Development of High-Performance Green Concrete using Demolition and Industrial Wastes for Sustainable Construction

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Abstract: Growth of population, increasing urbanization and industrialization contributed to fast consumption of available natural resources and generation of considerable amount of wastes. The recycling of wastes in concrete industry will lead to greener and sustainable concrete, unless they are proven harmful by testing. This study was conducted to investigate the feasibility of recycling air-cooled slag (ACS) as a substitute of natural coarse aggregate on the strength and durability of high performance concrete containing natural aggregates or a blend of natural aggregates and recycled concrete aggregate (RCA) as a new approach to massively recycle these wastes for sustainable construction. The durability of concrete was evaluated by assessing abrasion resistance, water permeability, behavior of concrete after exposure to wetting and drying cycles, resistance to sulfate attack, and alkali-aggregate reaction. The results indicated that it is feasible to produce high performance concrete with satisfactory properties by using recycled aggregates and supplementary cementing material. ACS can be recycled successfully as a coarse aggregate in high performance concrete as it offers an approach to solve the problems arising from its disposal; in the meantime modified properties are added to the concrete. In general, concrete containing ACS had better performance compared to concrete entirely made with natural aggregates. Furthermore, the use of ACS is particularly beneficial for concrete containing RCA as it attenuated the negative impacts of RCA on concrete strength and durability without the need to increase the cement content.

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1. Introduction

Concrete is one of the most widely used construction materials in the world. Annually, concrete industry is consuming about 1.6 billion tons of cement, 10 billion tons of aggregates, and 1 billion tons of mixing water in addition to water used for washing aggregate and concrete trucks, and also for curing concrete. It is evident that among the manufacturing industries worldwide, concrete industry is considered the largest consumer of natural resources. At the same time it generates huge amounts of construction and demolition (C&D) wastes which are conventionally disposed to landfill leading to severe environmental problems. Reportedly, over 1 billion tons of C&D wastes are generated every year. Furthermore, the production of cement is not only energy-intensive, but is also responsible for large emissions of carbon dioxide (CO_2) "a greenhouse gas" leading to global warming. Thus, concrete industry is neither environmentally friendly nor compatible with the demands of sustainable development. It is expected that by the year 2050, the demand for concrete will grow from 10 to 18 billion tons a year. Thus, it is urgent to implement life cycle and sustainable engineering approaches in concrete industry. Sustainable development will happen by pursuing the principles of resource efficiency, saving of energy and enhancement of concrete durability. The resource efficiency principle can be implemented by substituting Portland cement, natural aggregates and fresh water with recycled wastes to produce a "green" concrete. Furthermore, supplementary cementing materials such as fly ash, silica fume, rice husk ash and metakaolin can be used as partial replacements of cement for enhancing concrete durability and lengthening its service life, thereby reducing the rate of concrete consumption (**Mehta, 1999; Mehta, 2002; Naik and Moriconi, 2005; Deshpande *et al.*, 2011**).

The recycling of wastes in concrete has become more and more popular in recent years, as it can lead to environmental benefits (i.e., conservation of natural resources, saving of energy, reducing the demand of land for waste disposal and reducing the pollution). Extensive research work was carried out to recycle crushed concrete as a substitute of natural aggregate in new concrete. However, the limited use of recycled concrete aggregate (RCA) in structural concrete is due to its inherent deficiency. In comparison with natural aggregate, RCA is weaker, more porous and has higher water absorption. It has a negative influence on most hardened and durability concrete properties particularly for higher strength concrete and this influence is strongly dependent on the quality and percentage of RCA in concrete (**Kumutha and Vijai, 2010**). **Corinaldesi, 2011,** reported that the substitution of 30% natural coarse aggregate with RCA in structural concrete reduced the compressive strength by 20%, regardless of cement type, while **Kumutha and Vijai, 2010**, found that the compressive strength of concrete, designed for a target compressive strength of 20 MPa, decreased by 3.6% and 28% for 20% and 100% replacement of coarse aggregate by RCA, respectively compared to concrete containing natural aggregates. It was also reported that the splitting tensile strength, flexural strength and modulus of elasticity decreased by 36%, 50% and 18% for 100% replacement of natural aggregates by RCA, respectively (**Kumutha and Vijai, 2010**). Furthermore, for equal compressive strength of concrete, the shrinkage and creep increase with increasing the content of coarse RCA in the mix. This is due to the lower RCA modulus and the presence of attached cement paste (**Mandal and Chakraborty, 2002; Limbachiya *et al.*, 2007**). The chloride conductivity and water sorptivity of RCA concrete are significantly higher than those of natural aggregate concrete. **Olorunsogo and Padayachee, 2002,** reported that the chloride conductivity and water sorptivity increased by 73.2% and 38.5%, respectively for concrete containing 100% coarse RCA.

