and steam curing on hardened properties of recycled aggregate concrete has been studied in chapter 5 and chapter 6, respectively. An investigation into the microstructure properties of the cement matrix-aggregate interfaces in recycled aggregate concrete has been presented in chapter 7. The fracture properties and the compressive stress-strain behavior of recycled aggregate concrete have been presented in chapter 8.

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.

9.2 CONCLUSIONS

9.2.1 Fresh Properties of Recycled Aggregate Concrete

In chapter 4, the fresh properties of recycled aggregate concrete with and without fly ash 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 replacement of cement by 25% fly ash increased the slump of concrete mixtures with and without recycled aggregates.

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

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

6. The replacement of cement by 25% fly ash decreased the air content of concrete mixtures with and without recycled aggregates. This due to the spherical particle shape of fly ash participates in improving workability of fly ash concrete because of the so-called "ball bearing" effect

7. 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.

9.2.2 Hardened Properties of Fly Ash Recycled Aggregate Concrete

In chapter 5, the effect of fly ash was used as a substitution of cement or an additional mineral admixture on hardened properties of recycled aggregate concrete was 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/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.

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 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.

7. The resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, the resistance was improved by incorporating fly ash in the concrete mixtures. A decrease in the W/B ratio improved the resistance to chloride ion penetration. Furthermore, it was found that the resistance increased as the curing age increased from 28 to 90 days.

8. 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.

9.2.3 Hardened Properties of Steam Cured Recycled Aggregate Concrete

On the influences of steam curing on hardened properties of recycled aggregate concrete the following conclusions can be drawn from the test results:

1. Steam curing at 65 ºC increased the early ages (1, 4, and 7-day) strength of all concrete mixtures compared to that of the water cured concrete. However the 28

and 90-day strengths of the steam cured concrete were lower than those of the water cured concrete.

2. The detrimental effect of steam curing on the long-term hardened properties of concrete was reduced when compared with natural aggregate concrete.

3. The drying shrinkage value of concrete prepared with 100% recycled aggregate was about 30 % higher than that of natural aggregate concrete. Nevertheless, steam curing reduced the drying shrinkage. The reduction was about 15 % for the steam cured concrete prepared with 100 % recycled aggregate.

4. Steam curing reduced the drying shrinkage of fly ash recycled aggregate concrete. When fly ash was used a substitution 25% of cement and addition of 25% fly ash, the reduction was about 10-15% and 20-25% for the steam cured concrete prepared with 100% recycled aggregate, respectively.

5. Steam curing reduced the creep strain of recycled aggregate and fly ash recycled aggregate concrete. When fly ash was used a substitution 25% of cement and addition of 25% fly ash, the reduction was about 27% and 17% for the steam cured concrete prepared with 100% recycled aggregate, respectively.

6. The resistance against chloride-ion penetration of the concrete decreased with an increasing recycled aggregate content where concrete prepared with 100% recycled aggregate had the highest charge passed. An initial steam curing regime decreased the resistance of the concrete against chloride-ion penetration. However, the detrimental effect of steam curing on the concrete against chloride-ion penetration of recycled aggregate concrete was reduced for recycled aggregate concrete.

7. An initial steam curing regime significantly increased the resistance of the fly ash conventional and recycled aggregate concrete against chloride-ion penetration at both ages of 28 and 90 days.

8. 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.

9.2.4 Effect of Fly Ash and Steam Curing on Microstructure Characteristics of Matrix- Aggregate Interfacial Zone of Recycled Aggregate Concrete

In chapter 7, an analysis of microstructure and pore size distribution of the concrete made with conventional and recycled aggregates prepared with and without fly ash by different curing regimes was carried out and the conclusions obtained are:

1. According to the microstructure analysis the distribution of aggregates was homogeneous in all concretes. All the recycled aggregates studied behave similarly from this point of view. The high porosity of original cement paste was evident.

2. The Interfacial transition zone between the recycled aggregates and the new paste of the steam cured conventional aggregate concrete were more porous with more cracks than that of the recycled aggregate concrete.

3. For the concrete made with recycled aggregates, the quality of new interfacial transition zone was better than that in the old paste, consequently in these concretes, the weakest point could be the adhered mortar. Therefore the adhered mortar strength will be what determines the material strength and behavior. This is one of the greatest differences with respect to conventional aggregate concrete

4. Total porosity and average pore diameter increased as the recycled aggregate content increased. The pore size distribution of the concrete made with recycled aggregates was shifted to the bigger pore size range demonstrating the pore clarifying effect of the recycled aggregates.

5. The replacement of cement by 25% fly ash resulted in lower MIP porosities of recycled and conventional aggregate concrete at the ages of 28 and 90 days.

However, the replacement of cement by 35% fly ash resulted in slightly higher MIP porosities of the concretes.

6. All the fly ash concretes specimens recorded lower intrusion volumes in pores of sizes larger than that 0.01μm in comparison with the concrete mixtures without fly ash.

7. Steam curing regime increased the total porosity and average pore diameter of conventional and recycled aggregate concrete prepared with and without fly ash at the test ages of 28 and 90 days. However, these increases were reduced with an increase in recycled aggregate content.

9.2.5 Effect of Recycled Aggregate on Mechanical and Fractural Properties and Compressive Stress-Strain Relationship of Concrete

In chapter 8, the fracture properties of concrete with various recycled aggregate contents were tested. From this investigation, the following conclusions can be drawn:

1. Recycled aggregates increased the matrix-aggregate interfacial bond strength and fracture energy. Fly ash replacement at a level of 25% also increased the bond strength and fracture energy of recycled aggregate concrete. The experimental results showed a substantial improvement in the post-peak ductility for the recycled aggregate concrete when fly ash was used.

2. The failure mode of recycled aggregate concrete was a shear mode under the experimental conditions of this study. The failure process of recycled aggregate concrete is relatively short. The inclination angle between the failure plane and the vertical load plumb was about 62-75°.

3. The peak strain of recycled aggregate concrete was higher than that of conventional concrete. It increased with the increase of recycled aggregate contents. For concrete mixture R100 with 100% recycled aggregate, the peak strain was increased by 20%.

4. The replacement of cement by 25% fly ash resulted in a substantial improvement in the post peak stress-strain behavior of recycled aggregate concrete. The stress-strain curves of recycled aggregate concrete made with 25% fly ash indicated an increase in the peak strain and the ductility.

9.2.6 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.

9.3 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.

9.4 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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