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Properties and sustainability evaluation of green concrete utilizing waste and recycled materials

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廃棄物やリサイクル材料を活用したグリーンコンクリートの物性および持続可能性評価

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ABSTRACT

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Michael Henry & Yoshitaka Kato

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This ICUS report is a summary of several years of research works and experimental investigations conducted at the Institute of Industrial Science, the University of Tokyo, on the usage of various waste and recycled materials in "green" concrete towards reducing the environmental impact of concrete materials and structures and improving sustainable practices in the concrete industry. These works and experiments approached the problems related to green concrete from two perspectives: the effect of utilizing waste and recycled materials in concrete and the properties and performance of green concrete materials; and the development of different metrics and methods for evaluating the environmental performance and means for balancing the mechanical and environmental performances.

Chapter 2 is a review of sustainability and environmental issues in the concrete industry, including environmental impact, strategies for sustainable practice, and examples of sustainable concretes. Chapter 3 reviews environmental impact and sustainability evaluation methods, focusing particularly on sustainability indicators. The environmental performance indicator is introduced as a means for weighting mechanical performance by environmental impact, and the application of the analytic hierarchy process, a multi-criteria framework for making complex decisions, is proposed as an original means for examining the balance between different concrete properties and environmental impacts. Both of these were applied during the experimental investigations.

Chapter 4 introduces the results of three experimental phases designed to investigate problems with recycled aggregate and fly ash, such as the statistical relationship between varied aggregate quality and reduced performance and the quantitative effect of these materials on the environmental impact as well as the balance between the mechanical and environmental performance by applying the methods proposed in Chapter 3. Some key results from these investigations are as follows:

- Variation of compressive strength for concrete with low-grade recycled aggregates was higher than for normal aggregates, but still fell below a JSCE-specified limit and thus an overdesign factor does not need to be considered. Mixing different types of aggregates, however, increased the variation higher than when using either of the aggregates types alone; particularly when mixing two types of recycled aggregate, the JSCE-specified limit was exceeded.
- An index factor combining cement-water ratio and aggregate density and absorption properties was proposed and could be used to estimate the compressive strength of recycled aggregate concrete with a very high degree of linear correlation.
- CO_2 footprint of concrete is primarily affected by binder composition and secondarily by binder content, whereas the volume of raw material is affected primarily by aggregate type; thus, evaluating the environmental performance of concrete by CO_2 footprint doesn't show the value of low-grade recycled aggregate, whereas evaluating by volume of raw materials doesn't show the value of fly ash. After calculating the environmental performance indicators, it was seen that replacing cement with fly ash or reducing the amount of binder reduced the CO_2 footprint more than it reduced strength; in contrast, low-grade recycled aggregates reduced raw material volume more than they reduced strength.
- When comparing CO_2 footprint vs. air permeability and CO_2 footprint vs. volume of raw materials, a single material could be found to have the best balance, but when comparing volume of raw materials vs. air permeability no single material could be selected as having the best balance due to the direct relationship between recycled aggregate usage and these two

factors. Applying the analytic hierarchy process with four weighting scenarios showed that, in general, the usage of normal aggregates was preferred in most cases except when giving high importance to the volume of raw materials. In addition, a water-binder ratio of 45 with 25% fly ash, 25% blast furnace slag, and 50% cement was the preferred binder composition in most cases because it met the required strength with a reduced CO_2 footprint and better air permeability coefficient.

Chapter 5 introduces the results from an investigation on the properties and environmental impact of concrete combining recycled rubber crumbs with recycled aggregates and fly ash in concrete. Increasing the amount of rubber crumbs was shown to linearly reduce compressive strength, and the combination of rubber crumbs with recycled aggregates, with fly ash, and with both recycled aggregates and fly ash reduced strength in that order. The effect of rubber crumbs on air permeability depended primarily on binder type and presence of recycled aggregates. The mechanical-environmental efficiency was calculated as the environmental performance indicator utilizing volume of raw materials and compressive strength, and overall the usage of only 100% recycled aggregates had the highest efficiency. Rubber crumbs were found to be an inefficient means for reducing environmental impact when using weighted strength as an index.

Chapter 6 summarizes an investigation on fly ash mortar and concrete reinforced with fibers made from recycled PET bottles. The PET fiber-reinforced mortars performed similarly in compressive and flexural strength testing as polypropylene fiber-reinforced mortar. For the concrete mixes, environmental performance indicators were used to normalize the mechanical performance by considering the environmental impact, and it was found that these indicators could reverse the trends shown by the mechanical performance alone, particularly in the case of high volume fly ash concrete.

Overall, these experimental investigations showed that certain combinations of waste and recycled materials could achieve similar performance as normal-use concretes currently in practice, and do so while reducing environmental impact such as CO_2 footprint and volume of raw materials. However, without the means for evaluating and balancing the environmental impact with the mechanical performance, it’s difficult to quantify the value of these green concretes. The value of the approaches taken in this report can therefore be clearly understood, but it will require institutional changes in the attitudes and systems used for evaluating and selecting concrete materials before green concretes can become more widely applied.

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As this report is a summary of extended research and experimental work in Katoyosh Laboratory in the International Center for Urban Safety Engineering (ICUS), the authors would first like to express their appreciation for the hard work of the students who prepared, mixed, cast, and tested the concrete reported here:

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Chapter 1
Introduction

1.1 BACKGROUND

Concrete is the most widely used construction material on the planet, and the second-most utilized natural resource after water. It's a composite material, consisting of a binder (typically Portland cement), water, fine and coarse aggregates, and chemical admixtures. The hydraulic reaction between the cement and water causes the concrete to solidify, binding the different phases together and creating a hardened, rock-like material. Concrete serves as the primary material utilized for constructing the infrastructure necessary to provide society with basic safety and living requirements. Globally, the usage of concrete has been increasing as developing countries have begun investing in infrastructure systems such as highways, bridges, tunnels, and so on. As human populations continue to grow and urbanize, so too will the demand for infrastructure increase, resulting in increased utilization of concrete to meet that demand. Growth and urbanization has, however, also been a primary driver of environmental deterioration, from destruction of ecosystems to increased emissions of greenhouse gases and other air-born pollutants. Observed changes in the global climate have increased awareness of the impacts of human activities on environmental systems, and led to the formation of international committees on how to reduce environmental deterioration and mitigate future climate changes.

The environment is one aspect considered by sustainable development, along with society and the economy. The basic concept of sustainable development is that the effects of development in modern societies need to consider and protect the ability of future societies to develop. There is a complex interaction between the three aspects. Although they are sometimes considered as separate entities to be integrated, a better approach considers them as systems contained within each other – economy exists within society and society exists within its surrounding environment. Viewed this way, the effects of changes in the environment can be felt in both of the aspects that exist within it.

Increased awareness of the environment has led the concrete industry to consider its environmental impact. Concrete's negative impact comes in several forms, from large-scale emission of greenhouse gases to massive consumption of natural resources such as water, sand, and aggregates. Approaches to reducing the industry's environmental impact include increasing the durability of concrete structures, utilizing the waste products of other industries as a replacement material, and the recycling of demolition waste back into the construction process. The concrete material itself is an important part of the shift to sustainable practice and reduced environmental impact. Durable materials utilizing waste and recycled materials could form the foundation of sustainable concrete. However, there is oftentimes a trade-off between the environmental impact and mechanical properties, such as the reduction in quality and durability when utilizing recycled aggregates or the increase in CO_2 emissions when reducing water-binder ratio to increase strength. Therefore, it's important not only to investigate the usage of the waste and recycled materials in concrete but to also consider their effects on the environmental performance and material properties and develop metrics whereby both the mechanical and environmental aspects can be considered simultaneously.

1.2 REPORT OVERVIEW

This ICUS report is a summary of several years of research works and experimental investigations conducted at the Institute of Industrial Science, the University of Tokyo, on the usage of various waste and recycled materials in "green" concrete towards reducing the environmental impact of concrete materials and structures and improving sustainable practices in the concrete industry. These works and experiments approach the problems related to green concrete from two perspectives: first, the effect of utilizing waste and recycled materials in concrete and the properties and performance of green concrete materials; and second, the development of different metrics and methods for evaluating the environmental performance and means for balancing the mechanical and environmental performances.

The contents of this report are broken into five chapters which provide background and the results and discussion of each of the experimental investigations. Chapter 2 is a review of sustainability and environmental issues in the concrete industry, including the environmental impact, strategies for sustainable practice, and examples of sustainable concretes. Chapter 3 reviews environmental impact and sustainability evaluation methods, focusing particularly on sustainability indicators, and also includes means for evaluating sustainability and environmental impact of concrete and an original approach utilizing the analytic hierarchy process. Chapter 4 covers three related experimental investigations on the usage of low-grade recycled aggregates and fly ash in concrete, including quality variation and estimation of recycled aggregate concrete strength and the relationship and balance between mechanical and environmental performance utilizing methods proposed in Chapter 3. Chapter 5 introduces the results from an investigation on the properties and environmental impact of concrete combining recycled rubber crumbs with recycled aggregates and fly ash in concrete. Finally, Chapter 6 summarizes an investigation on mortar and concrete reinforced with fibers made from recycled PET bottles and combined with fly ash.

Chapter 2
Sustainability and usage of waste and recycled materials in concrete

2.1 INTRODUCTION

Concrete is an integral part of infrastructure construction, providing the very foundation upon which society and its quality of life are built. However, concrete also plays a major role in environmental deterioration. The environmental impact comes from a variety of sources over the entire life cycle, from material manufacturing to the disposal of waste concrete, and various strategies for reducing this impact have been proposed which target different aspects of concrete practice. General concepts for sustainable practice in the concrete industry have, therefore, primarily targeted the reduction of the industry's negative environmental impact.

In order to meet the challenges of sustainability, the American Concrete Institute (ACI) established a Board Advisory Committee on Sustainable Development (BACSD) to develop recommendations for ACI on how to promote sustainable practice. In 2005, the BACSD proposed that the concrete industry adopt a definition of sustainability containing the following elements (ACI BACSD, 2005):

- Specification, design, and proportioning of concrete must be performed considering durability, conservation, and minimal environmental impact;
- Production of ingredients, concrete, and construction practice must be environmentally responsible
- Concrete industry must remain competitive

In addition to this definition, the BACSD also made several recommendations to ACI for promoting sustainable practice in the concrete industry, ranging from policy statements to documentation and guidelines for sustainable practice to education for both concrete engineers and non-engineers alike.

Although different professional groups around the world, like ACI, have tried to establish guidelines for sustainable practice, no over-arching guideline has yet been decided upon – perhaps due to the large regional differences between construction cultures around the world. However, there still remain two unavoidable challenges. The first is to meet the growing demand for infrastructure necessary to provide an acceptable standard of living as the human population continues to grow and urbanize. The second challenge is to achieve the first while reducing the environmental impact caused by concrete industry activities. This chapter will review the environmental impact of concrete, and discuss practices and approaches taken in the concrete industry to meet these challenges and move towards the ultimate goal of sustainable development.

2.2 ENVIRONMENTAL IMPACT OF CONCRETE

Sakai (2009) estimated that the global consumption of concrete, based on the assumption that all cement produced world-wide was used in concrete, is roughly 3.2 tons per person, making it the second-most used resource after water. Although the utilization of concrete is necessary for producing the infrastructure to maintain quality-of-life requirements, it also carries with it a high environmental impact in several forms: CO_2 and other GHG emissions, particulate matter and air contamination, natural resource and energy consumption, waste material generation and contaminants disposal, as well as other impacts such as noise and vibration from manufacturing and construction.

The CO_2 emissions of selected concrete-making materials are given in Figure 2.1. From this figure, it is clear that cement is the largest source of CO_2 emissions in concrete production, and global cement production is a major contributor to world GHG emissions. In 2000, roughly 1.37 billion metric tons of CO_2 were emitted by the production of cement, representing roughly 6% of the world's total emissions at that time.

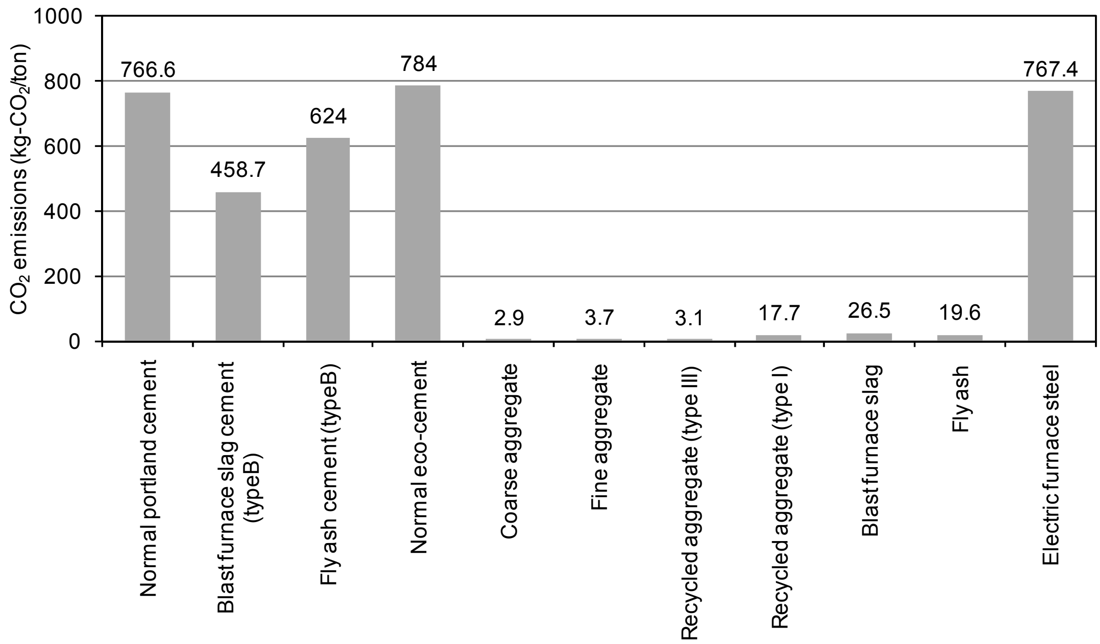

Figure 2.1 CO_2 emissions for concrete-making materials in Japan (data source JSCE, 2006)

Although cement is the primary contributor of CO_2 in concrete, most of the volume in concrete is occupied by fine and coarse aggregates. However, as seen in Figure 2.1, these materials contribute only a small amount of CO_2 emissions. Emissions related to water, an essential ingredient in concrete production, are so small that typically they are not considered. Modern reinforced concrete structures typically utilize steel reinforcement in addition to concrete, which contributes CO_2 on the same level as cement; however, the reinforcement ratio may vary widely depending on the loading conditions, and emissions are much higher for blast-furnace steel than for electric furnace. For Japan, roughly 0.11 tons of CO_2 emissions are attributed to reinforcement for every ton of cement (Sakai, 2009).

In addition to the manufacturing emissions, there are also emissions related to the actual mixing of concrete as well as transportation of concrete from the ready-mix concrete factory to the construction site. These emissions contribute roughly 25% of the total concrete production emissions, but this estimation was based on the prevailing conditions in the Japanese industry and global conditions and efficiency vary widely, so the global average may be much higher (Sakai, 2009).

Figure 2.2 shows the input energy needed for producing concrete-making materials. Again, it can be seen that most energy is used in the production of cement. This figure, however, does not include the energy consumed in the transportation of these materials or in the production of concrete material.

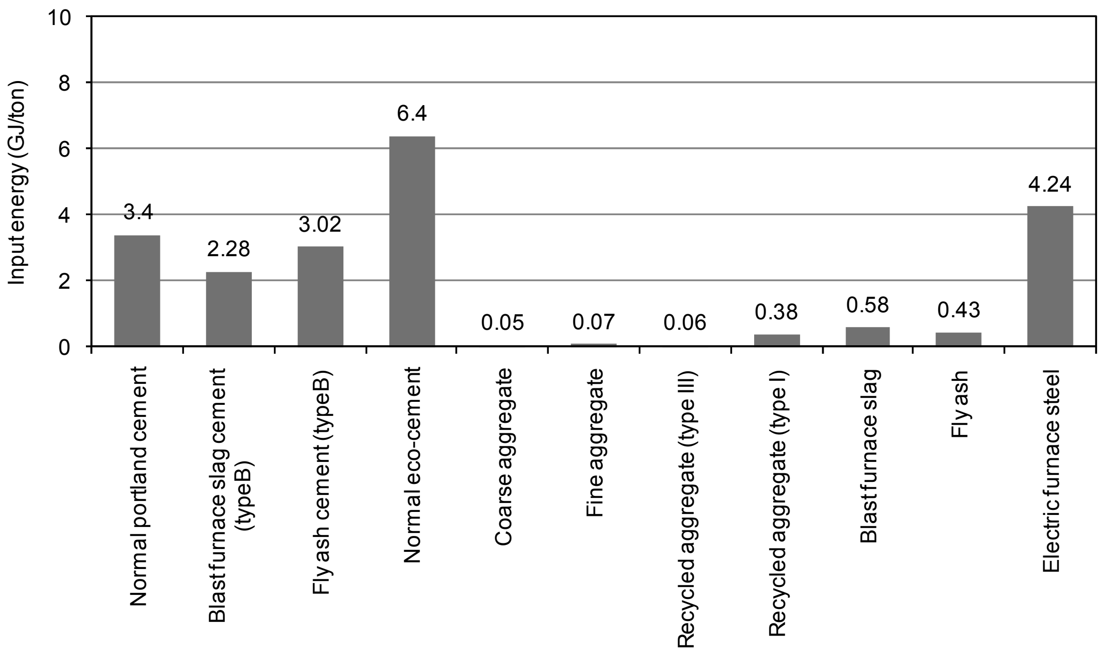

Figure 2.2 Input energy for concrete-making materials in Japan (data source JSCE, 2006)

Cement production not only requires energy but also consumes large quantities of natural resources such as clay and limestone. Concrete production consumes roughly 10 to 11 billion tons of sand, gravel, and crushed rock per year, in addition to over 1 trillion liters of water (Mehta, 2001). This water consumption does not include water used for washing at ready-mix concrete plants or applied for concrete curing. The mining of these materials results in deforestation and loss of top soil, and has a large effect on forest and river ecology.

Worldwide generation of concrete and masonry rubble from construction demolition in 1998 was estimated at roughly one billion metric tons (Lauritzen, 1998). In Japan, total construction waste was estimated to be roughly 85 million tons in 2000, of which 41% (35 million tons) was waste concrete (Figure 2.3). However, between 1995 and 2000 the recycling rate of concrete increased from 65% to 96%, but the majority of this material was utilized as fill for road construction (MLIT, 2009). While recycling for usage in road construction is better than disposal to landfills, this could be considered “down-cycling” because it does not help reduce the consumption of virgin aggregates in concrete construction (Mehta, 2001).

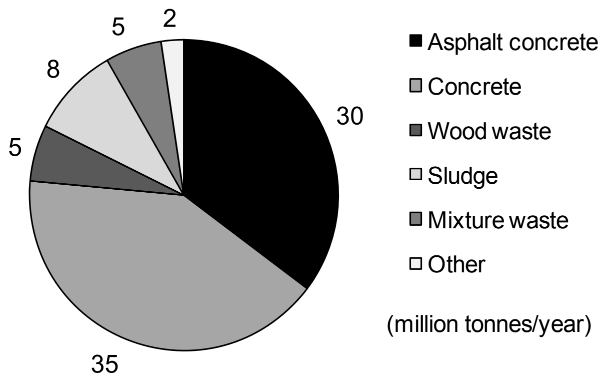

Figure 2.3 Japan construction waste in 2000 (data source MLIT, 2009)

In addition to GHG emissions, concrete construction also contributes to air pollution and health concerns from concrete dust. Water and soil may also be contaminated by operations related to cement and concrete production, such as mining or transportation, and water quality compromised by water runoff over impervious concrete surfaces such as roads, where the water picks up pollutants and then carries it downstream. Surface runoff can also increase soil erosion, and water which cannot properly drain decreases the safety of vehicles traveling on roadways.

Concrete as a paving and surfacing material also contributes to the urban heat island effect. Lighter-colored concrete can reflect radiation, such as light, which reduces the amount of energy absorbed and keeps the concrete cooler (EPA, 2005). Darker-colored paving materials, such as asphalt, absorb more heat and raise the temperature in the surrounding area.

Finally, there are other indirect environmental impacts such as the noise and vibration produced when producing cement, concrete-making materials, concrete itself, or at the construction site; as well as the impacts over the service life of the structure, such as those related to repair, maintenance, and the ultimate demolition and disposal of the structure (JSCE, 2006). These can generally be measured directly and correlated to different construction activities.

2.3 STRATEGIES FOR SUSTAINABLE PRACTICE

Mehta (1999) proposed one of the first strategies for sustainable practice in the concrete industry with his foundation for environmentally friendly concrete technology, shown in Figure 2.4. This proposal consisted of three elements: conserving the raw materials used for producing concrete, improving the durability of new construction, and shifting to a holistic approach in both technology and education. For conserving concrete-making materials, he identified recent research works which examined the replacement of normal aggregates with demolition waste or the usage of recycled water from concrete plants for mixing water, but the utilization of alternative cementitious materials, particularly fly ash, for reducing the usage of Portland cement consumption was emphasized as the most important target. Enhancing the durability of concrete construction would conserve natural resources by reducing consumption, but many problems with new construction, such as poor workmanship and cracking due to the chemical composition of cements with high early-age strength gain, need to be addressed. For existing structures, extending the service life through maintenance, repair, and rehabilitation should be considered options. Finally, a holistic approach should be taken which considers the concrete industry as part of society, so that the concrete industry should not only be responsible for providing a construction material but also take social and environmental obligations. However, this will require a shift in philosophy from the current reductionist practices in not only the concrete industry, but also in the education of concrete engineers and education in general.

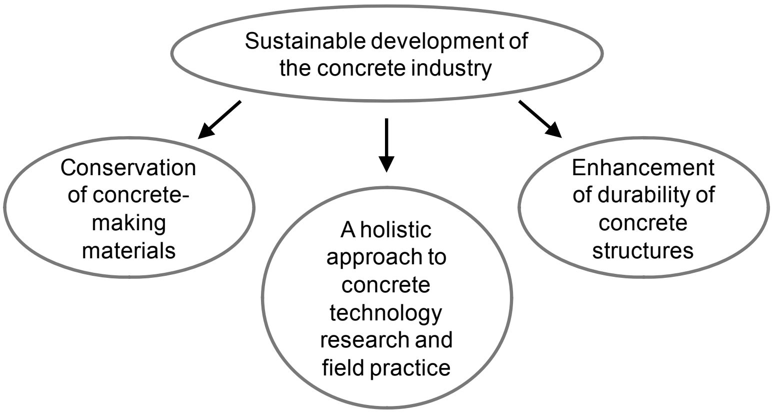

Figure 2.4 Mehta's foundation for sustainable development in the concrete industry (adapted from Mehta, 1999)

Sakai (2009) reviewed four CO_2 reduction scenarios for the concrete industry. Although CO_2 reduction is just one aspect of sustainability, most emphasis on sustainability in the concrete industry focuses on reduction of the environmental impact. Sakai's four scenarios included: utilization of carbon capture and storage (CCS); reducing CO_2 emissions and energy usage from cement production by developing new cement systems; reducing cement content by utilizing alternative cementitious materials or water-reducing admixtures; and selection of low-impact construction methods. Although the IPCC recommends implementing carbon capture and storage to the cement industry as a mitigation technique, the level of technology is still too low to be practically implemented, and focusing on CCS may distract from the development of other mitigation techniques. Since Japan has the lowest CO_2 emissions for producing cement (Figure 2.5), CO_2 and energy reduction could be achieved by transferring Japanese cement production technology to other countries, such as specialized kiln systems and the usage of industrial waste as raw material and fuel for cement kilns. Another approach is utilizing admixtures to reduce the unit water content, which then allows for a reduction of the unit cement content. This approach requires no specialized technology, only careful consideration of mix design and access to high-range water reducing admixtures. The final scenario for reducing CO_2 focuses on the concrete structure, rather than the material. New structural forms or construction methods can have a large effect on the CO_2 emissions, so low-impact options should be selected.

2.3.1 Resource conservation

Conservation of virgin materials for making concrete can be achieved by utilizing replacement materials such as industrial by-products or recycled waste. The term "industrial ecology" refers to the practice of recycling waste products from one industry as a substitute for virgin materials in another industry. Not only does this reduce the consumption rate of virgin materials, but it also reduces the volume of material being sent to landfills. For the concrete industry, there are many opportunities for this practice to be implemented, and many different replacement materials have already been investigated for concrete application, as summarized in Figure 2.6.

One widely-used industrial by-product is fly ash. Fly ash is a pozzolanic material generated by the combustion of coal and can be used as a replacement for Portland cement due to its cementitious properties when mixed with lime. The addition of fly ash to concrete improves long-term strength and durability. In addition, the spherical shape helps improve the workability of fresh concrete and allows for the reduction of mixing water. Ground-granulated blast furnace slag (GGBS), a by-product of the steel industry, is more common in Japan and, similar to fly ash, improves durability and long-term strength. The production of one ton of pig iron produces roughly 300 kilograms of slag, and the recycling of slag which can be utilized in the concrete industry – either in blended cements or as a mineral admixture – provides the concrete industry with a way to practice industrial ecology and help reduce the steel industry's environmental impact, which in turn has a greater benefit to Japan as a whole by reducing waste generation and raw material consumption.