On the other hand, in Egypt, various and significant quantities of industrial by-products are generated every day causing environmental and health impacts. Slag is a good example for these by-products as huge quantities of slag is generated as a by-product from steel industry. When it is allowed to cool slowly under atmospheric conditions, it solidifies to a crystalline material, known as air-cooled slag (ACS) (**Galal *et al.*, 2004; Demirboğa and Gül, 2006**). ACS is not a cementitious materials but it can be used after screening as aggregate for road construction (**Slag Cement Association, 2003; Galal *et al.*, 2004; Kalalagh *et al.*, 2005; Demirboğa and Gül, 2006; Australasian Slag Association, 2011).** The asphalt mixes containing ACS aggregate have the following advantages: good binding property, impermeability to humidity and high stripping, skid and rutting resistance (**Kalalagh *et al.*, 2005**). **Kalalagh *et al.*, 2005,** recommended the use of at least 50% of ACS aggregate in asphalt mixes for heavy traffic roads. However, today in Egypt very little quantity of ACS is used in road construction and the majority is dumped in slag storing yards regardless of its premium physical and mechanical properties compared to natural aggregate. Moreover, there are rare researches regarding the utilization of ACS aggregate in concrete although it was reported that the inclusion of ACS as coarse aggregate improves the hardened concrete properties such as compressive and splitting tensile strengths, modulus of elasticity and drying shrinkage (**Demirboğa and Gül, 2006; Australasian Slag Association, 2011**). Thus, the objective of this paper is to investigate the effect of recycling ACS as coarse aggregate on the properties of high performance concrete containing natural aggregates or a blend of natural aggregates and RCA as a new approach to massively recycle these wastes for sustainable construction. Compressive strength, microstructure and durability-related properties (i.e., abrasion resistance, permeability, behavior after exposure to repeated cycles of wetting and drying, resistance to sulfate attack, and alkali-aggregate reaction) of concrete were determined.

2. Materials and Methods

2.1. Materials

The used cement was CEM-I 42.5 N Portland cement complying with Egyptian Standard Specifications ES 2421/2005. Silica fume was used as a supplementary cementing material. The chemical composition and physical properties of cement and silica fume are summarized in Table 1. A superplasticizer admixture compatible with ASTM C494 Type F was added to concrete mixes. The natural coarse aggregate (NA) was crushed basalt with nominal maximum size of 20 mm, and the fine aggregate was local sand. Two types of recycled aggregates namely; recycled concrete aggregate (RCA) and air-cooled slag (ACS), were used as coarse aggregates. RCA was obtained from crushing of old concrete cubes after testing, while ACS was obtained as a by-product from Iron and Steel Company at Helwan, Egypt. Either RCA and ACS were separated by manual sieving into various size fractions and then were recombined to obtain the appropriate gradation according to Egyptian Standard Specifications ES 2421/2002 for coarse aggregate of size 5-20 mm and the size fractions <5 mm were rejected. Fig. 1 shows the used wastes before processing, while Figs. 2 and 3 show the appearance of the produced recycled aggregates and their morphological features, respectively. It should be noted that RCA is a piece of concrete composed of original coarse aggregate and attached mortar (Fig. 3a). Thus, it may contain microcracks and fissures resulted from the crushing process of old concrete. These microcracks and fissures may be generated in three different locations; in the original aggregate, in the attached mortar and/or at the interface between them. Fig. 3b demonstrates the extensive cracking in the attached mortar in RCA. Fig. 3c shows that ACS had different texture and morphology from RCA as it is vesicular and contains unconnected voids. The properties of the used aggregates are shown in Table 2. The results showed that RCA had lower specific gravity than natural aggregate, while its water absorption was several times higher than that of natural coarse aggregate. Similar findings were reported by **Limbachiya *et al.*, 2007,** that coarse RCA had 7 to 9 % lower saturated surface dry density and two times higher water absorption than gravel. This is due to the presence of attached mortar in RCA with low density and high water absorption in addition to the microcracks and fissures generated in RAC as illustrated previously (**Limbachiya *et al.*, 2007; Deshpande *et al.*, 2011**). On the other hand, the properties of ACS were comparable to those of natural coarse aggregate. Both RCA and ACS were superior to natural aggregate in magnesium sulfate soundness test which can be used as a measure of their durability. Therefore, ACS can be considered as a high quality aggregate with properties comparable to those of natural aggregate and better microstructure compared to RCA.

Table 1. Properties of Portland Cement and Silica Fume

Component/property		Cement	Silica fume
Chemical composition (%)			
SiO_2		21.0	96.39
Al_2O_3		6.1	0.65
Fe_2O_3		3.0	0.33
CaO		61.5	0.62
MgO		2.1	0.04
K_2O		0.3	0.37
SO_3		2.5	0.05
Na_2O		—	0.2
Loss on ignition		2.4	1.34
Insoluble residue		0.9	—
Physical and mechanical properties			
Specific gravity		3.15	2.15
Specific surface area (cm^2/g)		3,550	264,500
Strength activity index (%)		—	116
Setting time (min.)	Initial	135	—
	Final	195	—
Soundness (mm)		1	—
Compressive strength (MPa)	2-days	26.2	—
	28-days	48.6	—