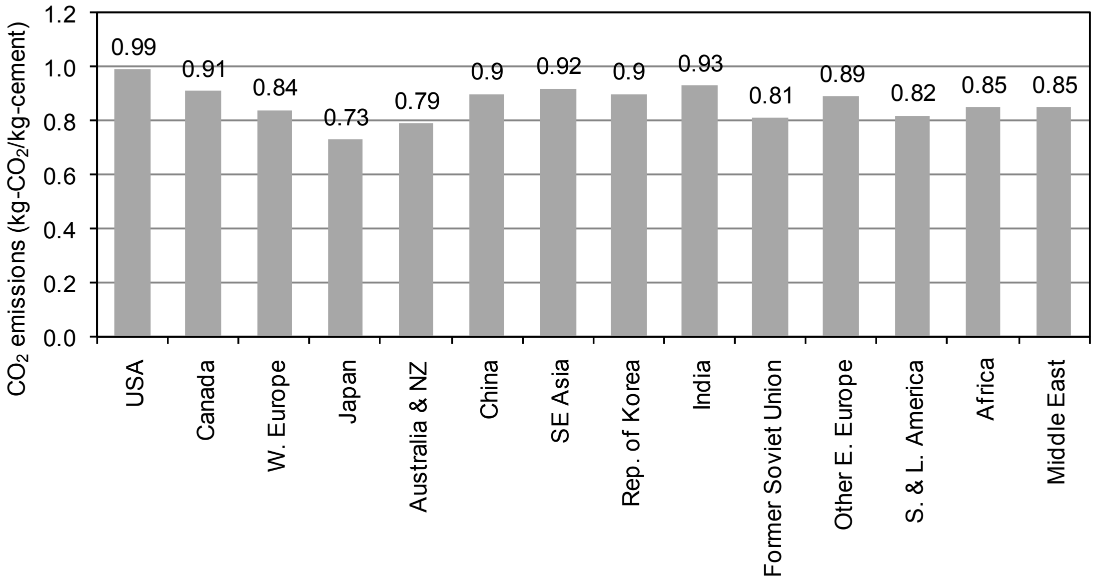

Figure 2.5 Comparison of CO_2 emissions in cement production (data source Humphreys & Mahasenan, 2002)

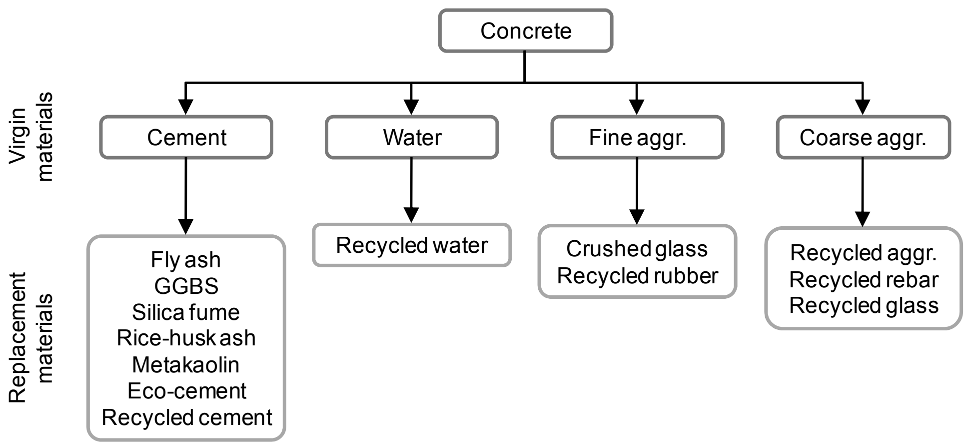

Figure 2.6 Selected replacement materials

The demand for concrete is particularly high in developing countries such as China and India. These same countries also produce large amounts of fly ash and blast furnace slag, the majority of which is not being utilized in concrete construction (Mehta, 1998). Utilizing these materials instead of cement could meet increasing demand without increasing production capacity, thus demonstrating the importance of utilizing by-products in future development. Other supplementary cementing materials include silica fume, metakaolin, and rice-husk ash. The availability and application of all these materials depends highly on regional characteristics, but their use is generally increasing.

In addition to fly ash and blast furnace slag, by-products from other industries also have potential application in the concrete industry. Some examples include: semimetallic waste from metallurgical processes as aggregate for producing high-density concrete; filter cake from calcium carbide production as filler in concrete mixes; and anhydrite from flocculant production residue as a partial cement replacement material in controlled conditions (Jahren, 2002). Limited practical application of these materials has already been achieved and demonstrates the new opportunities for the concrete industry to practice industrial ecology.

Another source of waste is the demolition of old buildings and infrastructure. This waste concrete can be processed and reused as a replacement for aggregates in new construction, which reduces the need for virgin materials as well as the volume of material disposed of in waste sites and landfills. Recycled aggregates, however, typically have greater porosity and water absorption characteristics due to the cement mortar attached to the surface of the original coarse aggregate, which results in lower durability and strength. Furthermore, low-quality recycled aggregate may contain large amounts of non-cementitious demolition waste, such as nails, glass, wood, and so forth, as shown in Figure 2.7. The production process of the recycled aggregate plays an important role in assuring the quality of concrete constructed using these aggregates. Unfortunately, increased processing time for producing better quality recycled aggregates requires large amounts of energy and CO_2.

Figure 2.7 Demolition waste mixed with low-grade recycled aggregates

Some research works have investigated the application of recycled glass as a raw material for concrete. In particular, lightweight aggregate made from foamed glass has potential for future applications (Jahren, 2002). This type of aggregate has an uneven surface which increases bonding capability but requires cement paste with a high filler content to meet workability requirements. However, glass may be considered reactive in some forms when used in concrete, so careful mix design is necessary if this material is to be used. Waste material from other industries can be used as a replacement for the fuel necessary to produce Portland cement. Eco-cement, while not a waste product itself, is made by using reactive kiln materials to reduce the energy consumption of the production process, which reduces the CO_2 emissions related to energy production.

In order to reduce the amount of water consumption, mixing water can be reduced by improved aggregate grading or the utilization of admixtures for retaining workability at lower water content. Also, the concrete industry could utilize recycled industrial water or non-potable (brackish) water in concrete mixing or for washing or curing.

2.3.2 Concrete durability

Material conservation can also be achieved by extending the service life of infrastructure. For concrete, durability is typically associated with cracking, which allows the ingress of corrosive agents and leads to deterioration of structural performance and appearance. Unfortunately, modern concretes tend to crack at an early age due to the increased use of high-early-strength cements, which are prone to cracking, and research has found that the emphasis on fast construction schedules and achieving load-carrying capacity as soon as possible is responsible for the large volume of low-durability structures constructed in the 1980s and 1990s (Mehta, 2002). Poor workmanship in concrete construction, such as insufficient vibration, low-quality formwork, incorrect placement of steel reinforcing, premature removal of formwork, and so forth also result in poor structural durability. A lack of communication between the structural designer and the contractor, resulting in difficult-to-construct structural forms or congested steel reinforcement, is another factor.

Cracks are primarily caused by thermal contraction and drying shrinkage in the early stages of construction or through fatigue loading. These cracks, by themselves, do not reduce the durability of the structure unless they form an inter-connected pathway which allows for water or corrosive agent transport. These cracks may propagate under loading or from exposure to weather until the water tightness of the structure is lost. Deterioration then occurs as a cyclic process whereby deterioration processes cause further cracking, which then allows for water intrusion and thus more deterioration.

The deterioration of concrete can be broken down into four primary causes: corrosion of steel reinforcement, frost action, alkali-silica reaction, and sulfate interactions in cement paste. These causes have several common factors, such as the need for water saturation, presence of microcracks, and occurrence of defects in the cement paste microstructure. In order to adopt a new approach for durability design and improvement, Mehta (2009) proposed several key points. First, reducing the amount of cement paste and eliminating inhomogeneities in the cement paste can have a large influence on the reduction of microcracks. Second, reducing the water-cement ratio (a typical means for improving durability under the current-popular reductionist approach to durability design) alone is not sufficient – the actual cement paste content should also be reduced along with the water content. Finally, sources of defects in the microstructure should be reduced by transforming the weaker phases into stronger phases through the application of pozzolanic materials, producing a more homogeneous cement paste.

For new construction, under certain conditions utilizing slag or fly ash may help reduce cracking, thus improving crack resistance and durability. Other solutions include admixtures for preventing corrosion, epoxy-coated bars, surface coatings, and cathodic protection. Some materials, such as self-compacting concrete, were designed to provide durability in response to human factors such as poor workmanship.

For existing structures, unless high durability is specified and assured at the construction phase, proper maintenance management consisting of inspection and repair is necessary to assure the structure's performance over time and prevent deterioration. The goal of maintenance is to keep the structural performance above the limit of performance, below which the safety of the structure cannot be assured. If the structure is constructed with high durability, then the structural performance will only gradually decrease over time, as shown in Figure 2.8 (left), so the cost for maintenance will decrease. Specifying high durability at the early age, however, usually results in a higher initial cost. If the structure does not have high durability, then it becomes necessary to conduct repair works to restore performance to acceptable levels. Conducting minor maintenance before reaching the maintenance or performance limit will increase the number of times maintenance works must be conducted (Figure 2.8, middle), but may reduce total life cycle costs as the extent of work done for minor maintenance is significantly less than that required for major corrective maintenance. If the performance of the structure is allowed to deteriorate past the maintenance limit to the performance limit (Figure 2.8, right), then large-scale, corrective maintenance works must be conducted. Since the cost of these works can be prohibitively expensive, this may increase the life cycle cost immensely.

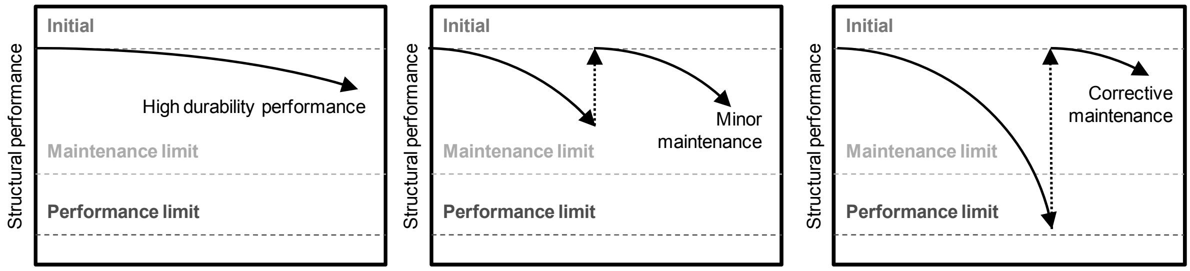

Figure 2.8 Maintenance strategies for deteriorating structures
(adapted from Yokota et al., 2008)

In developed countries, such as the USA and Japan, where most of the necessary infrastructure is already in place, maintenance management of that infrastructure will be necessary in the future in order to extend service life. If the service life can be extended, this can reduce material consumption and waste generation by avoiding the demolition of the existing structure and the construction of a new structure. However, as structures age and the loading requirements increase (due to increasing traffic from a growing population, for example), there may be a point where it is more economically and environmentally feasible to construct a new structure rather than extend the service life of the existing structure.

2.3.3 Holistic approach

In his paper on sustainable technology, Mehta proposed that the concrete industry's reductionist approach is responsible for many unsustainable practices (Mehta, 1999). A holistic approach is necessary to shift the concrete industry toward sustainable practice.

A holistic approach values the whole as greater than the sum of its individual parts. For the concrete industry, this approach would suggest that society is the greater whole, with the concrete industry as just one part. One way to implement a holistic approach would be to place more emphasis on durable, crack-free construction rather than faster construction speed (Mehta, 2002). Such an approach would place responsibility on the concrete industry to provide not only a cheap construction material, but also carry other societal needs. Considering other societal needs could open up new markets for the concrete industry. Jahren (2002) suggests that the concrete industry should look at the production of artificial reefs and sea life breeding-ground restoration as two areas where the concrete industry could create a product which would contribute to the well-being of society by helping to meet the growing demand for seafood necessary to feed a growing world population.

Following Mehta's model, another example of a holistic approach in concrete materials can be shown by using a ternary representation of concrete durability (Collepardi, 2008). This representation, shown in Figure 2.9, demonstrates the interaction between the different factors which cause damage and deterioration of concrete structures. Damage only occurs if all three elements – interconnected pores, water, and aggressive agents – are present. In situations where only one or two elements are present, there is no risk of damage to the concrete structure. The concrete industry's reductionist approach has resulted in policies which assume that damage will occur, regardless of whether all three of the elements are present or not. As an example, in the case of alkali-silica reaction, this has led to the rejection of materials such as high-alkali cement or reactive aggregates, thus requiring the use of other virgin materials, even though the usage of these cements or aggregates would not be damaging to the structure if a proper holistic approach to durability and structural design were taken (Mehta, 1999). According to Collepardi (2008), such a holistic approach to durability design can be taken with other deterioration mechanisms, such as sulfate attack or corrosion of reinforcing steel.

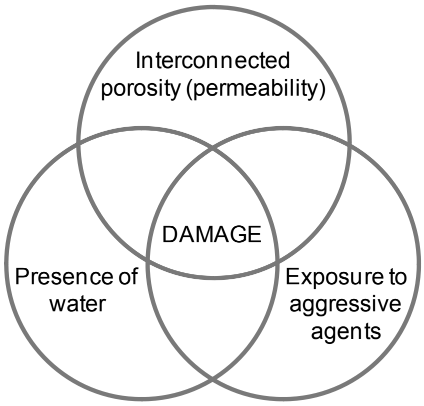

Figure 2.9 Ternary representation of damage in reinforced concrete (adapted from Collepari, 2008)

The difficulty in shifting from reductionist to holistic practice lies with problems in how engineering and science are taught at the university level (Mehta, 1999). There is a lack of courses on concrete technology and few students pursue graduate-level study of concrete material. In addition, the problems faced in the real world often cannot be solved by application of scientific or engineering knowledge alone, but require an integration of knowledge from many fields such as the social sciences or humanities. A holistic approach is necessary to bring together these different areas of knowledge and apply concrete material technology for sustainable practice.

2.4 EXAMPLES OF SUSTAINABLE CONCRETES

Early papers on the topic of sustainability in the concrete industry often mentioned high-volume fly ash concrete as one of the best options for the concrete industry to institute sustainable materials (Malhotra, 1999; Mehta, 2002). As discussed in Section 2.3.1 on resource conservation, fly ash is a by-product from the coal industry, and can be used as a supplementary or replacement cementitious material. While the replacement of fly ash is often limited by prescriptive codes, high-volume fly ash concrete has been developed which replaces up to 60% of Portland cement (Sivasundaram et al., 1989; Malhotra, 1994). This technology not only provides superior strength and durability performance, but also greatly reduces the amount of cement necessary in construction, resulting in concrete mixtures with significantly lower environmental impact and reducing the amount of waste disposed in landfills.

Enhancing the durability of concrete structures is another strategy for improving sustainable practice in the concrete industry, so materials which improve durability may also be thought of as sustainable materials. One example of high-durability concrete is self-compacting concrete, a material with high flowability in the fresh state which allows the concrete to fill the formwork around the steel reinforcement without requiring the use of vibrators (Figure 2.10). This material was developed in response to observed durability problems caused by poor workmanship and lack of communication between the structural designers and the contractors. Two solutions were proposed to solve these problems: the first was to establish a comprehensive design method for durability, and the second was to develop a material which could provide structural durability even under poor conditions (Okamura, 1986). Self-compacting concrete was developed in response to the second solution, and was designed to have high durability in each material state (fresh, early age, and hardened) (Ozawa, 1990).

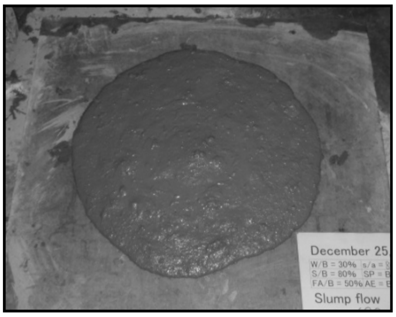

Figure 2.10 Concrete with self-compacting behavior (high flowability)

Another approach to durable performance is self-healing concrete, a special type of concrete which has the capability to autogeneously repair cracks under water supply conditions (Ahn, 2008). The development of this material derives from the concept of "maintenance-free" construction, which reduces both direct and indirect costs associated with maintenance works. Maintenance-free construction is part of a shifting trend in construction philosophy, whereby the contractor is responsible not only for the design-construction aspects, but maintenance as well. Self-healing concrete ensures water-tightness by closing cracks of a certain width in the presence of water (Figure 2.11), thus preventing further intrusion into the concrete and enhancing durability. The application of this material is currently limited to structures which are under constant water supply, such as tunnels or other underground structures.

Pervious (or porous) concrete is a special type of concrete which is composed mostly of aggregates and cement paste. The lack of fine aggregate results in concrete with high permeability and allows water to easily pass through. This greatly reduces the amount of water runoff associated with concrete pavements, and is recommended as an effective means for managing stormwater runoff. More efficient land use can also be realized by eliminating other stormwater management devices which are needed in conjunction with normal concrete pavements.

Although concrete materials which reduce environmental impact are often referred to as "green concrete," no material better embodies the meaning of green concrete than concrete materials which serve as foundations for the growth of plants. Green concrete was developed as a means for introducing nature in urban spaces, such as on buildings, in parks or as part of infrastructure

(Yanagibashi & Yonezawa, 1998). This material, which consists of no-fines concrete, a water retentive material, and a light layer of soil on the surface, not only serves as a structure, such as slope retention, but also encourages plant growth within the structure itself, improving the structure's aesthetic image and allowing for a wider variety of landscaping options. The development of materials such as green concrete not only represents a holistic approach to material development by considering needs beyond the concrete industry, but also serves to open new markets and lead to new technological challenges.

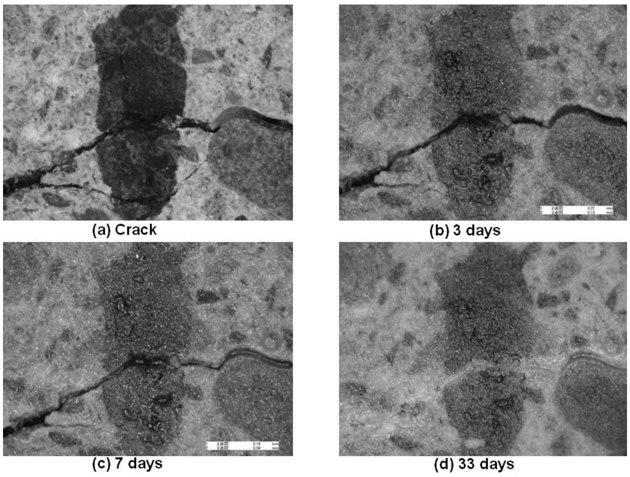

Figure 2.11 Crack self-healing under water supply (Ahn & Kishi, 2008)

2.5 CONCLUSION

The concrete industry is a fundamental part of the construction industry, as concrete is the world's most-utilized construction material and second-most utilized resource after water. Although concrete contributes positively to the improvement of society through the construction of civil infrastructure, it also carries with it a significant environmental impact in the form of GHG emissions, resource and energy consumption, and waste generation. Strategies for adopting sustainable practice in the concrete industry generally focus on reducing these three impacts by utilizing waste and recycled products, which reduces consumption of raw materials and recycles waste back into the product life cycle, and by enhancing the durability of concrete structures. The concrete industry's reductionist approach to practice and education has, however, had a negative effect which needs to be overcome by adopting a holistic approach. In such an approach, the concrete industry would consider itself as a part of the greater society, and serve not only to provide a cheap construction material but also take responsibility for other social needs, such as the disposal of waste materials. A holistic approach would also help durability design by considering the actual exposure conditions of a structure. Concrete material itself is an important part of the paradigm shift to sustainable practice, and there are currently several material technologies available or under development which can help the industry reduce its environmental impact.

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Chapter 3
Environmental impact and sustainability evaluation methods

3.1 INTRODUCTION

Means of evaluating sustainability are necessary in order to determine whether practices are more or less sustainable and to evaluate the state of a system. By evaluating the state of a system, decisions can be made on how to improve the sustainability of that system or to get feedback on the effectiveness of a practice. This is popularly achieved by using sustainability indicators, such as those provided by the United Nations, but there are problems with simplifying the behavior of a complex system into discrete variables. The construction industry has also developed means for evaluating sustainable practice, most notably in the form of green building rating and evaluation systems. These systems, however, typically do not have explicit consideration or evaluation of the concrete materials themselves, although there are a few standards being developed specifically to address the issues of the concrete industry. This chapter will introduce the general concept behind sustainability and environmental impact evaluation, followed by general sustainability evaluation systems and construction industry-specific approaches. Finally, standards developed for the concrete industry will be introduced, followed by the proposal of an evaluation system for concrete materials which utilizes analytic hierarchy process as a means for balancing different performance characteristics of concrete and for integrating variable socio-economic conditions into the evaluation process.

3.2 EVALUATING SUSTAINABILITY

3.2.1 Sustainability indicators

Sustainability indicators (SI) are typically used to evaluate different aspects of a system, with the total trend of all the indicators providing some idea of how sustainable the system is. As shown in Figure 3.1, this requires breaking a system down into representative indicators, then evaluating the state of those indicators and interpreting the results of the evaluation for future action. However, the key points are how many indicators to use and which indicators are necessary for properly representing the system. This simplification is critical and will be discussed later.

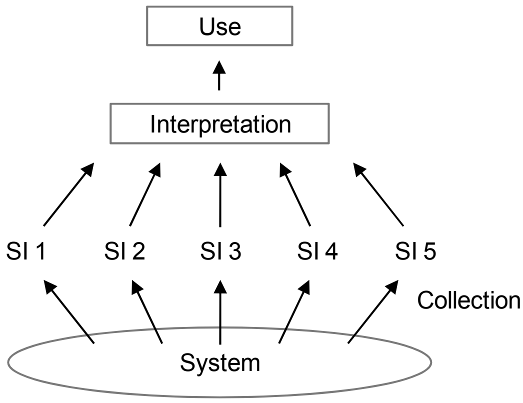

Figure 3.1 Concept of sustainability indicators (Bell & Morse, 2008)

SIs can be divided into two types: state SIs and pressure SIs (Bell & Morse, 2008). The UN also includes a third type, the response indicator. State SIs are used to describe the state of a variable, such as contaminant level. Pressure SIs, which may also be called control, process, or driving force SIs, evaluate the processes which affect state SIs, such as how traffic density affects ambient air pollution. The UN's response indicator was developed to measure the progress governments were making towards sustainable development.

SIs are typically established by a top-down approach, where experts decide on a set of SIs based upon research, theory, and so forth. However, a bottom-up approach may be more appropriate, as the stakeholders may be the best-placed to define sustainability and determine the SIs (Bell & Morse, 2008). In addition, how to interpret the SI is also important – whether the indicator is absolute (sustainable versus not sustainable) or discrete (various levels or grades). Taken over time, a trend in an SI's behavior may emerge, so relative change may become more important than the absolute values.

The primary criticism of SIs is that they attempt to represent an immensely complex system with quantitative values. These values are selected through a simplification process which is reductionist in nature, contrary to the holistic approach typically advocated for sustainability-related issues. Since difficulties necessarily arise in the simplification process, transparency in how values were arrived at, and what assumptions were made, becomes increasingly important. In the end, however, sustainability is a human vision with human values (Bell & Morse, 2008). Beginning with an established definition of sustainability, the SIs relevant for reaching that goal should be identified, but the SIs themselves do not need to be tested for whether they describe sustainability – this would create complications if the SIs were changing while progress was being evaluated.

3.2.2 United Nations sustainability indicators

The UN first established a list of indicators for sustainable development (ISD, which is the same as SI), from the Agenda 21 document at the 1992 Rio Earth Summit. At that time, the UN's framework was based around the concept of driving force-state-response (DSR), whereby a force drives or determines the state of some variable, which then requires action or a response to deal with that change (Bell & Morse, 2008). The original UN indicators were grouped into categories based on the structure of the Agenda 21 document, such as social, economic, environmental (water, land, atmosphere, and waste), and institutional aspects of sustainable development.

The most current approach to SIs by the UN, however, is based around a theme/sub-theme approach, rather than the DSR model. The themes are divided into four different areas: social, environmental, economic, and institutional, and the themes and sub-themes are given in Table 3.1. Each of the sub-themes has indicators related to it, such as "percent of population living below poverty line," "Gini index of income equality," and "unemployment rate" for poverty; "floor area per person" for living conditions; "emissions of greenhouse gases" for climate change; "abundance of selected key species" for species; "GDP per capita" and "investment share in GDP" for economic performance; "implementation of ratified global agreements" for international cooperation; and "expenditure on research and development as a percent of GDP" for science and technology.

Table 3.1 UN sustainable themes and sub-theme framework (United Nations, 2001)

Theme	Sub-themes
SOCIAL	
Equity	Poverty; gender equality
Health	Nutritional status; mortality; sanitation; drinking water; healthcare delivery
Education	Education level; literacy
Housing	Living conditions
Security	Crime
Population	Population change
ENVIRONMENTAL	
Atmosphere	Climate change; ozone layer depletion; air quality
Land	Agriculture; forests; desertification; urbanization
Oceans, seas, and coasts	Coastal zone; fisheries
Fresh water	Water quantity; water quality
Biodiversity	Ecosystem; species
ECONOMIC	
Economic structure	Economic performance; trade; financial status
Consumption and production patterns	Material consumption; energy use; waste generation and management; transportation
INSTITUTIONAL	
Institutional framework	Strategic implementation of SD; international cooperation
Institutional capacity	Information access; communication infrastructure; science and technology; disaster preparedness and response

3.2.3 Visualization of sustainability indicators

Another problem with using SIs to describe a complex system – besides the loss of detail through simplification – is that the models and theories for modeling these systems are necessarily complex. However, the policy makers who use these indicators for decision making need simple and clear presentation instead of complicated scientific models (Ten Brink, 1991). In order to simply and visually display the results of SI calculations, a visual approach called AMOEBA was proposed by Ten Brink (1991). In this approach, the quantitative data is translated into a visual representation of the change in a system over time, and a reference condition or baseline is also included which may represent the system's level of sustainability – but the baseline selection is difficult because it's not always clear whether the baseline actually represents a sustainable state and the selected condition can greatly affect final conclusions. A simple example of what an AMOEBA looks like is shown in Figure 3.2. With just one AMOEBA, comparisons can be made between different indicators to evaluate which ones are closer or further from the baseline level, but comparing different AMOEBAS – either over time or at different locations – can give an idea of how different conditions change the distribution of SIs relative to the baseline level. Some criticisms of the AMOEBA approach are that it doesn't consider the mechanism leading to the changes observed; that it is still a reductionist approach which combines a large number of SIs into a single representation; equal weight is given to the different SIs, so a diverse number of perspectives are not considered.

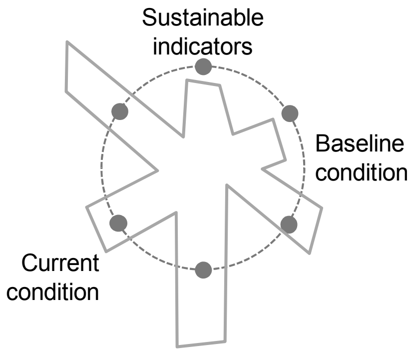

Figure 3.2 Example of AMOEBA

3.2.4 Sustainable evaluation systems in the construction industry

The green building movement has been one of the most visible approaches to evaluation of sustainability and environmental impact in the construction industry. It should be noted that "green building" – which focuses just on reduced environmental impact – and "sustainable building" – which considers all three aspects of sustainability – are different terms which get used interchangeably.

As summarized in Table 3.2, many green building assessment tools exist around the world. In 1990, the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM) was the first such system developed. The United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) system, started in 1998, is perhaps the most well-known system. Both of these systems use a criteria-based system for assigning points based upon the evaluation of a wide variety of parameters. In Japan, the Japan Sustainable Building Council's Comprehensive Assessment System for Built Environment Efficiency (CASBEE) is an example of a system which combines a single efficiency index with life cycle assessment. These systems generally focus on energy and resource efficiency, indoor air environment, water resources management, and sustainable site selection (Baruah et al., 2008).