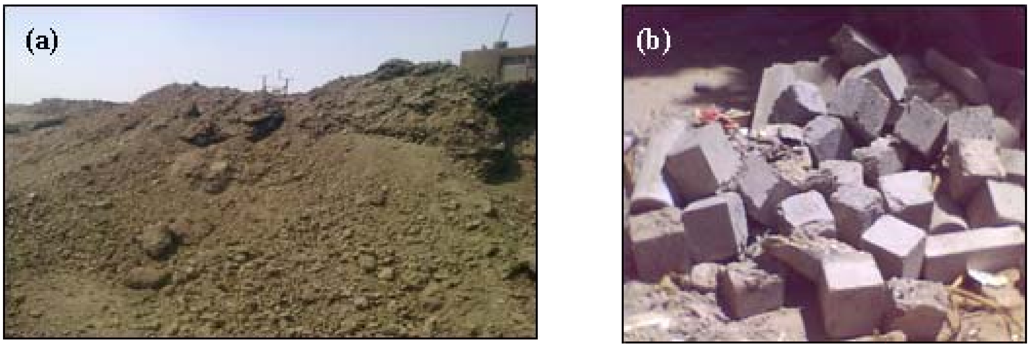

Figure 1. Wastes before Processing (a) Air-Cooled Slag and (b) Concrete Cubes

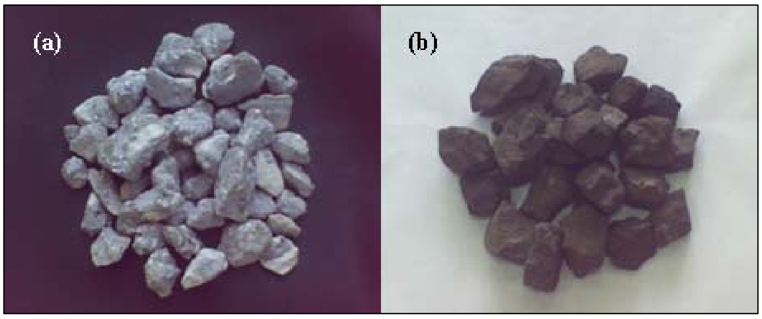

Figure 2. Recycled Aggregates Appearance (a) RCA and (b) ACS

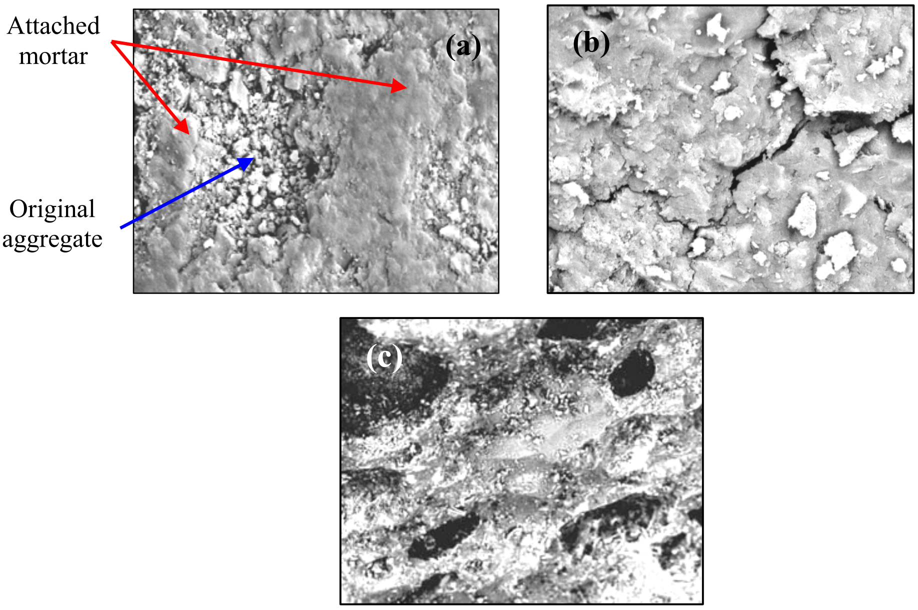

Figure 3. Microstructure of Recycled Aggregates: (a) A General View of RCA (800x), (b) Attached Mortar in RCA (650x) and (c) A General View of ACS (600x)

Table 2. Basic Properties of Aggregates

Property	Coarse aggregate			Limits for coarse aggregate	Fine aggregate	Limits for fine aggregate
	NA	RCA	ACS			
Specific gravity	2.73	2.41	2.66	—	2.5	—
Unit weight (t/m^3)	1.57	1.37	1.62	—	1.62	—
Absorption (%)	1.07	4.49	1.76	≤ 2.5**	—	—
Clay and fine materials (%)	0.12	—	—	≤ 4*	1.4	≤ 4*
Impact index (%)	14.4	19.3	12.4	≤ 45*	—	—
Flakiness index (%)	15.1	18.7	8.71	≤ 25**	—	—
Elongation index (%)	13.63	9.20	11.79	≤ 25**	—	—
Abrasion resistance (%)	18.01	26.40	15.33	≤ 30*	—	—
MgSO$_4$ soundness (%)	4.80	3.01	2.39	≤ 18*	—	—

* According to the Egyptian Standard Specifications ES 1109/2002

** According to the Egyptian Code of Practice, 2007

2.2. Concrete Mixes

This research program was divided in two phases: the first phase was carried out to select the highest possible substitution percentage of each type of recycled aggregate based on the compressive strength of concrete, while the second part was conducted to investigate the effect of recycled aggregates on the strength and durability of high performance concrete.