Although there has been a strong movement in the commercial construction sector for environmental certification, the civil construction sector still lacks assessment systems. However, the International Organization for Standardization (ISO) has developed several standards which are starting to be applied in the civil engineering field. ISO 14040, *Environmental management – life cycle assessment – principles and framework*, and its accompanying series provide a general outline for conducting the assessment of environmental impact over the service life of any type of product, and will be discussed in further detail in the following section. ISO 1568-6, *Buildings and constructed assets – service life planning – Part 6: procedures for considering environmental impacts*, focuses on how to assess future environmental impacts during the design stage and the comparison of design alternatives. It also considers the interaction between service life planning and environmental life cycle assessment.

Table 3.2 Green building assessment systems around the world (Baruah et al., 2008)

Country	Assessment system
United Kingdom	BRE Environmental Assessment Method (BREEAM) Environmental Estimator (ENVEST)
USA	USBGC Leadership in Energy and Environmental Design (LEED) NAHB National Green Building Standard USA-EPA Energy Star for New Homes DOE Building America Building Environment and Economical Sustainability (BEES)
Canada	Green Building Tool (GB Tool) Green Globes CEE & EEC LEED-Canada BREEAM-Canada
Australia	Green Star AGBC National Building Environment Rating Scheme (NABERS)
Germany	German Ministry of Transport, Construction, and Urban Development (DGNB) Sustainable Building Certificate
Netherlands	BREEAM-Netherlands Eco Quantum
Japan	JSBC Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)
Korea	Korea Green Building Label
Singapore	Building and Construction Authority (BCA) Green Mark
Hong Kong	Hong Kong Building Environment Assessment Method (HK-BEAM)
China	China Green Building Standard Green Olympic Building Assessment System (GOBAS)
India	LEED-India The Energy and Resources Institute GRIHA
Brazil	LEED-Brazil AQUA

3.2.5 Life cycle assessment

Life cycle assessment is a technique for evaluating the environmental impact of a product over its life cycle. The method was standardized by ISO in the 14040 series, *Environmental management – life cycle assessment – principles and framework*. Following the ISO methodology, there are four phases to an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006). The goal and scope definition phase establishes the application and reasons for the LCA, identifies the target audience, describes the target system and its characteristics, defines the system boundaries, and reviews the assumptions and limitations involved in the analysis. The inventory analysis phase develops data regarding the system inputs and outputs utilizing collection and calculation methodologies. The life cycle impact assessment phase examines the environmental impact by considering the inventory analysis results in terms of the actual impact on the environment, and consists of several elements, such as selecting impacts, indicators, and models; classifying inventory results; and characterizing the indicator results through calculation to produce categorized results by indicators. The final phase, interpretation, considers the inventory and impact assessment results and provides conclusions within the context of the established boundary conditions and goals set in the goal and scope phase. Reporting and review of the results are also important steps – particularly critical review, which is necessary to ensure transparency and credibility of the results.

The inventory analysis and impact assessment phases are iterative in nature, whereby as results are obtained, analyzed, and their role in the system understood, they can lead to new data or changes in the analysis and assessment phases. LCA can be widely applied, but is intended generally for use in management, performance evaluation, labels and declarations, integration into design, development, or into standards, and for quantifying, monitoring, and reporting of impacts (ISO, 2006). Consideration of the decision-making process is necessary when considering the potential application of LCA.

3.3 EVALUATING CONCRETE SUSTAINABILITY

3.3.1 Current methods and systems

There are very few evaluation standards for directly examining the sustainability of concrete materials, although ISO currently is working on a standard to specifically address life cycle assessment for the concrete industry and the Japan Society of Civil Engineers (JSCE) has a draft standard for evaluating and verifying environmental performance of concrete structures. In many cases, the sustainability evaluation systems used in the construction industry, such as LEED, BREEAM, CASBEE, and so forth, do not specifically consider or evaluate concrete, but the usage of concrete can help improve the final sustainability rating. An example of this will be given below for the LEED rating system.

In the USGBC LEED rating system, usage of concrete materials can earn from 19 to 28 LEED points (NRMCA, 2009). These credits are earned in four credit categories: sustainable sites (brownfield redevelopment; site development, protect or restore habitat/maximize open space; stormwater design, quantity/quality control; heat island, non-roof/roof), energy and atmosphere (minimum energy performance; optimize energy performance), materials and resources (building reuse, maintain 75%/95% of existing walls, floors and roof; construction waste management, divert 50%/75%; recycled content, 10%/20%; regional materials, 10%/20%), and innovation and design process (durability; concrete walls and ceiling with no coating; apply for other credits demonstrating exceptional performance; LEED accredited professional). Some of these credits are earned directly by concrete materials, such as recycled content or regional materials, whereas other credits are obtained indirectly by utilizing concrete materials, such as pervious concrete for stormwater design. The USGBC LEED system does not apply to civil infrastructure.

Although other ISO environmental standards for building have been established, such as ISO 15686-6, *Buildings and construction assets – Service life planning – Part 6: Procedures for considering environmental impacts* and ISO 21930, *Sustainability in building construction – Environmental declaration of building products*, members of the concrete industry felt that a separate standard which addressed the specific needs and practices of the concrete industry needed to be developed (Sakai, 2008). This led to the establishment of SC 8, *Environmental management for concrete and concrete structures*, a subcommittee of ISO/TC71, *Concrete, reinforced concrete, and pre-stressed concrete*. This standard is currently under development, and will consist of several parts, such as the establishment of boundary conditions and inventory data, environmental design, execution and usage, and end-of-life considerations, among others.

JSCE established the "Recommendation of Environmental Performance Verification for Concrete Structures (Draft)" to provide general principles for establishing performance requirements, evaluating environmental impacts, verifying environmental performance, inspecting environmental performance, and recording for the design, construction, usage, maintenance, dismantling, disposal, and reusage phases of a concrete structure (JSCE, 2006). The environmental impacts considered in the specification include greenhouse gases, air contaminants, resources, energy, waste, water and soil contaminants, noise, and vibration. Life cycle assessment and inventory analysis methodologies are equivalent to those presented in the ISO standards (ISO 14040 series).

3.3.2 Environmental performance indicator

Nielsen (2009) proposed a simple means for evaluating the balance between a single mechanical performance and single environmental performance, the environmental performance indicator (EPI). The EPI is a weighted index which evaluates the mechanical-environmental efficiency by normalizing a mechanical performance, such as compressive strength, by an environmental performance, such as CO_2 emissions. This approach will be applied during the second experimental phase in Section 4.3 as well as in Chapters 5 and 6.

3.3.3 Evaluation using analytic hierarchy process

One means for considering the balance between different performance indicators is through the application of the analytic hierarchy process (AHP), a multi-criteria framework for making complex decisions (Henry, 2010). The premise of AHP is to model a decision-making problem as a hierarchy composed of quantifiable elements and their relations and alternatives towards a goal (Saaty, 1999). The weights of the elements towards the goal is determined by comparing elements against each other in pairs using qualitative or quantitative judgment values, which are converted to numerical values that can be used to determine weights for the elements in the hierarchy and allows comparison between different elements. Weights can be similarly applied to the various alternatives for achieving the goal, based upon the weights of the elements in the hierarchy and the characteristics of the alternatives, and a decision can be made by analyzing the weights of the different alternatives. This evaluation methodology will be demonstrated in the third experimental phase in Section 4.4.

This approach can be used not only for finding the best balance between materials of differing performances, but can also be applied to convert qualitative values into quantitative data which can then be used for evaluating concrete sustainability. This is particularly useful considering that, as proposed by Bell & Morse (2008), sustainability is a human vision with human values, and it varies depending on who is applying it and under what conditions it is being applied. The concrete industry is composed of many stakeholders, each of which have their own perspectives and goals, and thus AHP can be flexibly applied to consider these different perspectives when attempting to select a material which best meets a specific group's definition of sustainability (Henry, 2010). For example, if the government establishes a goal of reducing CO_2 emissions by 20%, then the reduction of CO_2 emissions could be given higher weight in the material assessment process than other factors, such that a reduction in CO_2 could outweigh reduced performance in other aspects.

Furthermore, when assessing the sustainability of concrete materials, it is necessary not only to determine the relative sustainability between potential material alternatives but to also identify whether the properties of that material are moving towards overall sustainability. Therefore, it is useful to visually observe the distribution of the concrete material properties relative to a baseline condition, or a reference state, which can provide an indication of overall direction. Setting a baseline condition for the concrete industry is not easy because, unlike ecological systems, there is no historical reference point which can be labeled as a "sustainable" state to return to. Rather, the baseline condition should be set by looking forward and considering the direction the industry should move towards. As it has already been established that the concrete industry needs to become more sustainable and reduce its environmental impact from its current state, sustainable concrete should look to meet or exceed the performance of the general-use concrete in the areas identified for assessing sustainability. Therefore, when conducting the evaluation of concrete material sustainability, setting normal-use concrete as a baseline performance can provide a good indicator of the relative sustainability during the evaluation process. Naturally, this does not address the issue of absolute sustainability, but it does provide a means for moving in a more sustainable direction.

3.4 CONCLUSION

In this chapter, general means for evaluating sustainability and environmental impact were introduced, along with methods for the construction industry and for concrete in particular. Indicators are a valuable means for tracking and evaluating sustainability and representing the state of a system, but the complex details of the system may be lost when breaking it down into representative indicators. In the case of the concrete industry, there are few systems specifically designed to evaluate the sustainability of concrete materials, although green building assessment systems do take into account the beneficial performance of concrete. To directly assess the environmental impact and sustainability of concrete materials, the usage of environmental performance indicator and the application of analytic hierarchy process, respectively, were proposed as useful methods. These methods will be applied in the following experimental investigations on concrete containing various waste and recycled materials.

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Chapter 4
Effect of recycled aggregates and fly ash on concrete properties

4.1 INTRODUCTION

The recycling of construction and demolition waste to conserve natural resources and reduce waste generation is an important part of sustainable practice in the concrete industry. As discussed earlier in Section 2.3.1, usage of aggregate recycled from demolition waste in new concrete has been investigated in many past research works, where it has been shown that as the quality of recycled aggregate decreases the amount of residual mortar increases and thus the properties of the recycled aggregate become more varied (Lo et al., 2008). The interfacial transition zone (ITZ) between the recycled aggregate and new cement mortar is generally weaker than in the case of normal aggregates due to bonding between the new and old mortar layers and the core aggregate, which results in a decrease in concrete properties including workability, strength, and durability (Otsuki et al., 2003; Poon et al., 2004). The past research works have not, however, examined the statistical relationship between varied aggregate quality and reduced performance. On the other hand, the addition of fly ash to recycled aggregate concrete has been found to improve concrete properties, particularly durability, due to improvement of the pore structure and bonding (Corinaldesi et al., 2001; Reiner et al., 2010). As fly ash is a by-product of the coal industry, this provides an opportunity to practice industrial ecology by utilizing the waste of other industries as raw material in the concrete production process and helps limit CO_2 emissions by reducing cement content. Unfortunately, there is a lack of research on the quantitative effect of these waste and recycled materials on the environmental impact as well as the balance between the mechanical and environmental performance.

The results introduced in this chapter are the summary of three experimental phases designed to investigate the problems with recycled aggregate and fly ash concrete mentioned above. The first phase focused on lower-grade recycled aggregates considering various quality levels, whereas the second and third phases attempted to combine environmental impact with mechanical evaluation to explore the best balance of mix proportions, binder content, aggregate content, and other factors towards improving the sustainability of concrete at the material level. This was performed both experimentally and by utilizing some of the environmental impact and sustainability evaluation methods introduced in Chapter 3.

4.2 EFFECT OF RECYCLED AGGREGATE QUALITY

4.2.1 Overview

Although past research works have shown that the usage of recycled aggregates reduces performance, the effect of recycled aggregate quality and variation – particularly at lower quality levels – on the variation in concrete properties has not been clarified. This experimental phase therefore focused on investigating this effect in the case of compressive strength, looking at how lower quality recycled aggregates and combinations of normal and recycled aggregates affected the statistical distribution of compressive strength. Next, this study examined the relationship between aggregate properties and proposed an index factor which combines both mix proportions and aggregate properties for estimating the strength of recycled aggregate concrete.

4.2.2 Experimental program

4.2.2.1 Materials

Four different types of coarse aggregates – one normal and three recycled – were used in this experimental phase (Figure 4.1). Saturated surface dry (SSD) density and absorption were measured following JIS A 1109 ten times for each aggregate type and the averages and coefficients of variation are given in Table 4.1. The relationship between density and absorption for all data points is shown in Figure 4.2. The density of the recycled aggregates is lower and the absorption higher than the normal aggregates and it can be seen that the variation in density is also larger. The recycled aggregates were also classified according to JIS A 5002, with R1 meeting "low" grade requirements, whereas types R2 and R3 were ranked as "below low" grade due to their absorption properties exceeding the 7% maximum. In addition to coarse aggregates, concrete was prepared using tap water (W), type-I portland cement (C), river sand (S), and air-entraining and super plasticizer admixtures.

4.2.2.2 Mix proportions and fresh properties

Concrete mix proportions and fresh properties are given in Table 4.2. Three different water-cement ratios (W/C=30, 50, 70) were examined, along with the four different coarse aggregate types. Two combinations of coarse aggregates (N1-R1, R1-R3), split evenly by volume, were also investigated.

Figure 4.1 Four types of recycled aggregates (from left): normal, R1, R2, and R3

Table 4.1 Properties of coarse aggregates

Type	Density (g/cm^3) [coeff. var.]	Absorption (%) [coeff. var.]	Grade
Normal (N)	2.71 [0.14]	0.78 [9.76]	-
Recycled 1 (R1)	2.45 [0.53]	5.66 [6.32]	Low
Recycled 2 (R2)	2.38 [0.59]	7.53 [3.32]	< Low
Recycled 3 (R3)	2.36 [0.49]	7.91 [4.02]	< Low

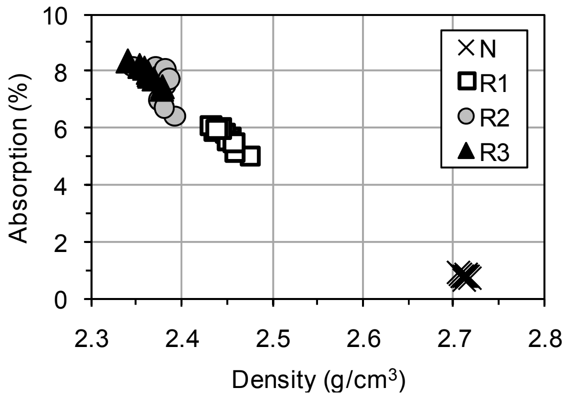


Figure 4.2 Relationship between density and absorption

Table 4.2 Concrete mix proportions and fresh properties

<table>
<tr><th rowspan="2">Series</th><th colspan="7">Mix proportions (kg/m³)</th><th rowspan="2">Slump (mm)</th><th rowspan="2">Air content (%)</th></tr>
<tr><th>W</th><th>C</th><th>S</th><th>N</th><th>R1</th><th>R2</th><th>R3</th></tr>
<tr><td>30-N</td><td>177</td><td>589</td><td>596</td><td>989</td><td>-</td><td rowspan="4">-</td><td rowspan="5">-</td><td>14.0</td><td>5.8</td></tr>
<tr><td>30-R1</td><td>171</td><td>569</td><td>609</td><td>-</td><td>914</td><td>14.0</td><td>6.9</td></tr>
<tr><td>50-N</td><td>177</td><td>353</td><td>742</td><td>1042</td><td>-</td><td>13.0</td><td>5.5</td></tr>
<tr><td>50-R1</td><td>177</td><td>354</td><td>785</td><td rowspan="3">-</td><td>897</td><td>13.5</td><td>6.5</td></tr>
<tr><td>50-R2</td><td>166</td><td>332</td><td>771</td><td rowspan="2">-</td><td>932</td><td>9.5</td><td>5.9</td></tr>
<tr><td>50-R3</td><td>176</td><td>352</td><td>787</td><td rowspan="5">-</td><td>866</td><td>14.5</td><td>5.3</td></tr>
<tr><td>50-N-R1</td><td>175</td><td>350</td><td>789</td><td>503</td><td>453</td><td>-</td><td>13.0</td><td>6.6</td></tr>
<tr><td>50-R1-R3</td><td>177</td><td>353</td><td>749</td><td>-</td><td>466</td><td>448</td><td>13.5</td><td>5.8</td></tr>
<tr><td>70-N</td><td>179</td><td>256</td><td>857</td><td>1001</td><td>-</td><td rowspan="2">-</td><td>13.0</td><td>5.5</td></tr>
<tr><td>70-R1</td><td>187</td><td>267</td><td>841</td><td>-</td><td>887</td><td>13.5</td><td>4.8</td></tr>
</table>

4.2.2.3 Specimens and curing

Cylinder specimens (10Ø×20cm) were cast for each concrete mix following JSCE-F 552. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and placed in water curing at 20°C.

4.2.2.4 Testing and results statistics

Compressive strength testing was conducted 28 days after casting according to JIS A 1108. Following the JSCE "Guideline for Experiment on Materials of Civil Works" (6.3.2C), 30 specimens were tested per series in order to statistically identify the mean and standard deviation of the compressive strength results, and the coefficient of variation was calculated as the percentage ratio of the standard deviation to the mean, which represents the normalized dispersion.

4.2.3 Variation of compressive strength results

4.2.3.1 Effect of water-cement ratio

The effects of water-cement ratio on compressive strength and coefficient of variation for normal and type-R1 aggregates are shown in Figure 4.3. The effect of recycled aggregate on compressive strength was found to decrease as water-cement ratio increases; at water-cement ratio of 30, recycled aggregate has only 76.2% of the strength of normal aggregate concrete, but this percentage increases to 77.5% and 83.9% for water-cement ratios of 50 and 70, respectively.

The effect of recycled aggregate on the coefficient of variation of the compressive strength results also varies depending on the water-cement ratio. The coefficient of variation for normal aggregate concrete at water-binder ratio 30 is actually higher than that of the recycled aggregate concrete at the same water-binder ratio. This may be related to the compressive failure behavior of high-strength concrete, rather than the aggregate type. In addition, the coefficient of variation for the normal aggregate concrete at water-cement ratio 30 barely falls below 5%. According to the JSCE "Guideline for Experiment on Materials of Civil Works" (3.10.3B), if the coefficient of variation exceeds 5% then the overdesign factor needs to be increased beyond the base factor of 1.1. It can be seen that the coefficients of variation for the recycled aggregate concretes, although higher than that of the normal aggregate concretes at water-cement ratios 50 and 70, still fall below the 5% threshold. Furthermore, the coefficients of variation for the recycled aggregate concretes remain similar regardless of the water-cement ratio or strength level.

4.2.3.2 Effect of aggregate type

Figure 4.4 shows the compressive strength and coefficient of variation results by varying aggregate type at water-cement ratio of 50. While the normal aggregate concrete has a 28-day compressive strength of 41.9 MPa, the strengths of the recycled aggregate concretes are generally similar and fall between 32.7 MPa (for type-R2) and 28.8 (for type-R3). This result shows that the varying properties of the recycled aggregates do not have a large effect on the compressive strength. The coefficient of variation results are also similar, with the normal aggregate concrete at 2.9% while the coefficients of variation for the recycled aggregates range from 3.9% (for type-R1) to 4.3% (for type-R2). Similar to the results by water-cement ratio, although the variation is higher for the recycled aggregate concretes the values still fall below the 5% limit established by JSCE.

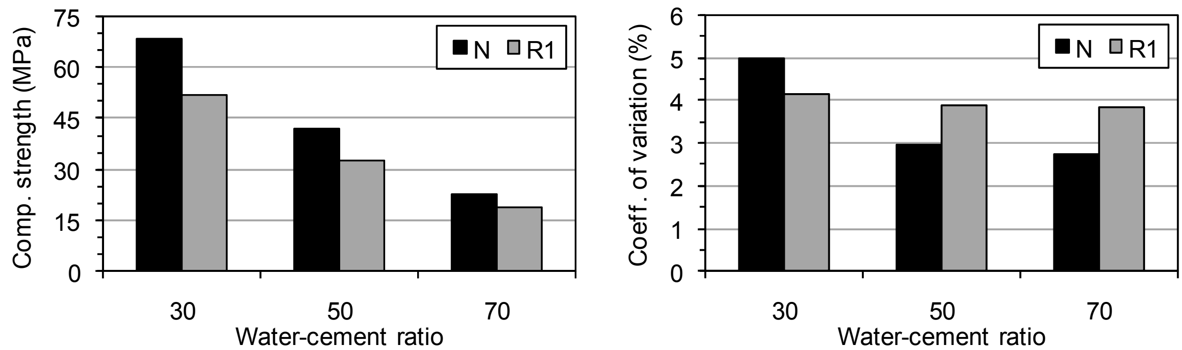


Figure 4.3 Effect of water-cement ratio on compressive strength (left) and coefficient of variation (right)

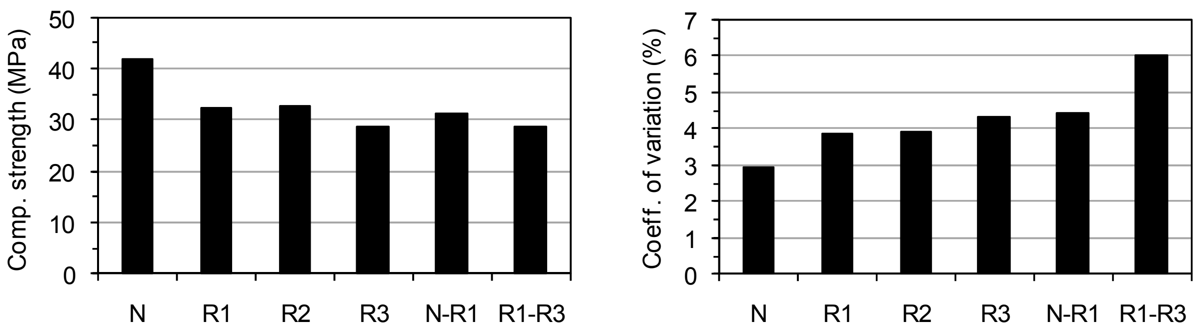


Figure 4.4 Effect of aggregate type on compressive strength (left) and coefficient of variation (right)

4.2.3.3 Effect of combining aggregate types

The effects of combining different aggregate types on compressive strength and coefficient of variation are also shown in Figure 4.4. The combination N-R1 has strength similar to concrete with just type-R1 but is 25.3% less than the strength of the normal aggregate concrete. This appears to indicate that the recycled aggregate quality played a limiting factor, even though it was used in equal volume as the normal aggregate. For the combination R1-R3, the strength is similar to that of the concrete containing just type-R3 but only slightly less than that of concrete containing just type-R1. Again, this seems to suggest that the lowest-grade recycled aggregate has a limiting effect.

In contrast, the combination N-R1 has a slightly higher coefficient of variation than either of the concretes containing only one type of aggregate. The value does, however, fall below 5%. On the other hand, the combination R1-R3 has a much higher coefficient of variation than either of the concretes with only one type of recycled aggregate, and this value exceeds the 5% limit. Therefore, although combining aggregate types may not have a detrimental effect on the compressive strength the coefficient of variation may increase significantly. In the case of the combination of N-R1, the higher quality of the normal aggregates may have served to help reduce the variation from combination, whereas combining two low-quality recycled aggregate types may amplify the variation.

4.2.4 Strength estimation index factor

If the variation of strength when using recycled aggregates falls within acceptable limits, as was shown for all cases except the combination of different recycled aggregate types, then the estimation of recycled aggregate concrete strength may be achieved simply by understanding how much strength reduction occurs as a function of the aggregate quality. Aggregate quality can be quantified by the density and absorption, as shown in Figure 4.2. However, the estimation of concrete strength also needs to take into account the mortar mix properties – specifically, the mix proportioning.

4.2.4.1 Mix proportion-strength relationship

The relationship between mix proportions and compressive strength was examined using the cement-water ratio. Figure 4.5 shows the results for all series, and it can be seen that strength linearly increases with the cement-water ratio. In this case, the strength is represented only by the mix proportion and doesn't take into account the aggregate properties; however, a good linear correlation (R^2=0.8689) between just the cement-water ratio and compressive strength can be seen.

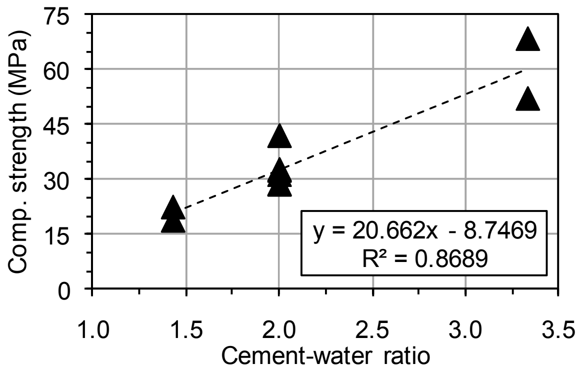


Figure 4.5 Relationship between cement-water ratio and compressive strength

4.2.4.2 Aggregate property-strength relationship

The relationship between aggregate properties and compressive strength are shown in Figure 4.6 for weighted density and weighted absorption. The aggregate properties were weighted by multiplying the properties of the utilized aggregates by their aggregate volume ratio; this is intended to provide representation for concretes with mixed aggregate types. In addition, for this relationship there is no consideration of the effect of the mix proportions so only the results from mixes with the same water-cement ratio of 50 are shown. The relationship between the weighted density and compressive strength can be represented with a direct linear relationship, whereas that of the weighted absorption and compressive strength can be represented with an inverse linear relationship. In both cases, the correlation is lower than that of the cement-water ratio/compressive strength case.

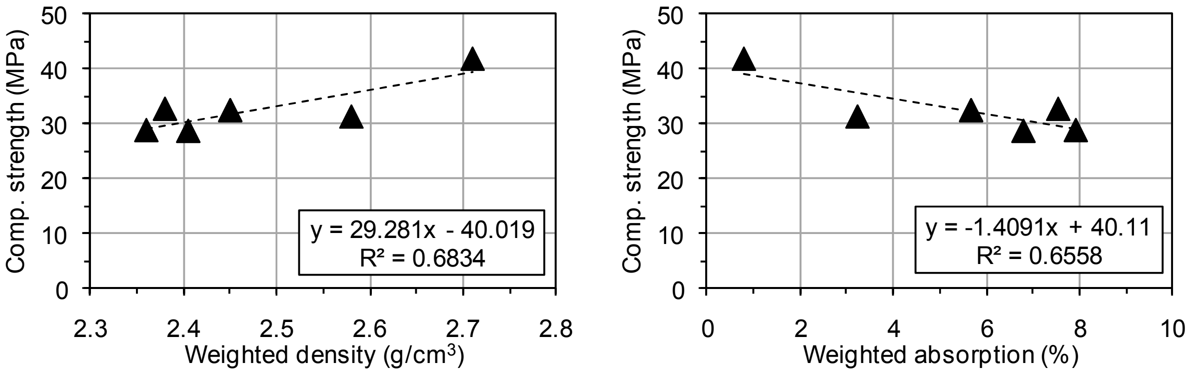


Figure 4.6 Relationship between weighted density (left) or weighted absorption (right) and compressive strength

4.2.4.3 Index factor for strength estimation

The relationships between the aggregate properties and the compressive strength considered the strength only in terms of a single aggregate property; however, as was shown in Figure 4.2, the density and absorption are also related and so strength estimation should take into account both simultaneously. However, focusing only on the aggregate properties neglects the contribution of the cement-water ratio. Therefore, the following index factor was proposed by Pardo (2010) to combine all three variables for estimating the compressive strength of recycled aggregate concrete.

$$IF = \left(\frac{C}{W}\right) \times \left(\frac{D_W}{D_{abs}}\right) \times \left(1 - \frac{A_W}{100}\right)$$

Where IF: index factor, C/W: cement-water ratio, D_w: weighted density (g/cm^3), D_{abs}: absolute density (g/cm^3), A_w: weighted absorption (%). For this calculation, the absolute density is set as that of the aggregate with the highest density (normal aggregate in the case of this investigation).

The relationship between the index factor and compressive strength for all series is shown in Figure 4.7. As the index factor increases the compressive strength also increases linearly with a very high correlation (R2=0.9629). Therefore, it can be clearly seen that the index factor provides the best estimation of recycled aggregate concrete compressive strength by considering both aggregate and mix proportion properties.

4.2.4.4 Index factor for past research results

The applicability of the index factor was examined by applying it to results reported in literature (Dhir et al., 1999; Otsuki et al., 2003; Kou et al., 2008). As summarized in Table 4.3, these cover 18 different cases from three separate investigations. Figure 4.8 shows the relationship between the index factor and compressive strength for the past research results. For each of the three investigations a high correlation can be seen; for Dhir et al. and Kou et al., the R^2 value exceeds 0.98. This result strongly demonstrates the applicability of the proposed index factor to research results obtained at other institutions using other methods and materials.

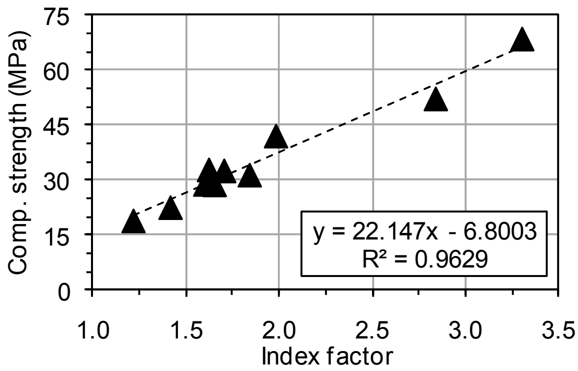


Figure 4.7 Relationship between index factor and compressive strength

Table 4.3 Summary of past research results

Source	W/C	D_w (g/cm^3)	A_w (%)	Comp. strength (MPa)
Dhir et al, 1999	0.29	2.60	2.50	71.5
	0.32	2.41	5.05	62.5
	0.36	2.60	2.50	60.0
	0.40	2.43	5.90	40.1
	0.44	2.41	5.05	52.0
	0.45	2.60	2.50	52.0
Otsuki et al, 2003	0.40	2.44	4.50	44.0
	0.55	2.41	5.13	30.0
	0.55	2.44	4.50	33.0
	0.55	2.47	3.58	32.0
	0.55	2.45	6.46	32.0
	0.55	2.54	2.68	30.0
	0.59	2.36	6.71	39.0
	0.60	2.58	5.50	32.5
Kou et al, 2008	0.40	2.53	3.89	58.5
	0.45	2.53	3.89	52.1
	0.50	2.53	3.89	43.4
	0.55	2.53	3.89	38.1

4.2.5 Summary

The following conclusions were made based on the results of this experimental investigation:

The effect of recycled aggregate on compressive strength variation was fairly similar regardless of water-cement ratio. Although the variation for recycled aggregate concrete was higher than for normal recycled aggregate concrete, it still fell below the JSCE-specified limit of 5% and thus the overdesign factor does not need to be increased. At the same water-cement ratio, varying the type of recycled aggregate did not greatly affect the compressive strength. Furthermore, the variation of the recycled aggregate concrete was higher than for normal aggregate concrete but within the JSCE-specified limit. When combining aggregate types, it was seen that the lowest-grade aggregate limited the strength level but the variation in strength was greater than when either of the aggregate types was utilized alone. When combining two different recycled aggregate types, the variation exceeded the JSCE-specified limit.

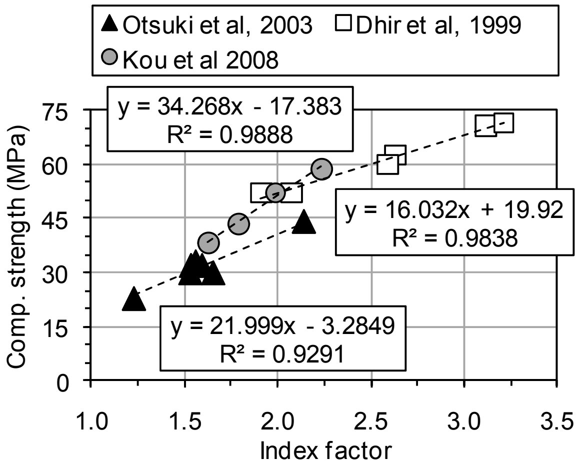


Figure 4.8 Relationship between index factor and compressive strength for past results

Linear relationships between both mix proportion (cement-water ratio) and weighted aggregate (density, absorption) properties and 28-day compressive strength could be seen, with stronger correlation for the cement-water ratio than for density or absorption. An index factor integrating all three of the afore-mentioned properties was then proposed, and a very strong linear correlation between this index factor and the compressive strength of recycled aggregate concrete was shown. This result demonstrates the usefulness of the index factor as a means for estimating strength by considering both mix proportion and aggregate properties. The applicability of the index factor was examined using results from literature. A very strong correlation could be seen between the index factor determined from the experimental cases and the compressive strength, thus verifying the applicability of the proposed index factor to other material and experimental conditions.

4.3 EFFECT OF REDUCED CEMENT CONTENT AND AGGREGATE TYPE

4.3.1 Overview

In the previous phase, focus was only given to the reduction of compressive strength due to varying recycled aggregate quality. Conversely, this experimental phase was conducted to investigate how reducing the volume of cement by either reducing absolute binder volume or by replacing cement with fly ash affected the mechanical behavior and environmental performance. The amount of binder, binder composition, and aggregate type were all treated as experimental variables, and a control series, representative of general-use concrete, was also used a reference. The effect of these variables was investigated by examining strength, air permeability, CO_2 footprint, and volume of raw materials, and the relationship between mechanical and environmental performance was considered using the environmental performance indicator (Nielsen, 2009) as introduced in Section 3.3.2.

4.3.2 Experimental program

4.3.2.1 Materials

Concrete was prepared using water (W), type-I portland cement (C), JIS type-II fly ash (FA), river sand (S), normal coarse aggregates (N), low-grade recycled coarse aggregates (RA), and air entraining and super plasticizer admixtures. The density and fineness were 3.15 g/cm^3 and 3300 cm^2/g for cement and 2.19 g/cm^3 and 4040 cm^2/g for fly ash, and met specifications of JIS A 6201. The specific properties of the utilized fly ash are also shown in Table 4.4. The recycled aggregate was obtained from crushed demolition waste and processed and classified as low grade by the recycled aggregate supplier following JIS A 5023. Wastes mixed with the recycled aggregates such as wood, glass and such were removed prior to mixing. Density and absorption were measured according to JIS A 1110 and are given in Table 4.5 along with the properties for sand and normal aggregates. Based upon the measured results the low-grade recycled aggregates were submerged in water for two days prior to casting and then surface dried using cloth in order to obtain saturated surface dry conditions.

Table 4.4 Properties of utilized JIS type-II fly ash

Property		Unit	Value
SiO_2 content		%	62.6
Moisture content		%	0.11
Loss on ignition		%	2.2
Density		g/cm^3	2.29
Specific surface area (Blaine value)		cm^2/g	4.087
Flow value ratio		%	107
Activity index	28 days	%	86
	91 days	%	98

Table 4.5 Properties of sand and coarse aggregates

Material	SSD density (g/cm^2)	Absorption (%)	Fineness modulus	Maximum size (mm)
Sand	2.62	2.09	2.74	4
Normal aggregate	2.72	0.50	6.67	20
Recycled aggregate	2.43	5.81	6.73	20

4.3.2.2 Mix proportions and fresh properties

Mix proportions are given in Table 4.6. The term binder is used to represent all cementitious materials – in this case, fly ash and portland cement. All mixes used a constant water-binder ratio of 30 and sand-aggregate ratio of 39. The effect of binder volume was obtained by varying the amount of binder from 550 kg/m^3 (normal binder) to 450 kg/m^3 (low binder), and at both binder volumes two binder compositions were used: 100% cement or 50% cement-50% fly ash. Both normal and recycled aggregates were used for all combinations of binder volume and composition to test the effect of aggregate type. Fresh properties are also shown in Table 4.6, where slump and air content were measured according to JIS A 1101 and JIS 1128, respectively.

4.3.2.3 Specimens and curing

Cylinder and beam specimens were cast for each concrete mix following JSCE-F 552. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours (non-fly ash concrete) or 48 hours (fly ash concrete), after which they were removed from the molds and water cured up to 56 days.

Table 4.6 Mix proportions and fresh properties

Series	Mix proportions (kg/m³)						Slump (mm)	Air content (%)
	W	C	FA	S	NA	RA		
Control	171	342	-	746	1015	0	11.0	4.0
NB-NA	165	550	-	624	1009	-	18.5	5.1
NB-RA					-	905	12.0	5.2
LB-NA	135	450		687	1111	-	8.5	3.5
LB-RA					-	996	7.5	4.5
NB-NA-FA50	165	275	275	590	955	-	10.0	3.0
NB-RA-FA50					-	856	16.0	4.5
LB-NA-FA50	135	225	255	659	1067	-	15.0	2.0
LB-RA-FA50					-	957	16.0	4.0

4.3.2.4 Mechanical performance testing

Three mechanical properties of the concrete mixes were tested experimentally. Compressive strength was measured according to JIS A 1108 and tested at 7, 28, and 56 days; flexural strength was measured according to JSCE-G 552 and tested at 28 days only. For all tests, reported values are the average of three specimens.

Durability was evaluated by the air permeability coefficient, which was measured at 28 days as follows. Air permeability specimens were taken from cylinders by cutting a 40 millimeter-thick section from the center of the cylinder. Specimens were then placed in an oven and dried for one week at 40°C. After dry conditions were met, the specimens were set into the air permeability machine and the volume of air flow was measured under steady-state conditions. The air permeability coefficient was calculated as follows and the reported values are the average of three specimens.

$$K = \frac{2P_2 \cdot h \cdot r}{P_1^2 - P_2^2} \cdot \frac{Q}{A}$$

Where K: air permeability coefficient (mm/s), P_1: loading pressure (MPa), P_2: atmospheric pressure (MPa), h: specimen thickness (mm), r: unit volume weight of air (1.205×10^{-6} MPa), Q: volume of air flow (mm^2/s), and A: sectional area (mm^2).

4.3.2.5 Environmental performance assessment

Environmental performance was evaluated using the CO_2 footprint and volume of raw materials. The CO_2 footprint was calculated from the mix proportions given in Table 4.6 and the CO_2 inventory data for concrete-making materials given in Section 2.2. The volume of raw materials was calculated by the percent volume of cement, water, sand, and normal aggregates per cubic meter of concrete. The environmental performance indicator (EPI) was calculated as the ratio of the mechanical performance (56-day compressive strength) to the environmental impact (CO_2 footprint and volume raw materials).

4.3.3 Mechanical performance results

4.3.3.1 Compressive strength

Compressive strength results are shown in Figure 4.9 for 7, 28, and 56 days curing. It can be seen that non-fly ash concrete mixes all achieved higher strength than the control mix, whereas only the fly ash mixes with normal aggregates have exceeded the control mix strength by 56 days. Strength development behavior for normal aggregate concrete without fly ash occurs at a similar rate to the control series, but the recycled aggregate concrete without fly ash does not show any strength gain from 28 to 56 days. This result may indicate that the strength of the mortar matrix reached or exceeded the strength of the recycled aggregates. The fly ash concretes are weaker than the control series at 7 days, but exhibit greater strength gain up to 28 days due to the delayed reaction speed of fly ash. From 28 to 56 days, the normal aggregate fly ash concretes continue to develop strength at a greater rate than the control series, but the recycled aggregate fly ash concretes' strength development is roughly the same as the control series. The weakness of recycled aggregates may be due to the residual mortar, which reduces the bond between the aggregate and the new matrix. Failure both around the aggregate as well as through the aggregate was observed (Figure 4.10).

In all cases, the recycled aggregate series are weaker than their counterpart normal aggregate series, but the difference is more pronounced for non-fly ash than for fly ash concrete because the strength of the non-fly ash mortar matrix is higher. Similarly, all the fly ash series are weaker than their counterpart non-fly ash series, but the difference is greater for normal aggregates. Finally, for normal aggregate non-fly ash concrete, the low binder specimens are stronger than the normal binder specimens; this may be due to the greater amount of aggregate, which increases the strength of the mix. In contrast, for the normal aggregate fly ash concrete, the normal binder specimens are slightly stronger than the low binder specimens. For both binder compositions types, there is almost no difference in strength between normal and low binder for recycled aggregate concrete.

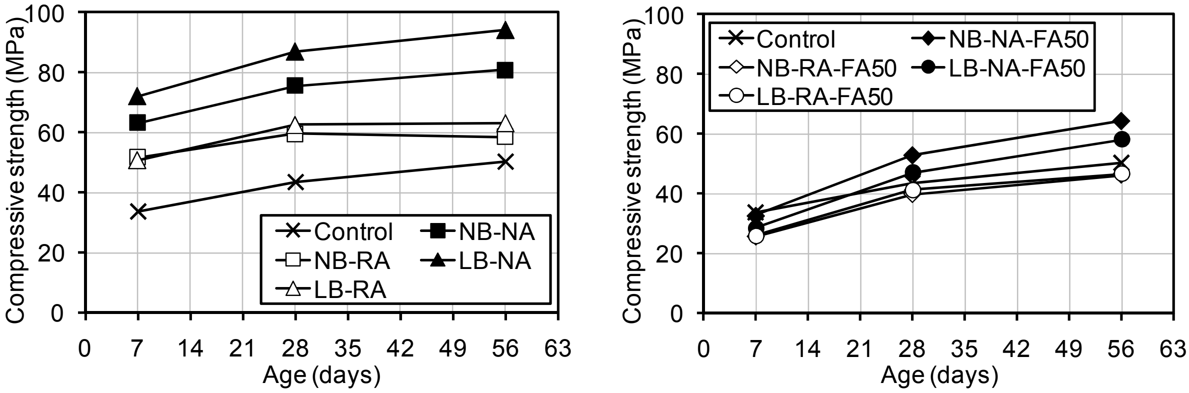


Figure 4.9 Compressive strength development for non-fly ash (left) and fly ash (right) concretes

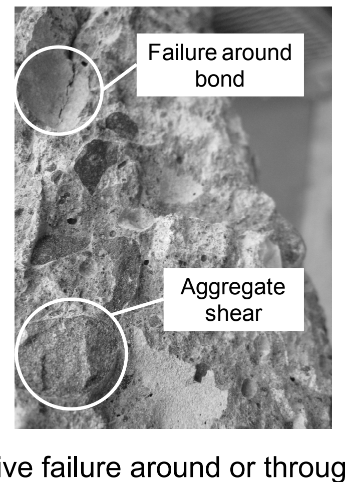


Figure 4.10 Compressive failure around or through recycled aggregates

4.3.3.2 Flexural strength

Flexural strength results at 28 days are shown in Figure 4.11. Non-fly ash concretes show greater flexural strength than the control series, whereas the fly ash concretes show lower flexural strength. For the non-fly ash series, there is a large difference between normal and recycled aggregate specimens, but for the fly ash series normal and recycled aggregate concrete have similar flexural strength levels. This may be due to the weaker of the fly ash mortar matrix, whereas the non-fly ash matrix is strong enough that the aggregate shape has some influence on the failure plane. For both binder compositions, low binder specimens have higher flexural strength than the normal binder specimens, but the difference is larger for non-fly ash concrete than it is for fly ash concrete. In the case of the non-fly ash concrete, the increase in aggregate volume may improve flexural strength due to the influence of aggregate on the failure plane.

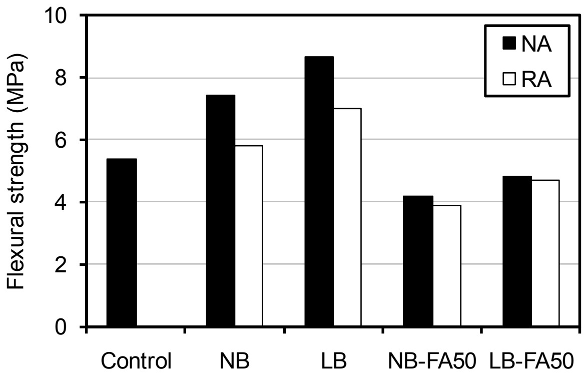


Figure 4.11 Flexural strength results at 28 days

4.3.3.3 Air permeability

The air permeability results at 28 days are shown in Figure 4.12. Unlike the compressive and flexural strength results, the air permeability of all the test series fell below the control series. The only clear difference which could be seen was between the normal and recycled aggregate series, as normal aggregate concrete consistently had much lower air permeability than recycled aggregate concrete. This result is due to the lower quality of recycled aggregates, which reduces the concrete durability. The normal aggregate series all showed roughly the same values, except for the low binder fly ash series, which was slightly higher. For recycled aggregate concrete, again the series all showed roughly the same values, but in this case the normal binder non-fly ash series was slightly higher.

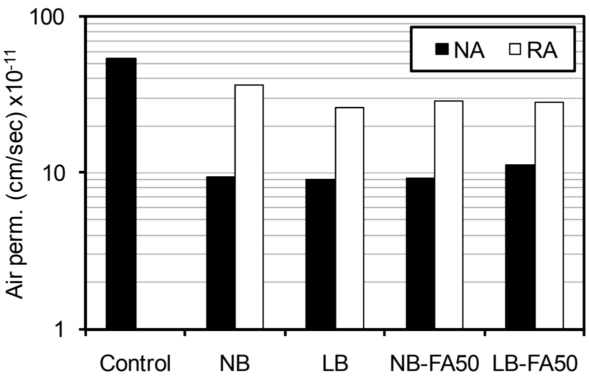


Figure 4.12 Air permeability results at 28 days

4.3.4 Environmental performance results

4.3.4.1 CO_2 footprint

The CO_2 footprints are shown in Figure 4.13. Since normal and low-grade recycled aggregates have roughly the same CO_2 emissions, there is little difference between the normal and recycled aggregate series. Reducing the binder content also reduces the CO_2 footprint, although the effect is larger for non-fly ash concretes than for fly ash concretes. The non-fly ash series all have much higher footprints than the control series, and the fly ash series are all lower. Replacing cement with fly ash produces the largest reduction in CO_2 footprint for both normal and low binder series because fly ash emissions are a fraction of the cement emissions.

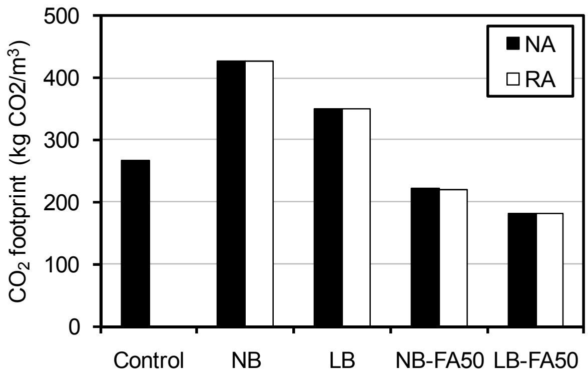


Figure 4.13 CO_2 footprint

4.3.4.2 Volume raw materials

The volumes of raw material are shown in Figure 4.14. It can be seen that the largest contribution to reducing raw material comes from recycled aggregates. Reducing the binder content slightly reduces the volume of raw materials for recycled aggregate series, but slightly increases it for normal aggregate fly ash concrete. The replacement of cement with fly ash also produces a reduction in raw volume for both normal and low binder series.

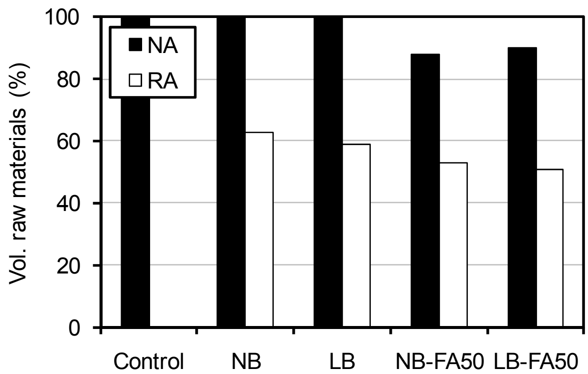


Figure 4.14 Volume raw materials

4.3.4.3 Comparison of CO_2 vs. raw materials volume

The CO_2 footprint and volume of raw materials results are plotted together in Figure 4.15. Reduced environmental impact is achieved by lower CO_2 footprint and lower volume of raw materials, so results trending leftwards and downwards indicate higher sustainable value. The results are clustered in four groups according to aggregate type and binder composition. The least sustainable mixes are the normal aggregate non-fly ash concrete mixes. Switching from normal to recycled aggregates reduces the volume of raw materials but doesn't reduce CO_2, whereas replacing cement with fly ash reduces CO_2 but doesn't greatly reduce raw volume. The most sustainable mixes are those with recycled aggregates and fly ash. The control mix falls between the normal aggregate non-fly ash group and the normal aggregate fly ash group.

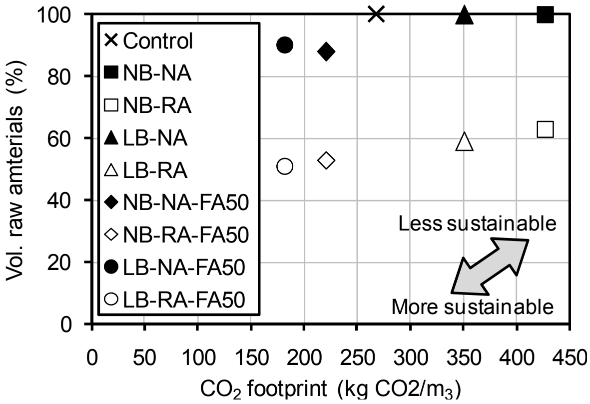
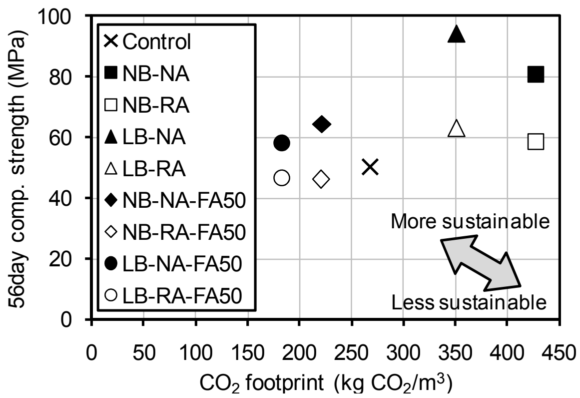


Figure 4.15 Comparison of CO_2 vs raw volume

4.3.5 Mechanical vs. environmental

4.3.5.1 Compressive strength vs. CO_2 footprint

Figure 4.16 shows the 56-day compressive strength results plotted against the CO_2 footprint and the calculated compressive strength-CO_2 EPI values. It can be seen that the general trend for strength vs. CO_2 is for increasing strength with increasing CO_2 footprint. The slope is greater for normal aggregates than for recycled aggregates, and the control series follows the trend of the recycled aggregate series. For non-fly ash concrete, it can be concluded that low binder mixes are superior to normal binder mixes, as they have higher strength and lower CO_2; this is supported by the EPI for low binder non-fly ash series, which is much higher than that of the equivalent normal binder series. For fly ash concrete, the difference is not as clear when looking at the difference in strength against CO_2 – low binder normal aggregate has lower CO_2 but lower strength when compared to normal binder normal aggregate. However, the highest EPI is for low binder normal aggregate with fly ash, indicating that CO_2 decreases faster than strength.



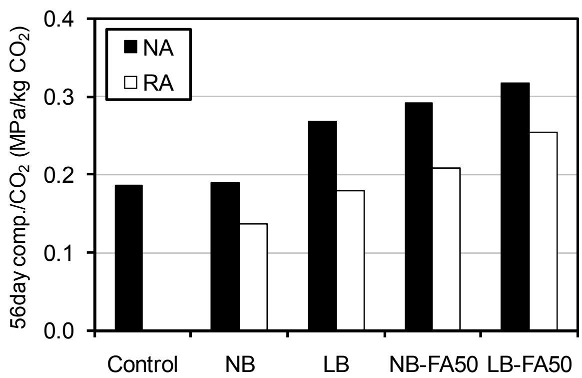


Figure 4.16 Compressive strength vs. CO_2 footprint (left) and EPI for compressive strength and CO_2 (right)

Two primary trends can be seen for the compressive strength-CO_2 EPI results: normal aggregates are higher than recycled aggregates and the EPI increases with decreasing cement content. Although the recycled aggregate non-fly ash mixes have a lower EPI than the control series, all other series are higher. This is due to the reduction in strength without an accompanying reduction in CO_2 when changing from normal to recycled aggregates, as seen in the top right of the EPI results. In general, it appears that reducing CO_2 has a greater effect on the EPI than increasing strength does.

4.3.5.2 Compressive strength vs. volume raw materials

Figure 4.17 shows the 56-day compressive strength results plotted against the volume of raw materials and the calculated compressive strength-raw volume EPI values. Similar to Figure 4.16, the general trend of increasing strength with increasing volume of raw materials can be seen, but the slope is greater for non-fly ash concrete than for fly ash concrete. The normal and low-binder series are also more closely clustered together than for the CO_2 footprint. No single series stands out as superior, but the recycled aggregate non-fly ash concrete does show better overall performance than the normal aggregate fly ash concrete, with roughly the same strength level but significantly lower volume of raw materials. All the experimental mixes have roughly the same or better performance than the control series, with higher strength at the same level of raw materials, higher strength and less raw materials, or similar strength with fewer raw materials. This is supported by the EPI results, where the control series is the lowest.

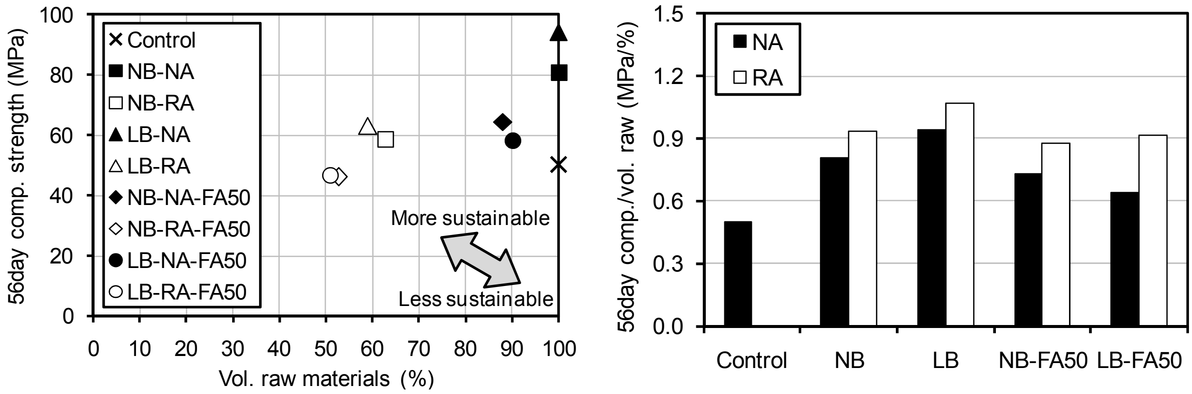


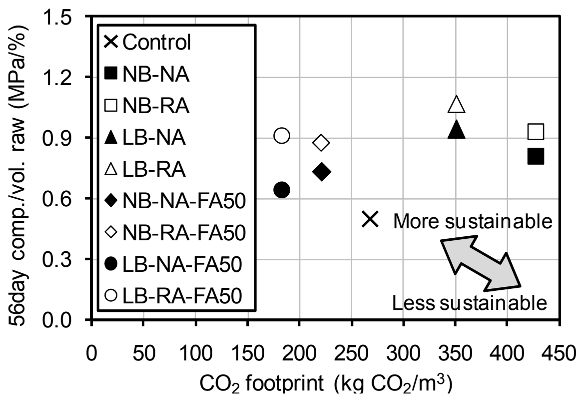
Figure 4.17 Compressive strength vs. volume raw materials (left) and EPI for compressive strength and raw materials (right)

For the EPI results, the primary trend is that the EPI is higher for recycled aggregate concrete than for normal aggregate concrete. Among the recycled aggregate mixes, normal binder non-fly ash and both fly ash mixes have similar EPI values, but the low binder non-fly ash concrete value is higher; it is also the highest value among all series. Normal aggregate fly ash mixes are lower than the non-fly ash mixes, and the trend is also different, with normal binder specimens higher than low binder; for non-fly ash mixes, the low binder EPI is higher for both normal and recycled aggregates.

4.3.5.3 EPI vs. other environmental performance

Finally, in order to examine all three performances (compressive strength, CO2 footprint, and volume of raw materials) simultaneously, the EPI were plotted against the environmental performances not used in the EPI. These results are shown in Figure 4.18. For the compressive strength-raw volume EPI vs. the CO_2 footprint, the results are clustered in two groups according to the binder composition because binder composition has the largest effect on CO_2 footprint, and in these two groups the recycled aggregate mixes have higher compressive strength-raw volume EPI values. From these results, it can be seen that the low binder recycled aggregate fly ash concrete has the best overall performance, as its EPI is higher than or similar to all other series except low binder recycled aggregate non-fly ash concrete, and its CO_2 footprint is the lowest of all series.

For the compressive strength-CO_2 EPI vs. the volume of raw materials, the results are again clustered in two groups but by aggregate type, rather than binder composition, because aggregate type has the largest effect on volume of raw materials. In both these groups, the fly ash concretes have the highest compressive strength-CO_2 EPI, as well as slightly lower volume of raw materials. Again, it can be seen that the low binder recycled aggregate fly ash concrete offers the best overall performance. Although its EPI value is lower than those of normal and low binder normal aggregate fly ash series, the volume of raw materials is not only significantly lower than those two series, but the lowest out of all series. Furthermore, all series have either higher EPI value, lower volume of raw materials, or both, compared to the control series.



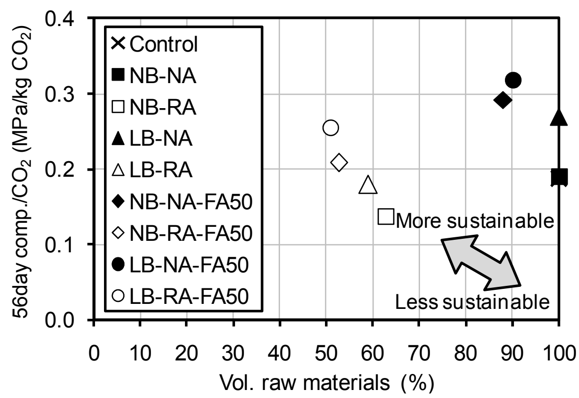


Figure 4.18 Compressive strength-raw volume EPI vs. CO_2 footprint (left) and compressive strength-CO_2 EPI vs. volume raw materials (right)

4.3.6 Summary

In this section, the mechanical and environmental performance of concrete with variable binder content, composition, and aggregate type were evaluated, and the balance between mechanical and environmental performance was also investigated. It was found that all series except recycled aggregate fly ash mixes gave compressive strength higher than the control series at 28 and 56 days, but at 28 days only non-fly ash series had higher flexural strength. However, all series had lower air permeability than the control series. In general, the strength and quality of the recycled aggregates are believed to be a limiting factor to compressive strength gain. The CO_2 footprint is affected primarily by the binder composition and secondarily by the binder content, whereas the volume of raw materials is primarily by the aggregate type. All series had higher sustainable value than the control series except for the normal aggregate non-fly ash concretes, which has the same volume of raw materials but a larger CO_2 footprint.

When comparing the compressive strength with the CO_2 footprint and volume of raw materials, it was found that evaluation only considering CO_2 footprint reduced the value of recycled aggregate concrete, as the strength for these specimens was typically much lower for the same level of CO_2. Replacing cement with fly ash or reducing the amount of binder reduced the CO_2 footprint more than it reduced the strength, so the value of these two approaches could be clearly seen. In contrast, when evaluating by the volume of raw materials the influence of recycled aggregates was much higher, as recycled aggregates reduced raw material volume consumption more than they reduced strength. However, the addition of fly ash reduced strength without significant reduction of materials. When evaluating compressive strength against both CO_2 footprint and volume of raw materials, low binder recycled aggregate fly ash concrete could be clearly identified as providing the best overall balance between the performance parameters. However, the overall strength behavior of this concrete was slightly lower than that of the control series.

4.4 EFFECT OF MIX PROPORTIONS, BINDER TYPE, AND AGGREGATE VOLUME

4.4.1 Overview

In the previous phase, different combinations of binder volume, binder type, and aggregate type were investigated considering both mechanical and environmental performances. A control concrete used to represent "normal-use" concrete was also cast and the performance of the target concretes was continually compared to the normal-use concrete. This comparison was conducted because, in order to improve sustainability in the concrete industry, current concretes in use need to be replaced with materials which can meet the same performance requirements with a lower environmental impact. From the previous phase's results, two materials (low binder fly ash concrete with and without recycled aggregates) with 28-day compressive strength similar to the normal-use concrete and with the lowest environmental impacts were selected as the base conditions for the next investigation. This experimental plan was conducted in order to understand the effect of mix proportion (water-cement ratio), binder type (combinations of cement, fly ash, and/or blast furnace slag), and aggregate volume (recycled aggregate replacement ratio) on the durability and environmental impact of the concrete mixes. Materials with similar strengths to the normal-use concrete were focused on and therefore durability was selected as the primary mechanical performance. In addition, recycled aggregate usage in particular has been identified in past research results as having a negative effect on durability (Otsuki et al., 2003), so the latter part of this phase applied the analytic hierarchy process (AHP), as outlined in Section 3.4, to determine the best balance between durability and environmental impact.

4.4.2 Experimental program

4.4.2.1 Materials

The materials used in this phase were the same as those introduced in Section 4.3.2.1, with the addition of ground granulated blast furnace slag (BS) as another cementitious replacement material. The density and fineness of the blast furnace slag are 2.91 g/cm^3 and 4440 cm^2/g, respectively, and meet the specifications of JIS A 6206.

4.4.2.2 Mix proportions and fresh properties

Concrete mix proportions and fresh properties are given in Table 4.7. Three different water-binder ratios (0.3, 0.375, and 0.45), two different binder combinations (C50%-FA50% and C50%-FA25%-BS25%), and three different recycled aggregate replacement ratios (0%, 50%, and 100%) were selected for this experimental investigation. The 50% replacement of cement with mineral admixtures and reduction of mixing water content from the standard 170 kg/m^3 to 135 kg/m^3 were selected based upon the results of the previous phase. A control concrete with a water-binder ratio of 50 and no waste or recycled materials was also prepared to serve as a reference for normal-use concrete.

Table 4.7 Mix proportions and fresh properties

Series	(kg/m^3)							Slump	Air
	W	C	FA	BS	S	NA	RA	(cm)	(%)
Control	171	342	-	-	746	1015	-	11.0	4.0
WB30-RA0	135	225	225	-	659	1067	-	15.0	2.0
WB30-RA50						533	478	13.5	6.0
WB30-RA100						-	957	16.0	4.0
WB375-RA0		180	180	-	721	1095	-	6.5	4.7
WB375-RA50						548	491	12.0	5.5
WB375-RA100						-	982	9.0	4.5
WB45-RA0		150	150	-	772	1114	-	7.5	4.5
WB45-RA50						557	500	9.5	3.7
WB45-RA100						-	999	12.0	5.6
WB45-BS-RA0			75	75	788	1125	-	7.5	5.6
WB45-BS-RA50						563	506	7.5	3.5
WB45-BS-RA100						-	1011	5.5	4.0

4.4.2.3 Specimens and curing

Cylinder (10Ø×20 cm) and beam (10×10×40 cm) specimens were cast for each concrete mix. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and placed in water curing at 20-21°C.

4.4.2.4 Testing

Compressive strength was measured according to JIS A 1108 and conducted at 7, 28, and 91 days. Young's modulus was measured according to JIS A 1149 at 28 and 91 days using stress values calculated from the compressive strength load data and strain values obtained from strain gauges installed on the cylinder under compressive testing. Reported values are the average of three specimens. The air permeability coefficient, an indicator of durability, was also measured at 28 and 91 days following the procedure outlined in Section 4.3.2.4.

The drying shrinkage test was conducted according to JIS A 1129. Beams were withdrawn from water curing after 28 days and simply supported (to allow free movement) in an atmospheric environment at 20-21°C and approximately 50% relative humidity, then two contact gauges spaced approximately 300 millimeters apart were attached to each beam. After this, shrinkage was measured periodically and calculated as follows.

$$\varepsilon = \frac{(X_{01} - X_{02}) - (X_{i1} - X_{i2})}{L_0}$$

Where ε: shrinkage, X_{01}: initial length of calibration bar (mm), X_{02}: initial length of specimen (mm), X_{i1}: length of calibration bar at time i (mm), X_{i2}: length of specimen at time i (mm), and L_0: reference length (mm).

4.4.2.5 Environmental impact assessment

Environmental impact was evaluated using the CO_2 footprint and volume of raw materials as outlined in Section 4.3.2.5.

4.4.3 Results and discussion

4.4.3.1 Compressive strength

Compressive strength development from 7 to 91 days for all series is shown in Figure 4.19. The control series has the highest strength level at 7 days but, from 7 to 28 days, the strength development is higher for the W/B=0.3, W/B=0.375, and W/B=0.45 with blast furnace slag series, regardless of aggregate type. In the case of the W/B=0.3 and W/B=0.45 with blast furnace slag, the strength level is comparable to the control by 28 days, but for W/B=0.375 the strength level is still lower than the control even though the strength development is higher. Finally, from 28 to 91 days the strength development follows a similar rate as the control series. For the W/B=0.45 series, the strength development is similar to the control from 7 to 91 days, albeit at a much lower level.

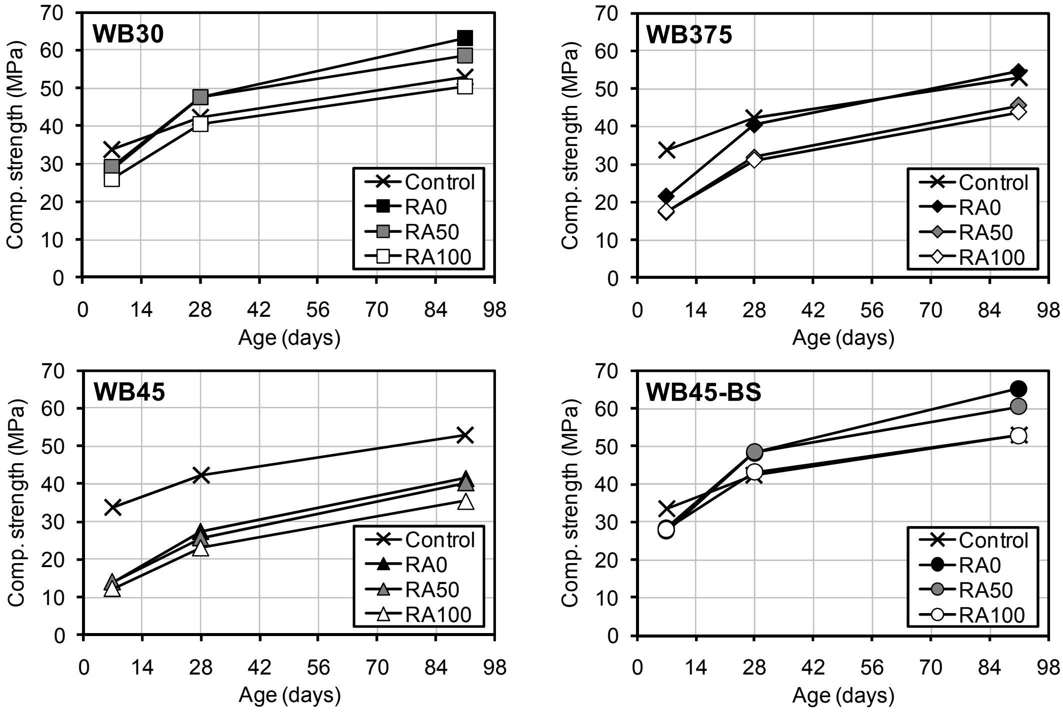


Figure 4.19 Compressive strength development from 7 to 91 days

Figure 4.20 shows the relationship between compressive strength and binder-water ratio for the mixes containing 50% fly ash. This relationship is linear for normal concrete (Uomoto, 2007), and it can be seen that the tendencies for the mixes combining 50% fly ash with 100% normal aggregate, 50% normal-50% recycled, or 100% recycled aggregate are also linear with a high degree of correlation.

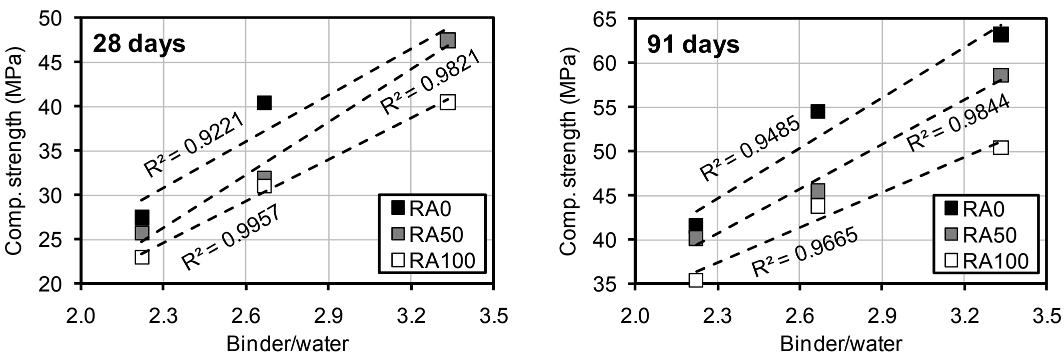
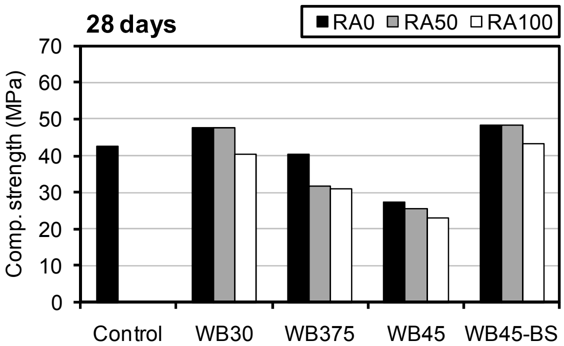


Figure 4.20 Binder-water ratio vs. compressive strength (50% fly ash series only)

The effect of recycled aggregate replacement ratio at different water-binder ratios is given in Figure 4.21 for both 28-day and 91-day compressive strengths. At 28 days, increasing usage of recycled aggregates to 50% did not affect the compressive strength of the W/B=0.3 and W/B=0.45 with blast furnace slag series; however, by 91 days a large difference developed between compressive strength of concrete with 0% and 50% recycled aggregate replacement. These two water-binder contents achieved higher strength than the W/B=0.375 and W/B=0.45 series, which have a similar trend for recycled aggregate usage regardless of curing time. It is possible that the strength development in the cement mortar exceeded the strength of the interface, thus limiting the strength of concrete utilizing recycled aggregates. Some researchers have suggested that replacement of normal aggregates with recycled aggregates in low amounts can be performed without an accompanying reduction in concrete compressive strength [26]. The results obtained here, however, cannot confirm this possibility as the number of replacement ratios investigated is not enough to identify at what point the usage of recycled aggregates becomes detrimental. Furthermore, the past results focused on recycled aggregates of various grades, and such a replacement ratio may not exist for low-grade recycled aggregates as the development of strength in the cement mortar matrix may exceed the strength of the bond with the recycled aggregate more easily for low-grade than for high-grade.



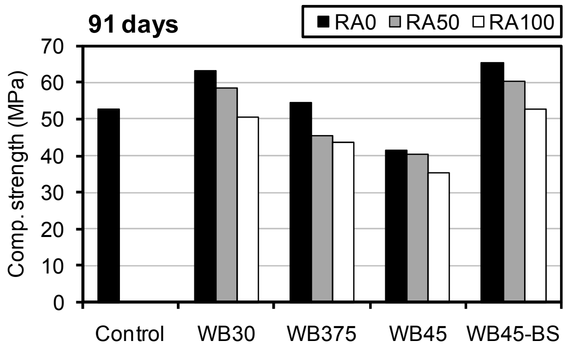


Figure 4.21 Effect of recycled aggregates at different water-binder ratios on 28-day and 91-day compressive strengths

4.4.3.2 Young's modulus

Figure 4.22 shows the effect of recycled aggregate on the Young's modulus at 28 and 91 days. Increasing recycled aggregate usage clearly reduces the Young's modulus, with the effect being fairly consistent at all water-binder ratios and at both 28 and 91 days. The Young's modulus results for all series are also lower than the control mix.

The relationship between compressive strength and Young's modulus is shown in Figure 4.23 for both 28 and 91 day compressive strengths for specimens with 50% fly ash. In this figure, the Japan Society of Civil Engineers standard curve, calculated per the following equation, is used as a reference (JSCE, 2002).

$$E_e(t) = \emptyset(t) \times 4.7 \times 10^3 \sqrt{f_c^{'}(t)}$$

Where E_e: Young's modulus (MPa), f'_c: compressive strength (MPa), t: days, and Ø(t): 0.73 up to 3 days, 1.0 after 5 days. It can be seen that the standard curve overestimates the Young's modulus of concretes using recycled aggregates, particularly when the compressive strength increases. At low compressive strengths, series with 50% recycled aggregates still fall above the curve at 28 and 91 days, whereas at higher strengths the gap between 0%, 50% and 100% recycled aggregates increases. Concretes with 0% recycled aggregates fall on or above the standard curve at both 28 and 91 days.

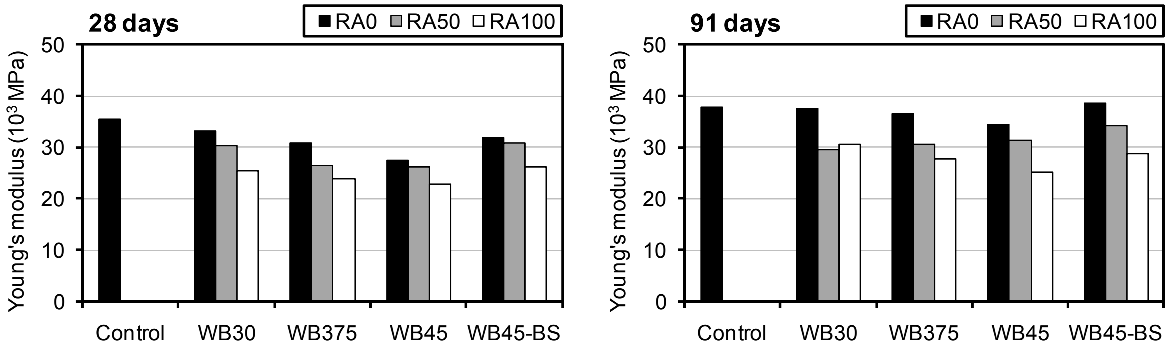


Figure 4.22 Effect of recycled aggregates at different water-binder ratios on 28-day and 91-day Young's modulus

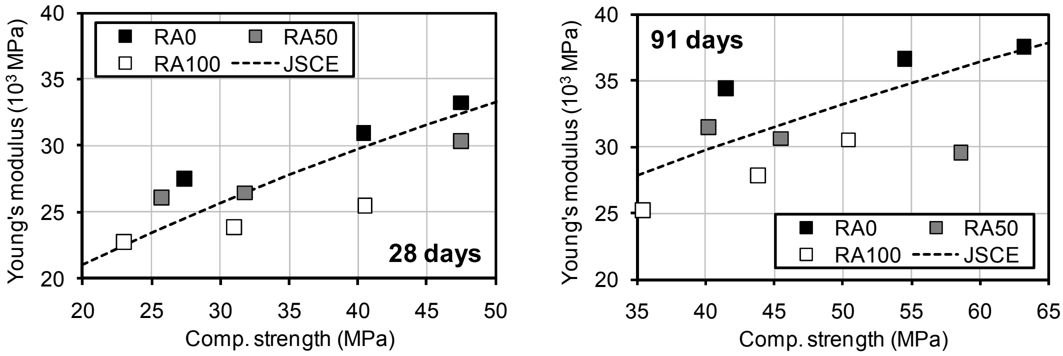


Figure 4.23 Compressive strength vs. Young's modulus with JSCE standard curve (50% fly ash series only)

4.4.3.3 Air permeability

The results of the air permeability test are given in Figure 4.24 by aggregate replacement ratio and water-binder ratio at 28 and 91 days. At 28 days, increasing the amount of recycled aggregate increases the air permeability for all water-binder ratios, and the effect is larger as water-binder ratio increases. By 91 days, however, the effect of recycled aggregate on air permeability is reduced, most significantly in the case of W/B=0.375 and 0.45, which may be attributed to the continued reaction of fly ash past 28 days. The air permeability coefficients of W/B=0.45 with 25% fly ash-25% blast furnace slag are similar to that of W/B=0.3 with 50% fly ash at 28 days, but the concretes with 50% fly ash see a further reduction in air permeability up to 91 days while there was little change for the 25% fly ash-25% blast furnace slag concretes, which again indicates the long-term development of pore structure in the fly ash concrete and suggests that the concrete combining fly ash and blast furnace slag develops most of its durability during the early curing period. When compared to the control mix, most of the mixes had lower air permeability at 28 days, a trend which continued to 91 days when only the two mixes with W/B=0.45 and 100% recycled aggregate had higher air permeability than the control. As found by past research works, the ITZ between the recycled aggregate and the new mortar matrix is a weak point for the durability of concrete utilizing recycled aggregates due to increased porosity and weak bonding (Otsuki et al., 2003; Poon et al., 2004). However, the usage of fly ash was shown here to reduce the effect of recycled aggregate, perhaps through densification of the ITZ, and higher durability performance could be achieved, even at higher water-binder ratios.

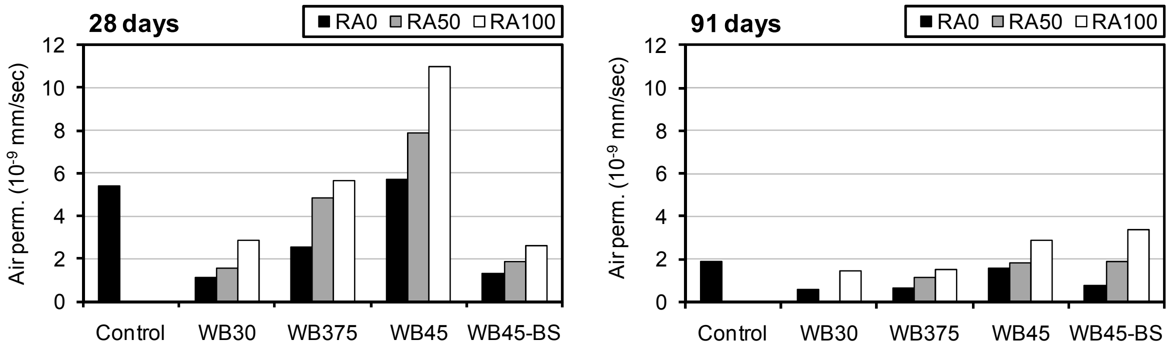


Figure 4.24 Effect of recycled aggregates at different water-binder ratios on 28-day and 91-day air permeability coefficients

4.4.3.4 Drying shrinkage

Drying shrinkage strain results up to 56 days are given in Figure 4.25 for specimens tested after 28 days of water curing. For the W/B=0.3 and W/B=0.45 with blast furnace slag series, shrinkage is comparable to that of the control series. In case of W/B=0.375 and W/B=0.45, however, early-age shrinkage is much higher than the control series; only after 28 days does shrinkage slow to a rate similar to that of the control.

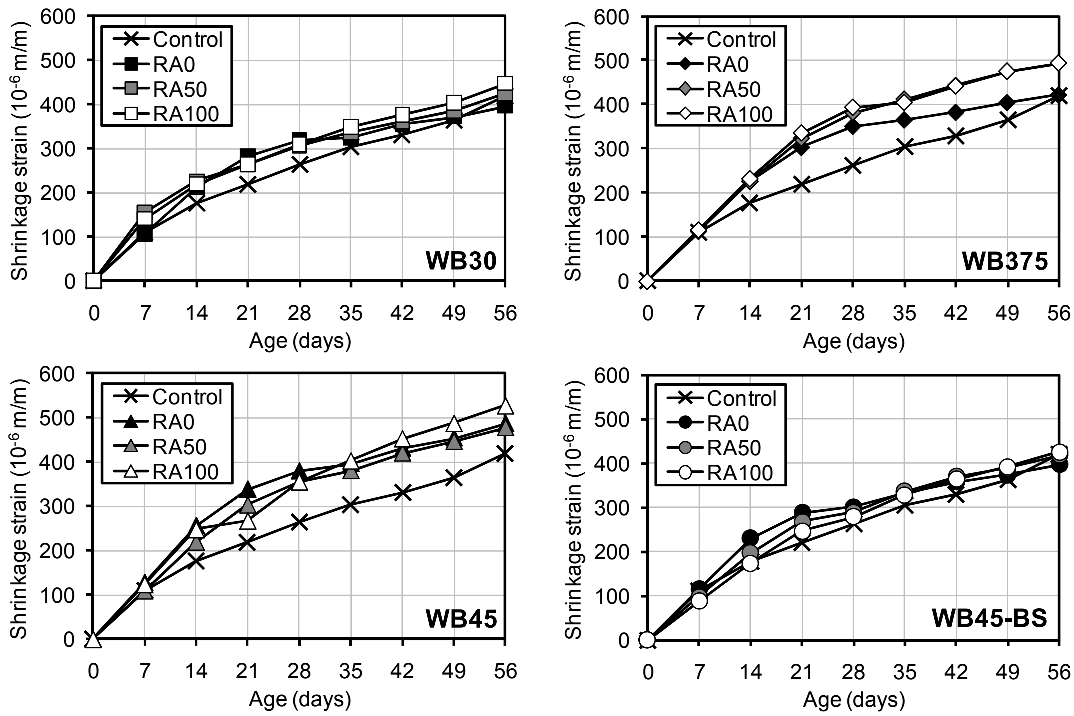


Figure 4.25 Drying shrinkage strain up to 56 days after 28 days water curing

Figure 4.26 shows the effect of recycled aggregate replacement ratio at different water-binder ratios on the 56-day drying shrinkage strain. Increasing the amount of recycled aggregates produces only a slight increase in 56-day shrinkage strain for the water-binder ratios with shrinkage behavior comparable to the control series (W/B=0.3 and W/B=0.45 with blast furnace slag). It has been previously reported that the usage of recycled aggregates, particularly highly-porous types such as the low-grade aggregates used in this investigation, may greatly increase shrinkage (Ravindrarajah & Tam, 1985; Meinhold et al., 2001); however, the usage of 50% fly ash appears to reduce the shrinkage of recycled aggregate concrete to levels comparable to that of normal aggregate concrete with 50% fly ash in this investigation. Overall, the highest 56-day shrinkage was observed for W/B=0.45 with 50% fly ash and 100% recycled aggregates and the lowest was observed for W/B=0.3 with 50% fly ash and 100% normal aggregate and W/B=0.45 with 25% fly ash-25% blast furnace slag and 100% normal aggregate.

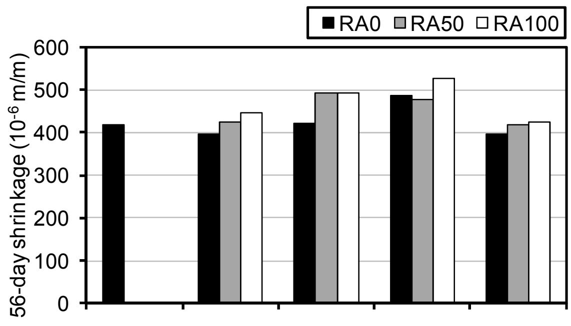


Figure 4.26 Effect of recycled aggregates at different water-binder ratios on 56-day drying shrinkage strain

4.4.3.5 Environmental impact

The CO_2 footprint calculation results are shown in Figure 4.27. The usage of 50% fly ash can be clearly seen to reduce CO_2 relative to the control series, even at lower water-binder ratios with higher binder volume. At W/B=0.3, the CO_2 footprint is 32% less than the control series; this value increases to a 45% and 54% reduction for W/B=0.375 and W/B=0.45, respectively. The combination of fly ash and blast furnace slag has no effect on the CO_2 footprint, nor does increasing the amount of recycled aggregate, as the emissions for low-grade recycled aggregates are nearly the same as the emissions for normal aggregates.

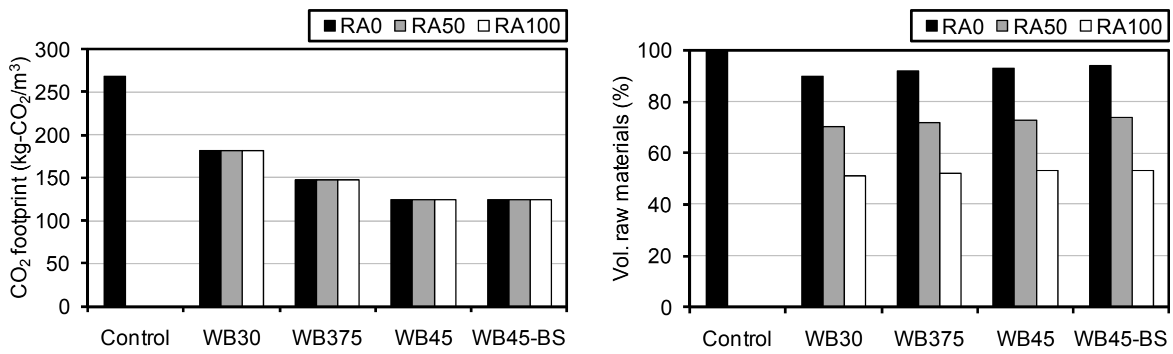


Figure 4.27 CO_2 footprint (left) and volume of raw materials (right) calculation results

For volume of raw materials, the calculation results are also shown in Figure 4.27. Replacing 50% of cement with fly ash provides a 6% to 10% decrease for all series; thereafter, the decrease in raw material volume is linear depending on the replacement rate of recycled aggregate, with 50% and 100% aggregate replacement reducing raw material volume roughly 20% and 40%, respectively. Mixes with 100% recycled aggregate have the lowest volume of raw materials at 51% to 53%.

4.4.4 Balancing durability and environmental impact

4.4.4.1 Performance trade-off

In order to improve sustainable practice in the concrete industry, current normal-use concrete should be replaced with materials which meet or exceed the required performance while reducing environmental impact. For concrete structures, the 28-day performance of test pieces (particularly the 28-day compressive strength) is the primary requirement; therefore, replacement materials should achieve similar or better strength at 28 days but enhance durability and reduce environmental impact – in other words, they need to meet the performance requirements while contributing additional value. As shown in the previous test results, however, there is oftentimes a trade-off between these, so it is necessary to examine the balance between different additional value characteristics.

Seven mixes provided similar or better compressive strength results than the control at 28 days: W/B=0.3 and W/B=0.45 with blast furnace slag (all three recycled aggregate ratios) and W/B=0.375 (0% recycled aggregate). The relationship between air permeability, CO_2 footprint, and volume of raw materials were examined for these seven materials in Figure 4.28. Drying shrinkage was not included as an additional parameter as the selected mixes showed comparable drying shrinkage behavior over the observed period.

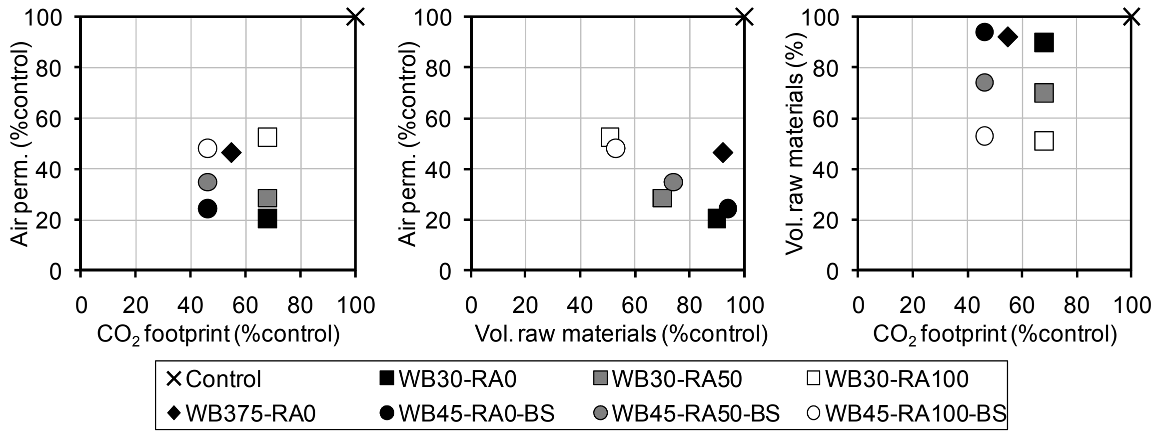


Figure 4.28 Comparison of mixes meeting strength requirement of control mix

It can be clearly seen that all seven mixes have better durability (represented by lower air permeability) and lower environmental impact than the control mix, so any single mix would satisfy the target of enhanced durability and reduced environmental impact. For CO_2 footprint vs. air permeability, W/B=0.45 with 25% fly ash-25% blast furnace slag and 0% recycled aggregates has the best balance. For volume of raw materials vs. air permeability, it's difficult to select a single mix due to the direct relationship between recycled aggregate usage and air permeability. Finally, for CO_2 footprint vs. volume of recycled materials, W/B=0.45 with 25% fly ash-25% blast furnace slag and 100% recycled aggregates has the lowest environmental impact. The two materials mentioned above (with the best balances for two of the comparisons) fall at opposite ends of the spectrum when looking at volume of raw materials vs. air permeability. The mix with 0% recycled aggregates has low air permeability but very high volume of raw materials, whereas the mix with 100% recycled aggregates has higher air permeability but lower volume of recycled materials. Therefore, it is difficult to determine which material provides the best balance between durability and environmental impact.

As introduced in Section 3.4, analytic hierarchy process (AHP) can be applied to quantitatively determine which material provides the best balance. The hierarchy for assessing the materials was constructed as given in Figure 4.29. Four different weighting scenarios were applied (Table 4.8): one applies equal weight to all three criteria, and the other three place high importance on one criterion over the others. For the equal-weight scenario, each criterion carries 33.3% of the weight. For the other three scenarios, the target criterion carries 71.4% of the weight while the other two criteria carry 14.3% of the weight.

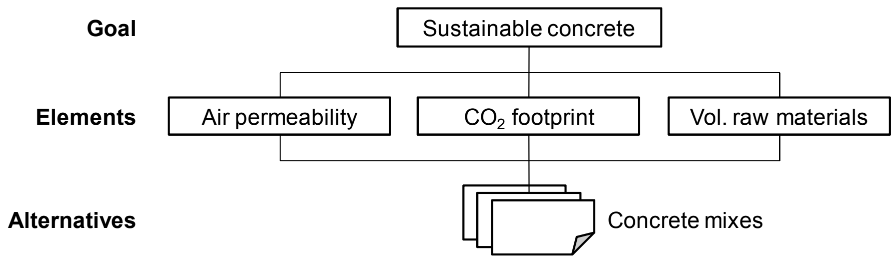


Figure 4.29 Analysis hierarchy including assessment criteria and alternative materials

Table 4.8 Weighting scenarios for additional value criteria

Criteria	Equal		Air perm. high importance	
	Importance	Weight	Importance	Weight
Air permeability	Normal	33.3%	High	71.4%
CO_2 footprint	Normal	33.3%	Normal	14.3%
Vol. raw materials	Normal	33.3%	Normal	14.3%
Criteria	CO_2 high importance		Vol. raw high importance	
	Importance	Weight	Importance	Weight
Air permeability	Normal	14.3%	Normal	14.3%
CO_2 footprint	High	71.4%	Normal	14.3%
Vol. raw materials	Normal	14.3%	High	71.4%

4.4.4.2 AHP calculation results and discussion

From the material properties and criteria weights, the comparative weights of the concrete mixes were calculated and are summarized in Figure 4.30 for the four weighting scenarios. When placing equal importance on the three additional value criteria, W/B=0.45 with 25% fly ash-25% blast furnace slag and 0% recycled aggregate has the best performance balance, which can be attributed to its low air permeability and CO_2 footprint. When placing high importance on air permeability over the other criteria, the W/B=0.3 with 50% fly ash and 0% recycled aggregate has the highest weight, which is determined primarily by its low air permeability. For the CO_2 footprint scenario, W/B=0.45 with 25% fly ash-25% blast furnace slag and 0% recycled aggregate again is the preferred alternative. In this case, all the series with W/B=0.45 and 25% fly ash-25% blast furnace slag have the same CO_2 footprint; the mix with 0% recycled aggregate gained the highest weight because it had the best balance between air permeability and volume of raw materials. Finally, when placing high importance on volume of raw materials, W/B=0.45 with 25% fly ash-25% blast furnace slag and 100% recycled aggregate had the highest weight. Although W/B=0.3 with 50% fly ash and 100% recycled aggregate had the lowest amount of raw materials, the other mix was preferred for this scenario because it had a reduced CO_2 content which, even at low importance, balanced out the difference in volume of raw materials.

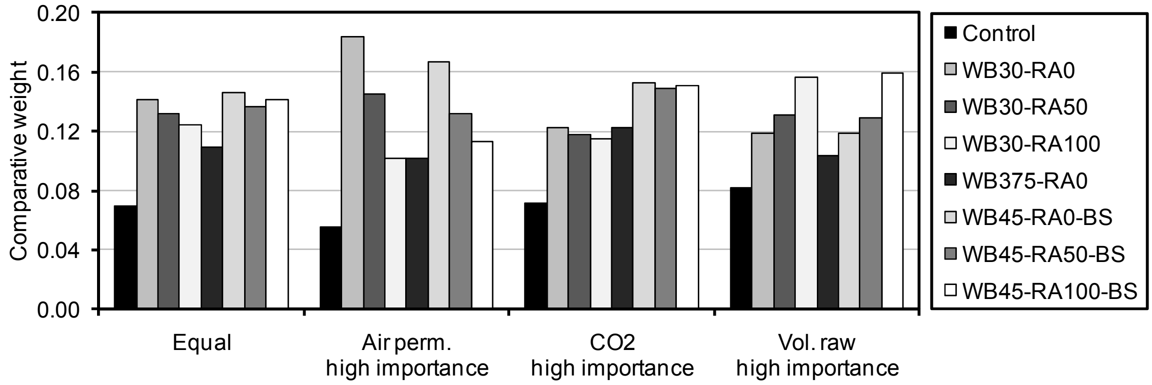


Figure 4.30 AHP calculation results by scenario

The combination of fly ash and blast furnace slag was the preferred binder composition in three of the scenarios, including the "equal" scenario in which the importance of all criteria was the same. This may be attributed to the higher strength of this mix at a higher water-binder ratio (W/B=0.45) which reduced CO_2 greatly compared to the W/B=0.3 mixes, as it could be seen that reduced CO_2 did, in some cases, serve to tip the balance. These results also showed that replacing only 50% of the normal aggregates with recycled aggregates generally reduced the mechanical performance more than it improved the environmental impact – thus, none of the mixes with 50% recycled aggregates were selected as the preferred option, with either the 0% or 100% recycled aggregate mixes being rated higher. Lastly, 0% recycled aggregates (that is, 100% normal aggregates) was the preferred alternative in the "equal" and "CO_2 footprint" scenarios, whereas 100% recycled aggregates was only the preferred option in the "volume of raw materials" scenario. This demonstrates that the decrease in air permeability outweighs the additional value of utilizing recycled materials, as this was the contributing factor when the 0% recycled aggregates mix was selected over the 100% recycled aggregate mix in both of the scenarios.

4.4.5 Summary

In this phase, mechanical properties and environmental impacts of concrete combining low-grade recycled aggregates in various amounts with mineral admixtures were measured and reported, and the balance between durability and environmental aspects was examined utilizing analytic hierarchy process. Mixes with W/B=0.3 with 50% fly ash or W/B=0.45 with 25% fly ash-25% blast furnace slag were found to reduce the effect of recycled aggregate, with performance comparable or better than the control series even when utilizing 100% low-grade recycled aggregates, and the improvement may possibly attributed to the densification of the ITZ. The effect of recycled aggregates was seen when examining Young's modulus, where it was shown that the JSCE standard curve overestimates the Young's modulus values for concrete with recycled aggregates, and also for the air permeability coefficient, where the effect was larger at 28 days than at 91 days. In the case of shrinkage, the effect of recycled aggregate was generally small, with the difference in shrinkage behavior due to the water-binder ratio. When examining the environmental impact, all mixes were found to have lower CO_2 footprint and volume of raw materials than the control series, with recycled aggregates contributing primarily to the latter and mineral admixture usage and water-binder ratio contributing to the former.

When examining the balance between durability and environmental impacts, a single material could be clearly identified as having the best balance when comparing CO_2 footprint vs. air permeability and CO_2 footprint vs. volume of raw materials; however, no single material could be selected when examining volume of raw materials vs. air permeability due to the direct relationship between recycled aggregate usage and these two factors. Applying AHP with four importance weighting scenarios showed that, in general, the usage of normal aggregates (0% recycled aggregates) was preferred in most cases – except when high importance was given to volume of raw materials – as the usage of recycled aggregates in either 50% or 100% replacement ratios tended to reduce air permeability more than increase volume of raw material relative to the other mixes. In addition, the W/B=0.45 with 25% fly ash-25% blast furnace slag binder composition was also preferred in most cases because it achieved strength similar to the control mix but with a higher water-binder ratio than the other mixes, thus reducing CO_2 footprint, and similar or better air permeability.

Although the experimental results showed performance comparable to the control mix could be achieved even when utilizing 100% low-grade recycled aggregates, mixes with recycled aggregates were not selected in the AHP analysis. However, it is important to consider that the mixes compared in the AHP analysis all had lower environmental impact and air permeability than the control, so any single mix would satisfy the goal of reducing resource consumption and CO_2 emissions and enhancing durability. As there exists any number of combinations of materials and mix proportions which can meet a given strength level, the utility of AHP for comparing these mixes to identify the mix with the best balance of performance is clearly demonstrated by these results.

4.5 CONCLUSION

In this chapter results from various investigations on the usage of recycled aggregate and fly ash in concrete were introduced. These investigations focused not only on the mechanical performance but also addressed other issues such as the statistical variation and estimation of strength and the relationship and balance between the mechanical and environmental performances. The usage of these waste and recycled materials in concrete reduced both mechanical properties as well as environmental impact, and thus the utility of the mechanical-environmental efficiency and the analytic hierarchy process as methods for quantitatively evaluating and balancing these trade-offs could be clearly seen.

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Chapter 5
Combining recycled rubber with waste materials in concrete

5.1 INTRODUCTION

Application of recycled coarse aggregates and fly ash only reduces the usage of raw coarse aggregates and cement-making materials; to further reduce resource consumption other waste materials need to be combined in concrete in order to reduce the usage of natural sand for fine aggregates. The recycled rate of waste rubber tires in Japan is high – roughly 89% in 2009 – but this materials is generally not used as raw material in concrete (JATMA, 2009). The usage of recycled rubber crumbs as a replacement for sand, however, has been investigated to some extent, with results showing that, while rubberized concrete has high energy absorption capacity, it may not be attractive as a structural material due to significantly reduced strength and adverse effects on fresh and hardened properties (Eldin and Senouci, 1994; Topçu, 1995; Toutanji, 1996). On the other hand, rubberized high-strength concrete may be applicable when combined with mineral admixtures and extended curing (Wong and Ting, 2009).

Considering these research results and setting the reduction of raw materials as a target, this chapter introduces the results of an investigation on the effect of replacing sand with recycled rubber crumbs in concrete containing both recycled aggregates and fly ash. High-strength concrete was set as the base concrete mix, and the effect of each combination of waste material on the hardened properties and the environmental impact – evaluated as the volume of raw materials – was investigated. As it can be expected that this combination will reduce mechanical performance, the mechanical-environmental efficiency was calculated using the environmental performance indicator introduced in Section 3.3.2 and normalizing it against a control material used to represent general-use concrete.

5.2 EXPERIMENTAL PROGRAM

5.2.1 Materials

Concrete was prepared using tap water (W), type-I portland cement (C), JIS type-II fly ash (FA), river sand (S), recycled rubber crumbs (GC), normal coarse aggregates (NA), low-grade recycled coarse aggregates (RA), and air-entraining (AE) and super plasticizer (SP) admixtures. The specific properties of the cement and type-II fly ash are given in Section 4.3.2.1, and the properties and details of preparation for the low-grade recycled coarse aggregates are also given in Section 4.3.2.1. Rubber crumbs with a maximum size of 3 millimeters, as shown in Figure 5.1, were processed from waste tires, and no steel wires or other materials were included. The properties of both the rubber crumbs and sand (fine aggregates) are summarized in Table 5.1.

Figure 5.1 Rubber crumbs (size 1 to 3 mm) from recycled rubber tires

Table 5.1 Properties of rubber crumbs and sand

Material	SSD density (g/cm^2)	Absorption (%)	Fineness modulus	Maximum size (mm)
Rubber crumbs	1.10	-	-	3
Sand	2.62	2.09	2.74	4

5.2.2 Mix proportions and fresh properties

Concrete mix proportions and fresh concrete properties are given in Table 5.2. The water-binder ratio was set at 0.3, and two recycled aggregate replacement ratios (0% and 100% by volume), two binder combinations (C100% and C50%-FA50% by mass), and three rubber crumb replacement ratios (0%, 25%, and 50% replacement of sand by volume) were selected for this experimental investigation. A control concrete with a water-binder ratio of 0.5 and no waste or recycled materials was also prepared to serve as a reference for normal-use concrete.

Table 5.2 Mix proportions and fresh properties

Series	(kg/m^3)							Slump (cm)	Air (%)
	W	C	FA	S	GC	NA	RA		
Control	171	342	-	746	-	1015	-	11.0	4.0
WB30	165	550	-	624	-	1009	-	18.5	5.1
WB30-RA						-	905	12.0	5.2
WB30-FA50		275	275	590	-	955	-	10.0	3.0
WB30-RA-FA50						-	856	16.0	4.5
WB30-GC25		550	-	468	65	1009	-	10.0	3.6
WB30-RA-GC25						-	905	9.5	5.1
WB30-FA50-GC25		275	275	442	62	995	-	17.0	2.7
WB30-RA-FA50-GC25						-	856	13.5	5.1
WB30-GC50		550	-	312	131	1009	-	9.5	5.7
WB30-RA-GC50						-	905	13.0	5.0
WB30-FA50-GC50		275	275	295	124	955	-	11.0	4.4
WB30-RA-FA50-GC50						-	856	12.5	3.7

5.2.3 Specimens and curing

Cylinder (10Ø×20cm) specimens were cast for each concrete mix. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and placed in water curing at 20-21°C.

5.2.4 Testing and environmental assessment

Compressive strength testing and the measurement of Young's modulus and the air permeability coefficient were conducted as explained in Sections 4.3.2.4 and 4.4.2.4 and conducted at 7, 28, and 91 days for strength and 28 days only for Young's modulus and air permeability.

The environmental impact was assessed using the volume of raw materials, which was calculated from the percent volume of cement, water, sand, and normal aggregates per cubic meter of concrete. Therefore, if the volume of raw materials in a given mix decreases then this is assumed to represent a reduction in natural resource consumption and thus a reduced environmental impact. CO_2 emissions and input energy – which may conversely increase for waste and recycled materials due to processing – were not considered in this investigation due to a lack of inventory data on the rubber crumbs.

5.3 RESULTS

5.3.1 Compressive strength

Compressive strength development from 7 to 91 days is shown in Figure 5.2 for concrete mixes with 0%, 25%, and 50% rubber crumb replacement ratios. At 0% rubber crumbs, the strength development of concretes with normal aggregate (both 100% cement and 50% cement-50% fly ash) and concrete with recycled aggregate and fly ash follows a similar trend, with the largest difference occurring from casting up to 7 days. In the case of concrete with recycled aggregate and no fly ash, very little strength gain was observed from 28 to 91 days; this may indicate that the bond between the high-strength mortar and the low-grade recycled aggregate is limiting the strength gain, as the mix with normal aggregates and 50% fly ash exceeds this mix's strength by 91 days. The strength development of the mix combining recycled aggregates and 50% fly ash is close to the behavior of the control mix up to 91 days.

At 25% replacement of sand with rubber crumbs, the overall strength levels are much lower than for 0% rubber crumbs and are either comparable to or lower than the control series, and there is less strength development observed from 28 to 91 days. Furthermore, the difference between normal and recycled aggregates is smaller, but again little strength gain is observed for the mix with recycled aggregate and no fly ash from 28 to 91 days. Finally, at 50% rubber crumbs the strength levels of all series are much lower than the control series and little to no strength development can be seen after 28 days, except in the case of the concrete with normal aggregates and 50% fly ash.

The effect of the rubber crumb replacement ratio on the 28-day compressive strength is shown in Figure 5.3. Increasing the amount of rubber crumbs linearly reduces the compressive strength regardless of binder composition or coarse aggregate type. The concretes with normal aggregates lose the greatest percentage of strength (59.1% and 58.6% for 100% cement and 50% cement-50% fly ash, respectively) when increasing the rubber chip replacement ratio from 0% to 50%; in contrast, the concretes with recycled aggregate lose only 47.8% and 49.8% for normal cement and 50% fly ash, respectively. The effect of recycled aggregates and fly ash is also reduced as the amount of rubber crumbs increases, but by 50% rubber crumb replacement ratio only the effect of fly ash can be seen.

Increasing the amount of rubber crumbs to 25% reduces strength below the level of the control mix for the fly ash concretes, and at 50% rubber crumb replacement ratio all mixes have lower strength than the control.

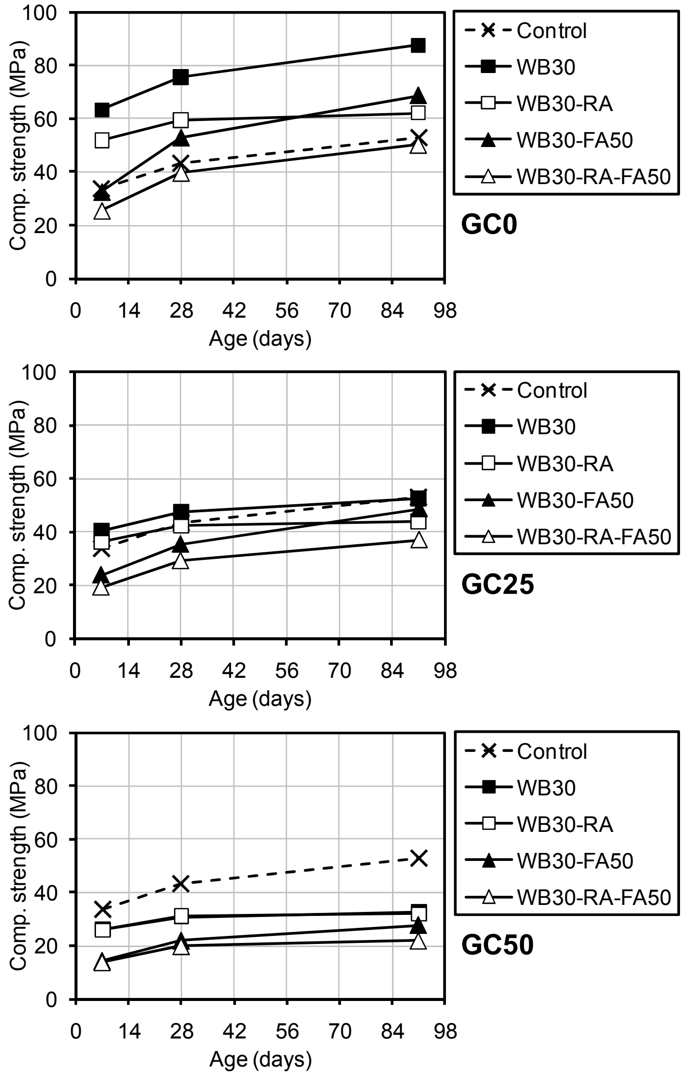

Figure 5.2 Compressive strength development from 7 to 91 days for 0% (top), 25% (middle), and 50% (bottom) rubber crumb replacement ratios

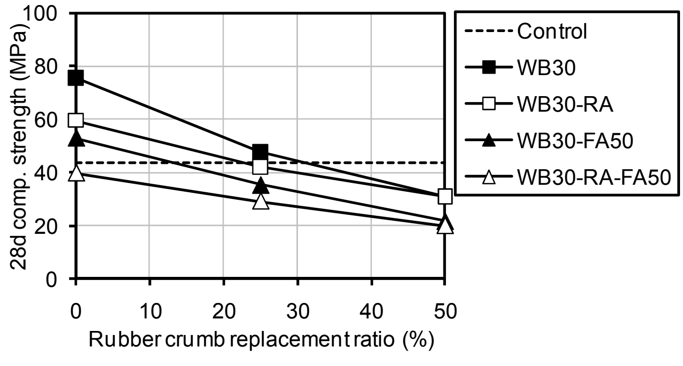

Figure 5.3 Effect of rubber crumb replacement ratio on 28-day compressive strength

5.3.2 Young's modulus

Figure 5.4 shows the effect of rubber crumb replacement ratio on the 28-day Young's modulus. Similar to the 28-day compressive strength, increasing the replacement ratio linearly reduces the Young's modulus. Unlike the compressive strength, however, the effect of recycled aggregate and fly ash remains fairly constant at all replacement ratios. It can also be seen that the Young's modulus for concretes with just fly ash and concretes with just recycled aggregate is nearly the same regardless of the amount of rubber crumbs. The Young's modulus of the control series is higher than that of the all series except for the concrete containing no waste materials.

The relationship between 28-day compressive strength and Young's modulus is shown in Figure 5.5. In this figure, the Japan Society of Civil Engineers (JSCE) standard curve is used as a reference (JSCE, 2002). The standard curve generally overestimates the Young's modulus for most of the concrete mixes, with the exceptions being the control mix and the two mixes containing 25% rubber crumbs without recycled aggregates. Other mixes without recycled aggregates also fall near to the standard curve, but mixes with recycled aggregates generally fall further below the curve, regardless of the amount of rubber crumbs.

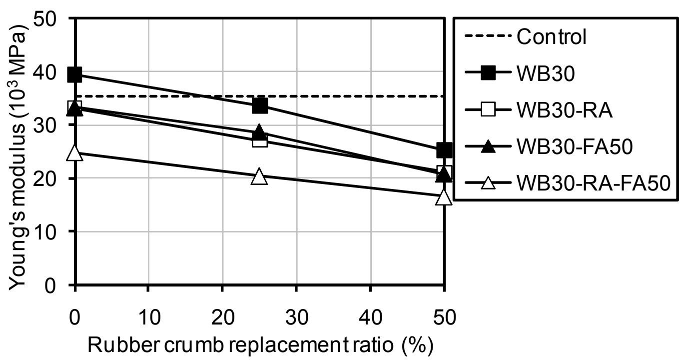

Figure 5.4 Effect of rubber crumb replacement ratio on 28-day Young's modulus

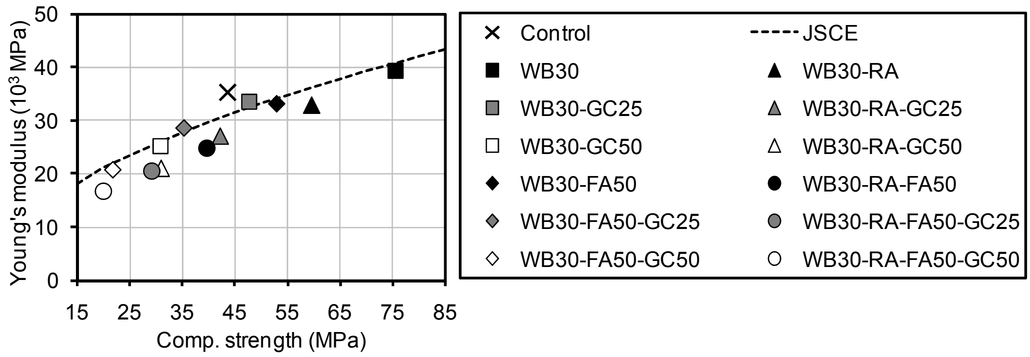

Figure 5.5 Compressive strength vs. Young's modulus with JSCE standard curve

5.3.3 Compressive failure mode

Differing failure modes under compressive loading could also be observed, as shown in Figure 5.6. Mixes without rubber crumbs, particularly those with high strength such as the non-fly ash concretes with normal and recycled aggregates, underwent brittle failure with specimens suddenly exploding into small pieces at the peak load. On the other hand, usage of 25% rubber crumbs significantly affected this failure mode, with specimens failing in a much less brittle fashion. The strength of these specimens, however, is much lower than that of the high-strength specimens but comparable to the strength of the normal concrete mix, but Figure 5.7 shows that even at this strength level normal concrete also undergoes brittle failure under compressive loading, so the effect of rubber crumbs on failure mode can be clearly seen.

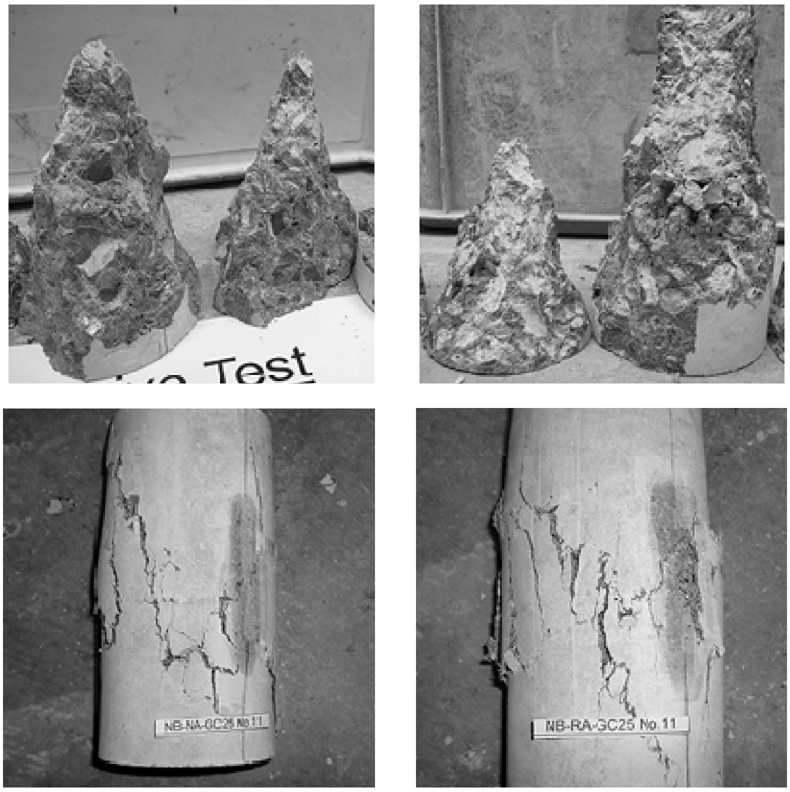

Figure 5.6 Failure mode of specimens under compressive loading: no waste (top left), recycled aggregate (top right), 25% rubber crumbs (bottom left), and recycled aggregate+25% rubber crumbs (bottom right)

Figure 5.7 Failure mode of normal concrete under compressive loading

5.3.4 Air permeability

The air permeability coefficient measurement results are given in Figure 5.8. The effect of rubber crumbs is markedly different depending on the binder composition. For non-fly ash concrete, increasing the amount of rubber crumbs increases the air permeability consistently, with a smaller increase from 25% to 50% than from 0% to 25%. A large difference can also be seen between normal and recycled aggregates for the non-fly ash concretes, with this difference remaining fairly constant regardless of rubber crumb replacement ratio. For the fly ash concretes, however, increasing the amount of rubber crumbs from 0% to 25% has little effect on the air permeability, but increasing from 25% to 50% produces a large increase. In addition, the type of aggregate does not have as large an effect in the fly ash concretes as it does in the non-fly ash concretes.

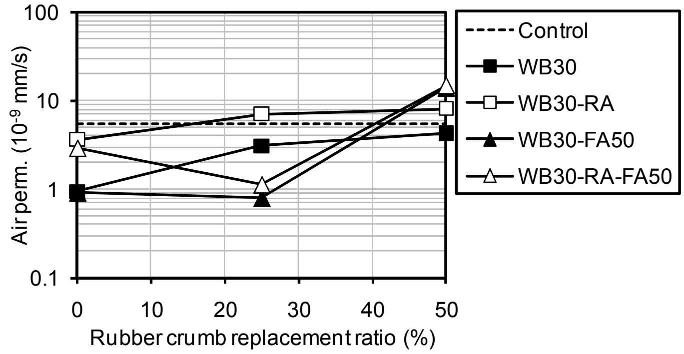

Figure 5.8 Effect of rubber crumb replacement ratio on 28-day air permeability coefficient

5.3.5 Environmental impact

The calculation results for volume of raw materials are shown in Figure 5.9. Increasing the rubber crumb replacement ratio linearly decreases the volume of raw materials roughly 6% for each 25% increase in amount of rubber crumbs. Replacement of 50% cement with fly ash reduces the volume of raw materials roughly 12%, whereas the usage of 100% recycled aggregates reduces the volume of raw materials roughly 37%. The combination of both fly ash and recycled aggregates can achieve roughly a 47% reduction, with the combination of all three waste and recycled materials reaching a maximum reduction of 52.8% and 58.5% for 25% and 50% rubber crumb replacement ratio, respectively.

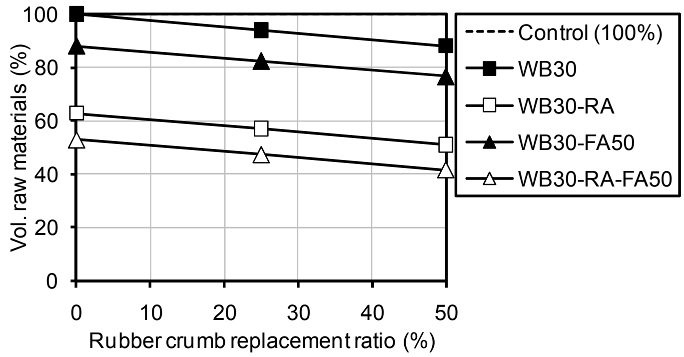

Figure 5.9 Effect of rubber crumb replacement ratio on volume of raw materials

5.3.6 Relationship between mechanical and environmental

In order to examine the relationship between environmental impact and mechanical performance, the volume of raw materials and 28-day compressive strength are plotted together in Figure 5.10. As both these properties varied linearly with the amount of rubber crumbs, the relationship between them is also linear with compressive strength increasing as volume of raw materials increases. The data points fall into two main groups depending on the type of aggregate, with recycled aggregate mixes having the lowest volume of raw materials but lower strength than the normal aggregate mixes. The results of the mixes combining fly ash and recycled aggregates and the mixes with just recycled aggregates also follow a linear trend, with the strength and volume of raw materials of the mixes combining fly ash, recycled aggregates, and 0% and 25% rubber crumbs falling near to the strength and volume of raw materials of the mixes combining recycled aggregate with 25% and 50% rubber crumbs. The difference between fly ash and non-fly ash mixes is slightly larger in the case of the normal aggregate concretes.

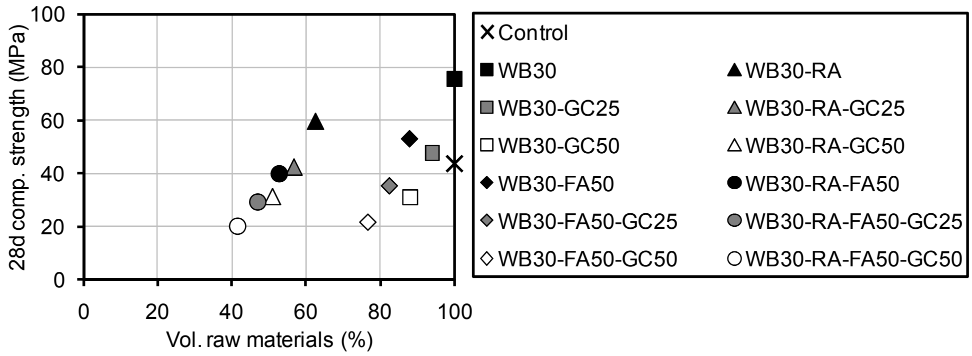

Figure 5.10 Volume of raw materials vs. 28-day compressive strength

5.3.7 Mechanical-environmental efficiency

While Figure 5.10 clearly shows that decreasing the volume of raw materials reduces strength, it is difficult to determine which mix has the best balance of strength and raw materials – that is, the most efficient combination of mechanical and environmental performance. To address the problem of which mix has the best mechanical-environmental efficiency, the following equation (based on the concept of the environmental performance indicator as proposed by Nielsen [2009]) was proposed to create a weighted strength index considering both the compressive strength as well as usage of raw materials.

$$f'_{c-w} = \frac{f'_c}{(V/100)}$$

Where $f'_{c\text{-}w}$: weighted strength index (MPa), f'_c: compressive strength (MPa), and V: volume of raw materials (%).

The calculation results are shown in Figure 5.11, where the effect of rubber crumb replacement ratio on the weighted strength can be seen. Relative to the normal compressive strength results, the weighted strength of the mixes with only rubber crumbs increased only slightly, as did the mixes combining fly ash and rubber crumbs. Mixes combining fly ash and recycled aggregates with rubber crumbs have the second-highest weighted strength. Furthermore, at 0% rubber crumb replacement ratio the weighted strengths of the mix combining fly ash and recycled aggregates and the mix with no waste materials are roughly the same; however, increasing the amount of rubber crumbs reduces the weighted strength faster in the case of the concrete with no waste, indicating that combining all three waste materials together is more efficient than utilizing rubber crumbs on their own. Finally, the mixes with recycled aggregates and rubber crumbs have the highest weighted strengths.

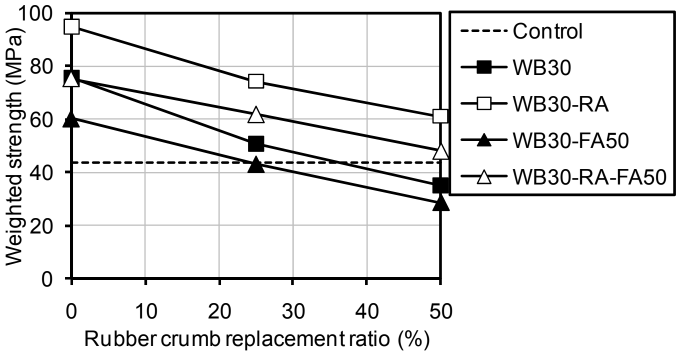

Figure 5.11 Effect of rubber crumb replacement ratio on weighted strength calculation results

The efficiency of normal-use concrete is represented by the weighted strength of the control mix, so to understand the efficiency of the concretes utilizing waste materials relative to this baseline the weighted strengths were normalized by the control mix. The results, given in Figure 5.12, show that almost all combinations of waste materials are more efficient than the control mix. The only exceptions to this result are the mixes using 50% rubber crumbs only or with fly ash. Concretes combining recycled aggregates with fly ash, with no waste materials, and combining 25% rubber crumbs with recycled aggregates all have comparable efficiency and are second-highest behind the concrete with only recycled aggregates.

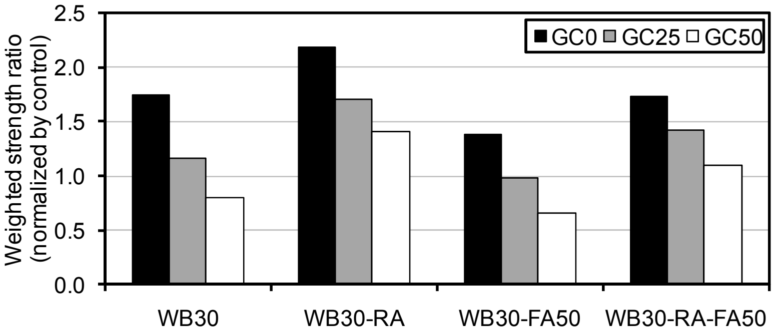

Figure 5.12 Weighted strength calculation results normalized by control mix

5.4 DISCUSSION

The test results showed that the usage of rubber crumbs clearly reduces the mechanical performance; however, combining rubber crumbs with other waste materials reduces mechanical performance even further, as the best compressive strength and Young's modulus (and reasonable air permeability) were all obtained in the case of high-strength concrete containing only rubber crumbs. The bonding between rubber and hardened paste has been cited as a weakness in rubberized high-strength concrete (Wong and Ting, 2009), and the results shown here demonstrate that this may also be the case even when using fly ash, as the amount of strength development between 28 and 91 days decreased as the amount of rubber crumbs increased. One exception to this is the combination of fly ash and rubber crumbs, which generally had a higher strength development in this time period compared to the other rubberized concrete mixes. The usage of fly ash also showed some benefit regarding air permeability, as the air permeability coefficient of concrete combining rubber crumbs and fly ash was generally lower than when fly ash was not used, although there was some unclear behavior when the amount of rubber crumbs was increased to 50%. The improvement of air permeability without an improvement in strength shows that, while fly ash may not necessarily improve the bonding of the cement matrix with the rubber crumbs, it can contribute to reducing mass transport properties to some extent. In addition, it was also observed that as the rubber crumb replacement ratio increased the effect of recycled aggregate was greatly reduced in the case of compressive strength, but this trend was different for air permeability, where the behavior varied depending on whether fly ash was included. In non-fly ash concrete, the effect of recycled aggregate on air permeability remained fairly constant even when 50% rubber crumbs were included, but for fly ash concrete the effect of recycled aggregate was almost entirely reduced when rubber crumbs were included. Therefore, fly ash does not serve to improve the bonding with recycled aggregates (as similar differences in strength between normal and recycled aggregates were observed for both non-fly ash and fly ash concretes) but it can improve air permeability when combined both with recycled aggregate and rubber crumbs.

Weighting the compressive strength by the volume of raw materials was conducted as a way to consider the environmental impact along with the mechanical performance. Considering this calculation, most combinations of waste materials may be considered more “efficient” than the control mix, as was shown when the weighted strengths were normalized by the control mix. However, when considering the actual specification of concrete materials, the foremost requirement is that the concrete meets a certain performance requirement, and the weighted strength does not explicitly consider this as it is a function of both strength and volume of raw materials. However, the normalized weighted strength may be useful when comparing mixes with similar strength levels. The control mix, used to represent a “normal concrete,” had a 28-day strength of 43.5 MPa. Other mixes with compressive strengths around this level include recycled aggregates and fly ash at 39.7 MPa, 25% rubber at 47.6 MPa, recycled aggregates and 25% rubber at 42.2 MPa, and fly ash and 25% rubber at 35.4 MPa; the normalized weighted strengths for these four mixes are 1.73, 1.16, 1.71, and 0.99, respectively. From this comparison, it can be said that at this strength level the combination of recycled aggregates and fly ash has the best balance of mechanical and environmental performance while meeting the strength requirement. Performing a similar exercise with a target strength level of around 30 MPa would yield recycled aggregates, fly ash, and 25% rubber (28-day strength: 29.1 MPa) as the most efficient combination of waste materials. This methodology of weighting mechanical by environmental to identify the efficiency of different combinations of waste materials could also be extended to other properties as well as other mix proportions or wastes.

5.5 CONCLUSION

The following conclusions were made based on the results of this experimental investigation:

Increasing the amount of rubber crumbs from 0% to 50% linearly reduced the compressive strength regardless of the aggregate or binder type, and also reduced the rate of strength development from 28 to 91 days. Combination of rubber crumbs with recycled aggregates, with fly ash, and with both recycled aggregates and fly ash reduced strength in that order. As the amount of rubber crumbs increased the effect of recycled aggregates on strength was reduced until only the effect of fly ash could be seen at 50% rubber crumb replacement ratio. The usage of fly ash did not appear to improve bonding between the rubber crumbs and the cement matrix nor between the recycled aggregates and the cement matrix.

Increasing the amount of rubber crumbs also linearly reduced the Young’s modulus, and the effect was the same regardless of aggregate or binder type. The effect of fly ash and recycled aggregate could be seen even when increasing the amount of rubber crumbs to 50%. The JSCE standard curve was found to overestimate the Young's modulus of nearly all the experimental series.

The usage of 25% rubber crumbs could drastically reduce brittle failure under compression loading and prevent explosive destruction of the high-strength specimens. This was observed to occur both when the water-binder ratio was held constant as well as between mixes with comparable compressive strength, and also for both normal and recycled aggregates.

The effect of rubber crumbs on the air permeability coefficient depended primarily on the binder type. In the case of non-fly ash concretes, air permeability increased steadily as the amount of rubber crumbs increased, and the effect of recycled aggregates was marked and constant. For fly ash concretes increasing the rubber crumbs to 25% produced only a small change, but increasing to 50% drastically increased the air permeability. The effect of recycled aggregates was small regardless of the rubber crumb replacement ratio, and the effectiveness of fly ash for improving the air permeability of both rubber crumb and recycled aggregate concretes could be seen.

The mechanical-environmental efficiency of the mixes was calculated using an index which weighted the compressive strength by the volume of raw materials in each experimental mix. Overall, the usage of only 100% recycled aggregates had the highest efficiency, followed by the mixes with no waste materials, combining recycled aggregate with 25% rubber crumbs, and combining recycled aggregates with fly ash. Rubber crumbs were found to be an inefficient means for reducing environmental impact when using the weighted strength as an evaluation index. When comparing the weighted strengths of concretes at a target strength level, the combination of recycled aggregates and fly ash was most efficient at the 40 MPa level and the combination of recycled aggregates, fly ash, and 25% rubber crumbs was most efficient at the 30 MPa level.

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Chapter 6
Utilizing recycled fibers in fly ash mortar and concrete

6.1 INTRODUCTION

Durability is an important aspect of improving sustainability in the concrete industry, as extending the service life of infrastructure can contribute to reducing resource consumption and demolition waste, and as such a durable concrete which replaces virgin materials with industrial waste or recycled products could provide an even more sustainable option for construction materials. Fly ash, as discussed in the previous chapters, is one means for improving some durability parameters while reducing CO_2 emissions. Another means of improving durability is the utilization of fibers, which may help reduce crack formation and propagation through their crack-bridging properties. This can greatly contribute to reducing the deterioration of concrete structures due to fatigue or corrosion of reinforcing steel. The combination of high-volume fly ash and polypropylene fiber has been investigated in shotcrete applications, where it was found that satisfactory fresh and hardened properties could be achieved (Malhotra et al., 1994). Fibers made from recycled plastics have also been successfully applied in concrete (Moriwake et al., 2004). These applications demonstrate the different possibilities which exist for utilizing alternative materials to develop sustainable concrete.

In this chapter, fly ash mortar reinforced with fibers was tested for strength and durability. Various mix proportions were examined to determine the best combination at the mortar level before examining the effect of recycled aggregates. The strength characteristics of concrete reinforced with recycled fibers in both mortar and concrete was also examined and compared to polypropylene fibers. Finally, the effect of these different mix proportions on the CO_2 emissions was also calculated.

6.2 EXPERIMENTAL PROGRAM

6.2.1 Materials

Cement mortar was prepared using tap water (W), normal Portland cement (C), river sand (S), JIS type-II fly ash (FA), normal (NG) and recycled (RG) coarse aggregates, polypropylene (PP) and recycled (RF) fibers, and air entraining (AE) and super plasticizer (SP) admixtures.

The properties of the normal Portland cement are given in Section 4.3.2.1, whereas the fly ash properties are given in Table 6.1, with fly ash meeting the requirements given by JIS A 6201. The properties of the sand, normal and low-grade recycled aggregates along with the preparation of the recycled aggregates are all outlined in Table 6.2. The polypropylene fibers are shown in Figure 6.2 along with the recycled fibers, which are manufactured from recycled polyethylene terephthalate (PET), and their properties are summarized in Table 6.3.

Table 6.1 Fly ash properties

Properties		JIS A 6201 requirement	Utilized fly ash
Density	(g/cm^3)	1.95<	2.19
Specific surface area	(cm^2/g)	2500<	4040

Table 6.2 Properties of sand and coarse aggregates

Material	SSD density (g/cm^2)	Absorption (%)	Fineness modulus	Maximum size (mm)
Sand	2.62	2.09	2.74	4
Normal aggregate	2.71	0.63	6.28	20
Recycled aggregate	2.43	5.81	6.73	20

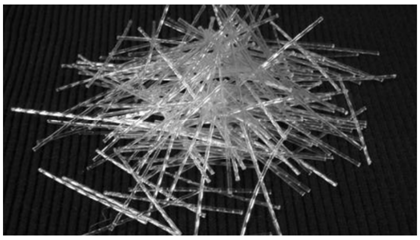

Figure 6.1 Polypropylene (left) and recycled PET (right) fibers

Table 6.3 Fiber properties

Fiber type	Dia. (mm)	Length (mm)	Density (g/cm^3)	Strength (MPa)
Polypropylene (PP)	0.75	32	0.91	-
Recycled (RF)	0.70	30	1.35	450

6.2.2 Mix proportions and fresh properties

Mortar and concrete mix proportions are given in Table 6.4. The term binder (B) is used to represent all cementitious materials – in this case, fly ash and Portland cement. All mixes used a constant water-binder ratio of 30% except the normal concrete mix, which used a water-binder ratio of 50%. To investigate the effect of sand-binder ratio, mortar with a constant fly ash-binder ratio of 30% was used with PP fibers at 2% volume, and three sand-binder ratios of 60%, 80%, and 100% were chosen. For investigating the effect of fiber type and fly ash-binder ratio, mortar mixtures containing either PP or recycled fibers at 2% volume were mixed at a constant sand-binder ratio of 80% with three fly ash-binder ratios of 30%, 50%, and 70%. The effect of recycled aggregate was investigated by holding the fly ash-binder ratio constant at 50% and varying the sand-aggregate ratio between 60% and 80%. The effect of varying fly ash with recycled aggregate was also examined by setting the sand-aggregate ratio at 60% and varying the fly ash-binder ratio between 30%, 50%, and 70%.

The fresh properties of mortar and concrete are summarized in Table 6.5. The slump flow test was conducted according to JIS A 1150; efflux time (flowability) was measured according to JSCE-F 512-1999; and air content was measured according to JIS A 1116. AE and SP were varied as necessary to maintain satisfactory fresh mortar properties.

Table 6.4 Mix proportions

<table>
<tr><th rowspan="2">Series</th><th colspan="4">(%)</th><th colspan="6">(kg/m^3)</th><th colspan="2">(% vol.)</th></tr>
<tr><th>W/B</th><th>S/B</th><th>FA/B</th><th>s/a</th><th>W</th><th>C</th><th>FA</th><th>S</th><th>NG</th><th>RG</th><th>PP</th><th>RF</th></tr>
<tr><td>FA30-SB60-M</td><td rowspan="3">30</td><td>60</td><td rowspan="3">30</td><td rowspan="3">-</td><td>298</td><td>695</td><td>298</td><td>596</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">2.0</td><td rowspan="3">-</td></tr>
<tr><td>FA30-SB80-M</td><td>80</td><td>274</td><td>639</td><td>274</td><td>731</td></tr>
<tr><td>FA30-SB100-M</td><td>100</td><td>254</td><td>593</td><td>254</td><td>847</td></tr>
<tr><td>FA30-PP-M</td><td rowspan="6">30</td><td rowspan="6">80</td><td>30</td><td rowspan="6">-</td><td>274</td><td>639</td><td>274</td><td>731</td><td rowspan="6">-</td><td rowspan="6">-</td><td rowspan="3">2.0</td><td rowspan="3">-</td></tr>
<tr><td>FA50-PP-M</td><td>50</td><td>266</td><td>443</td><td>443</td><td>709</td></tr>
<tr><td>FA70-PP-M</td><td>70</td><td>259</td><td>259</td><td>604</td><td>691</td></tr>
<tr><td>FA30-RF-M</td><td>30</td><td>274</td><td>639</td><td>274</td><td>731</td><td rowspan="3">-</td><td rowspan="3">2.0</td></tr>
<tr><td>FA50-RF-M</td><td>50</td><td>266</td><td>443</td><td>443</td><td>709</td></tr>
<tr><td>FA70-RF-M</td><td>70</td><td>259</td><td>259</td><td>604</td><td>691</td></tr>
<tr><td>FA50-sa60-NG</td><td rowspan="5">30</td><td rowspan="5">80</td><td rowspan="3">50</td><td rowspan="2">60</td><td>226</td><td>377</td><td>377</td><td>603</td><td>416</td><td>-</td><td rowspan="5">-</td><td rowspan="5">2.0</td></tr>
<tr><td>FA50-sa60-RG</td><td>226</td><td>377</td><td>377</td><td>603</td><td rowspan="4">-</td><td>373</td></tr>
<tr><td>FA50-sa80-RG</td><td>80</td><td>253</td><td>422</td><td>422</td><td>675</td><td>156</td></tr>
<tr><td>FA30-sa60-RG</td><td>30</td><td rowspan="2">60</td><td>231</td><td>539</td><td>231</td><td>616</td><td>381</td></tr>
<tr><td>FA70-sa60-RG</td><td>70</td><td>221</td><td>221</td><td>516</td><td>589</td><td>364</td></tr>
</table>

Table 6.5 Fresh properties

Series	Slump flow (mm)	Efflux time (s)	Air content (%)
FA30-SB60-M	495	6.5	-
FA30-SB80-M	495	5.7	-
FA30-SB100-M	585	5.7	-
FA30-PP-M	600	4.7	11.6
FA50-PP-M	360	10.7	12.1
FA70-PP-M	650	4.4	9.1
FA30-RF-M	595	5.5	9.9
FA50-RF-M	415	6.7	11.6
FA70-RF-M	660	4.6	8.6
FA50-sa60-NG	600	5.3	9.0
FA50-sa60-RG	570	5.4	10.0
FA50-sa80-RG	615	4.6	10.0
FA30-sa60-RG	600	5.3	10.0
FA70-sa60-RG	600	5.1	10.0

6.2.3 Mixing & casting

Mixing for specimens investigating the effect of sand-binder ratio was performed in two batches in a 25 liter mixer. Water, cement, and fly ash were mixed first, then sand was added, and finally the fibers were added gradually. Fiber mortar for investigating the effect of fiber type and fly ash-binder ratio was mixed in a 75 liter mixer in one batch. First sand, then cement and fly ash were added and mixed, then water was added. After that, the fibers were gradually added. Mixing for fiber concrete was similar to fiber mortar with the addition of coarse aggregate to sand at the beginning of mixing.

Cylinder (10Ø×20cm) and beam (10×10×40cm) specimens were cast for each concrete mix following JSCE-F 552-1999. Cylinder specimens were cast in two layers and beam specimens in one layer, with a vibrator applied to the outside of the mold after each layer was placed. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and moved to water curing. Testing was conducted 28 days after casting.

6.2.4 Mechanical performance testing

Four mechanical properties were tested experimentally. Compressive strength was measured according to JIS 1108, and flexural strength and flexural toughness were determined according to JSCe-G 552. Air permeability was measured following the procedure outlined in Section 4.3.2.4. All four properties were evaluated for mortar, whereas only compressive and flexural strength were evaluated for concrete. Reported values are the average of three specimens.

6.2.5 Environmental performance assessment

Environmental impact was evaluated using the CO_2 as outlined in Section 4.3.2.5. The mechanical-environmental efficiency was calculated using compressive and flexural strength along with the CO_2 footprint for the concrete mixes.

6.3 RESULTS

6.3.1 Effect of sand-binder ratio for mortar

Compressive strength results are shown in Figure 6.2. It can be seen that increasing the sand-binder ratio resulted in a marginal decrease in compressive strength; from 60% to 80% the compressive strength decreased 1.4 MPa, and from 80% to 100% the decrease was 4 MPa. The effect of sand-binder ratio is more pronounced for flexural strength and toughness, as shown in Figure 6.3, which shows that increasing the sand-binder ratio from 60% to 80% and from 80% to 100% resulted in flexural strength increases of 1.91 MPa and 0.54 MPa, respectively; flexural toughness increased 1.35 MPa and 0.37 MPa, respectively.

From these results, a sand-binder ratio of 80% is considered optimal, as it produces the best combination of compressive strength and flexural performance. A sand-binder ratio of 60% has slightly higher compressive strength but much lower flexural strength and toughness values, whereas a sand-binder ratio of 100% produces the highest flexural performance but with a much lower compressive strength value.

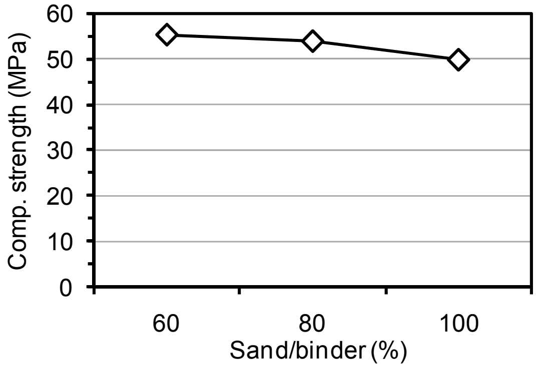

Figure 6.2 Compressive strength for variable sand-binder ratio with mortar

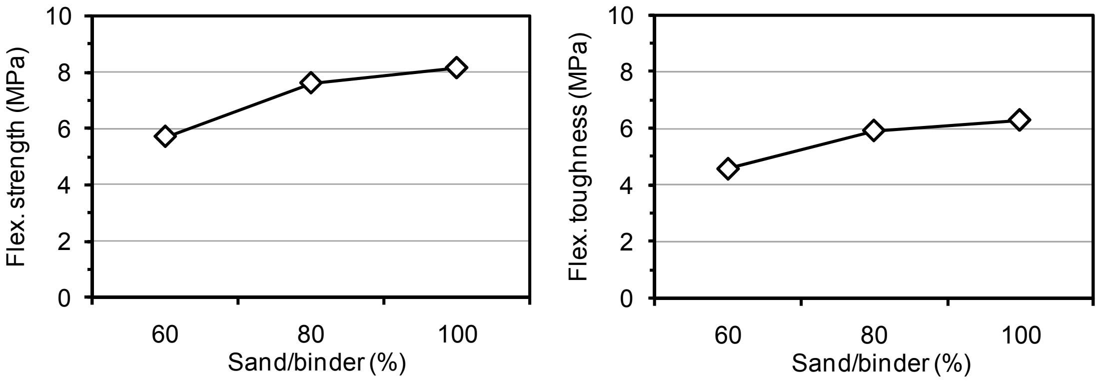

Figure 6.3 Flexural strength (left) and flexural toughness (right)
for variable sand-binder ratio with mortar

6.3.2 Effect of fly ash-binder ratio for mortar and concrete

Compressive strength results are shown in Figure 6.4, where it can be seen that the compressive strength decreases constantly for increasing fly ash-binder ratio; from 30% to 50% the compressive strength decreased by 12 MPa and 14.1 MPa for PP and recycled fibers, respectively, and from 50% to 70% it decreased by 14.4 MPa and 15.1 MPa for PP and recycled fibers, respectively. The effect of fly ash-binder ratio on flexural performance was different from that on compressive strength at higher ratio values, as seen in Figure 6.5. An increase in fly ash-binder ratio from 30% to 50% was accompanied by a 2.73 MPa and 1.41 MPa decrease in flexural strength for PP and recycled fiber specimens, respectively, and by a 2.01 MPa and 0.98 MPa decrease in flexural toughness for PP and recycled fiber specimens, respectively. However, increasing the fly ash-binder ratio from 50% to 70% resulted in a much smaller decrease of 0.33 MPa and a small increase of 0.30 MPa in flexural strength of PP and recycled fiber specimens, respectively, as well as small decreases of 0.17 MPa and 0.36 MPa in flexural toughness of PP and recycled fiber specimens, respectively.

For the air permeability results in Figure 6.6, the effect of higher fly ash-binder ratio is more apparent, as the air permeability increased 10.74×10-12 m/s for PP and 6.84×10-12 m/s for recycled fibers from 50% to 70%. In contrast, the change in air permeability was much lower when increasing from 30% to 50% - 0.07×10-12 m/s and 1.15×10-12 m/s decreases for PP and recycled fibers, respectively.

From these results, it can be seen that a higher volume of fly ash results in decreased strength and durability characteristics. However, it is important to note that these tests have been performed after 28 days of curing. While the behavior of plain cement mortar at 28 days can be assumed to be reflective of its overall behavior, fly ash requires a much longer curing period in order to realize its performance benefits. Since the fly ash reaction is delayed, the amount of cementitious reaction which has occurred by 28 days will be far less for mortars containing higher volumes of fly ash. This effect can be clearly seen in the air permeability results, as there is a sharp increase in air permeability when increasing the fly ash-binder ratio to 70%.

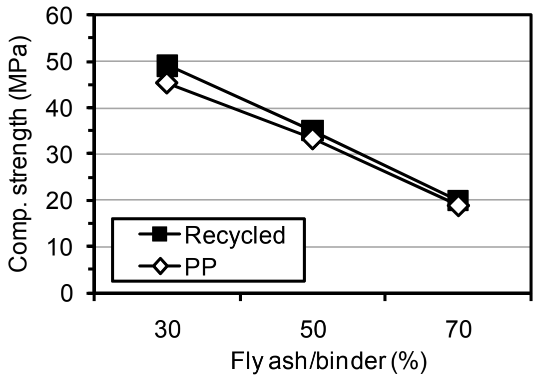

Figure 6.4 Compressive strength for variable fly ash-binder ratio with mortar

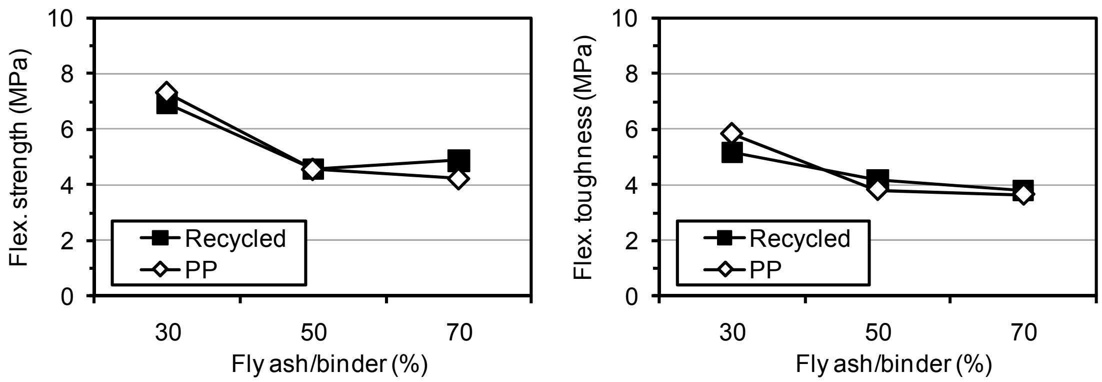

Figure 6.5 Flexural strength (left) and flexural toughness (right)
for variable fly ash-binder ratio with mortar

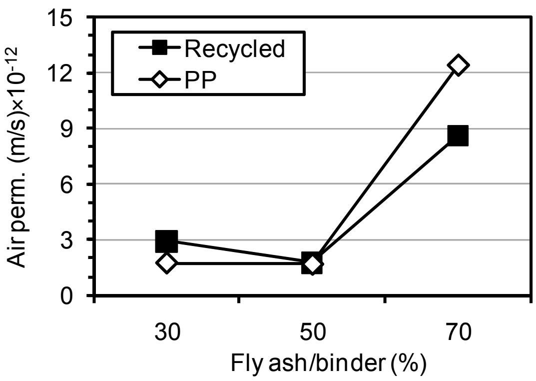

Figure 6.6 Air permeability for variable fly ash-binder ratio with mortar

The fly ash-binder ratio also has a large effect on the mechanical performance of recycled aggregate concrete, as shown in Figures 6.7. Increasing the fly ash-binder ratio results in a consistent decrease in compressive and flexural strength, although the effect is more pronounced for compressive strength. This reduction can be explained by the slower reaction speed of fly ash in concrete, which results in slower strength development.

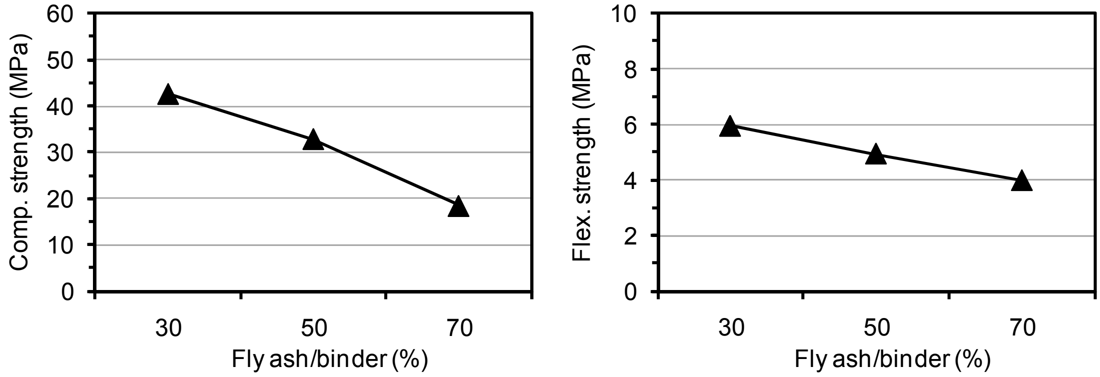

Figure 6.7 Compressive strength (left) and flexural strength (right) for variable fly ash-binder ratio with concrete with recycled aggregate

6.3.3 Effect of fiber type for mortar

Both PP and recycled fiber results are shown in Figures 6.4 through 6.6. From these figures, and as discussed above, it can be seen that fiber type does not have a significant effect on any of the strength properties measured. In the case of durability, it is difficult to interpret the air permeability results at this time due to the delayed reaction of fly ash, but as air permeability typically evaluates the cement paste, no significant difference is expected to occur.

6.3.4 Effect of sand-aggregate ratio and recycled aggregate for concrete

Compressive and flexural strength results are shown in Figure 6.8 for variable aggregate volume. It can be seen that increasing the volume of aggregates does not significantly affect the compressive or flexural strength. At the 15% aggregate volume, replacing the recycled aggregates with normal aggregates causes a slight increase in both compressive and flexural strength.

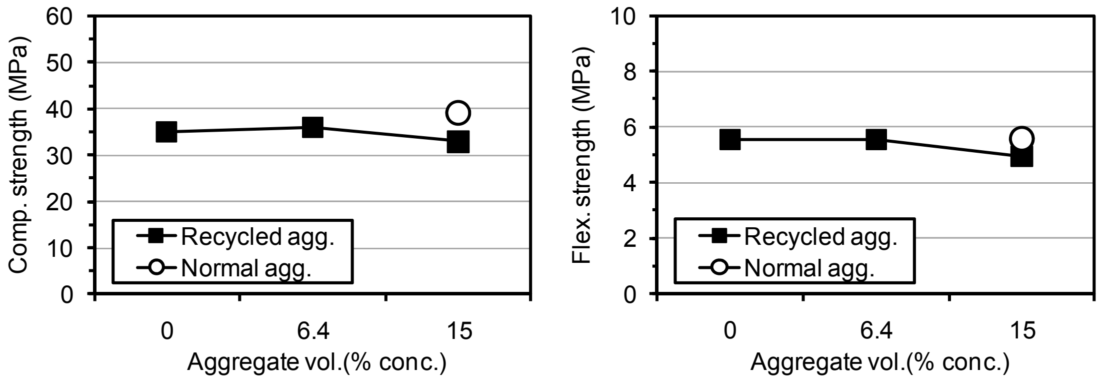

Figure 6.8 Compressive strength (left) and flexural strength (right) for variable aggregate volume with normal and recycled aggregate

6.3.5 Environmental impact for mortar and concrete

The CO_2 footprints for the mortar and concrete series are shown in Figures 6.9 and 6.10, respectively. For the mortar, the total CO_2 of the mixes decreases significantly when replacing cement with fly ash, with the FA70-PP/RF-M mixes releasing just less than 40% of the FA30-SB60-M mix. For the concrete mixes, a similar trend can be seen that the highest CO_2 emissions are produced by the concrete which contains only 30% fly ash replacement, whereas the lowest CO_2 emissions are produced by the concrete with 70% fly ash replacement. There is little difference between normal and recycled aggregates as the mix proportions are similar and the aggregates themselves have similar emissions values. Increasing the volume of aggregates produces a slight reduction in emissions. The value of fly ash replacement for reducing CO_2 is therefore clear, as a large savings in emissions can be realized by replacing the largest emitter of GHG with another material with a much smaller impact.

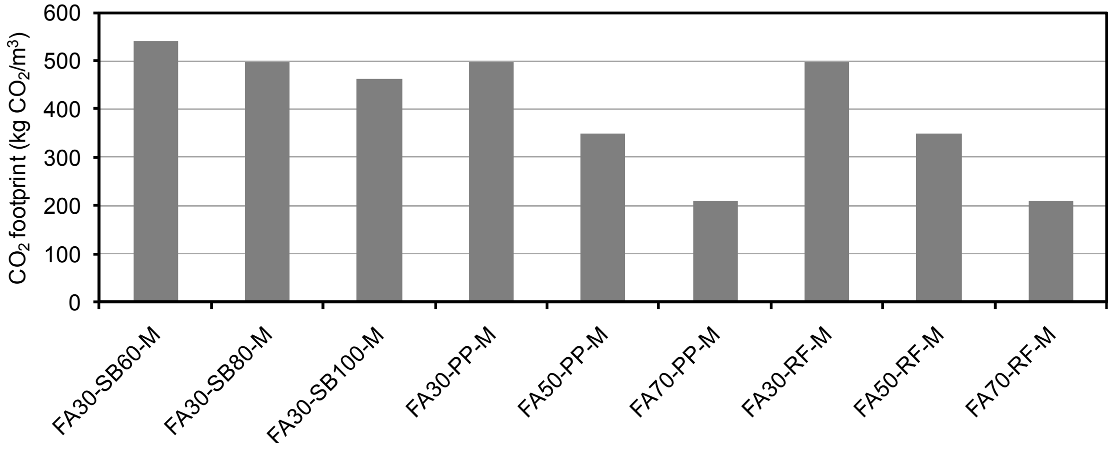

Figure 6.9 CO_2 footprint for mortar

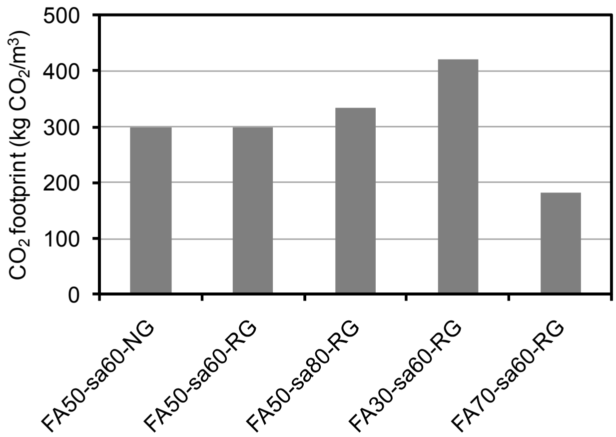

Figure 6.10 CO_2 footprint for concrete

Environmental performance indicators considering the compressive and flexural strength and the CO_2 footprint were calculated for the concrete series only and the results are shown in Figure 6.11 for variable aggregate volume and Figure 6.12 for variable fly ash-binder ratio. For variable aggregate volume and type, the slightly downward trends displayed by the mechanical behavior became slightly upward trends when normalized by the environmental impact. This is due to the slight decrease in CO_2 emissions as aggregate volume increased. Normal aggregate concrete displayed the highest normalized environmental performance. For variable fly ash-binder ratio, the environmental indicators show that the low emissions of higher volume fly ash concretes can significantly change the trend showed by the mechanical performance alone, particularly in the case of flexural strength.

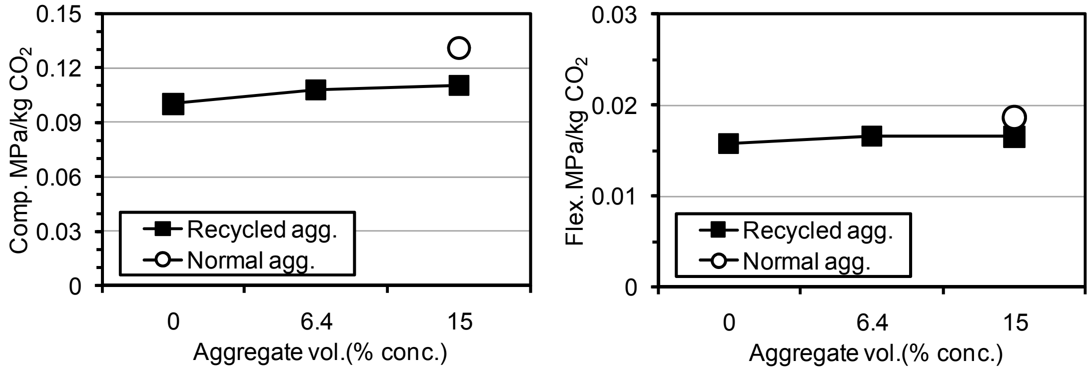

Figure 6.11 Environmental performance indicators for compressive strength (left) and flexural strength (right) by variable aggregate volume

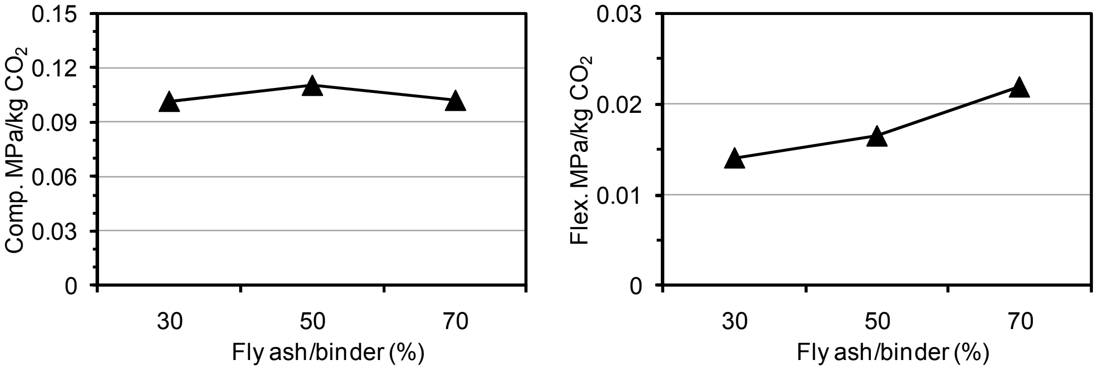

Figure 6.12 Environmental performance indicators for compressive strength (left) and flexural strength (right) by fly ash-binder ratio

6.4 SUMMARY

The following conclusions were made based on the results of this experimental investigation:

For the mortar series mixes, a sand-binder ratio of 80% provided the best balance between compressive and flexural behavior. Decreasing the sand-binder ratio produced slightly higher compressive strength but lower flexural strength, whereas increasing the sand-binder ratio reduced compressive strength but slightly increased flexural strength. Increasing the fly ash-binder ratio from 30% to 70% resulted in lower strength and durability properties. While the compressive strength decreased constantly, the flexural strength only slightly decreased when changing from 50% to 70%. Conversely, air permeability underwent a huge increase when moving from 50% to 70%. The decreased performance of higher-volume fly ash mortars may be attributed to the slow reaction speed of fly ash, which requires longer curing before full performance can be achieved. There was no observed significant difference in the performance between polypropylene and recycled fiber-reinforced mortars.

When considering the environmental impact of the mortar mixes, Portland cement is the primary contributor of CO_2 emissions in the mortar mixes. While replacing cement with fly ash at a fly ash-binder ratio up to 70% does not decrease the fraction contribution of cement, it can help reduce total CO_2 emission of the mortar mixture by over 60%. At this time it is difficult to fully determine the contribution of recycled materials such as recycled fibers to CO_2 emissions or other environmental measurements. However, the usage of such materials has an inherent positive benefit to society, so appropriate methods for evaluating this benefit need to be developed.

For the concrete mixes, environmental performance indicators were used to normalize the mechanical performance by considering the environmental impact of concrete materials. It was found that these indicators could reverse the trends shown by the mechanical performance alone, particularly in the case of high volume fly ash concretes, which develop strength more slowly than normal concrete but have significantly lower CO_2 emissions. The concrete with the highest environmental indicator for compressive strength had a fly ash-binder ratio of 50% and normal aggregates. The advantage of utilizing recycled aggregates is difficult to see in this case since recycled aggregates have the same CO_2 emissions as normal aggregates, but generally lower performance. The concrete with the highest environmental indicator for flexural strength had a fly ash-binder ratio of 70% and 100% replacement of normal aggregates with recycled aggregates. This value was driven by the extremely low CO_2 emissions achieved by replacing high volume of Portland cement with fly ash.

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