In the first phase, two series of concrete mixes were prepared. In each series, natural coarse aggregate was replaced by 0%, 25%, 50%, 75%, and 100% RCA or ACS. The control mix was designed using absolute volume method, with a cement content of 400 kg/m^3, sand-to-total aggregate ratio of 40%. Both recycled and natural coarse aggregates were used in a saturated surface dry condition to avoid the effect of water absorption of coarse aggregate during mixing and, consequently, to assess the real effect of recycled coarse aggregate on concrete behavior. The fine aggregate was used at the as received moisture condition. The mixing water was adjusted to maintain a slump of 10±2 cm.

In the second phase, a new series of high performance concrete mixes with compressive strength in excess of 50 MPa was prepared using the same mix design procedure used in the previous phase. All mixes had a constant water to cementitious ratio of 0.35 and a superplasticizer was used to maintain a constant slump of 10±2 cm. Five mixes were prepared as follows: a control mix made with 100% natural aggregates (mix M1), concrete mixes M2 and M3 included the highest possible substitution ratio of RCA and ACS (i.e., 25% and 100% by weight of coarse aggregate) respectively, based on the results from Phase I. Mix M4 contained a blend RCA and ACS replacing 50% of natural coarse aggregate. The ratio between RCA and ACS in mix M4 was 1:1 (by weight). Mix M5 had the same ingredients of mix M4 in addition to using 10% silica fume as a partial replacement of cement to study the effect of using a supplementary cementing material on the behavior of concrete containing a blend of recycled and natural aggregates. Table 3 shows the proportions of concrete mixes. It should be mentioned that the amount of superplasticizer was increased by using recycled aggregates regardless of recycled aggregate type, although the coarse aggregates were used in a saturated surface dry condition. This increase may be due to the texture and shape of the used recycled aggregates (i.e., RCA or ACS) compared to natural coarse aggregate as the particles of the used recycled aggregates are rougher and angular than natural coarse aggregate and ACS has sharp edges and vesicular surface that forced the introduction of more water to compensate a higher particles friction (**Abou-Zeid, 2002**; **Timms, 2005**).

Table 3. Proportions of Concrete Mixes

Mix ID	Coarse aggregate type	Concrete ingredients, kg/m^3							
		Cement	Silica fume	Water	Fine aggregate	Coarse aggregate			SP, l/m^3
						NA	RCA	ACS	
M1	100%NA	400	—	140	772	1158	—	—	7.2
M2	75%NA+ 25%RCA	400	—	140	757	852	284	—	10.4
M3	100%ACS	400	—	140	760	—	—	1141	13.6
M4	50%NA+ 25%RCA+ 25%ACS	400	—	140	755	566	283	283	11.1
M5	50%NA+ 25%RCA+ 25%ACS	360	40	140	736	552	276	276	13.2

2.3. Casting, Curing and Testing

After the slump test, the specimens were cast and hand compacted. The specimens were kept in laboratory conditions for 24 hrs and then they were demoulded and cured in water. After 28 days of curing, the specimens were tested according to the following procedures, taking into account that each reading is the average of three specimens:

Compressive Strength:

This test was conducted according to European Standard EN 2390-3/2001 using 100 mm cubic specimens. The test was carried out using a 2000 kN compression testing machine and a loading rate of 0.6 MPa/s.

Abrasion Test:

This test was carried out using 70 x 70 x 30 mm specimens according to Egyptian Standard Specifications ES 269/2005 and the loss in thickness of each specimen due to surface abrasion was calculated.

Permeability Test:

This test was carried out on cylinders of 150 mm diameter and 150 mm length using "Automatic Concrete Water Permeability Apparatus". The specimens were coated on all surfaces except the top and bottom surfaces, to ensure one dimensional water flow, and subjected to hydrostatic pressure. The amount of water passing through the specimen thickness in a given time was measured and the coefficient of water permeability was determined from Darcy's law.

Sulfate Attack:

Resistance to sulfate attack was determined by immersing concrete cubes, after 28-days of water curing, in 5% magnesium sulfate solution for 12 months and determining the reduction in compressive strength due to sulfate attack every three months. The solution was replaced with a fresh one every month. The reduction in compressive strength is the ratio between the strength of specimens exposed to sulfate solution and the strength of specimens cured in tap water.

Wetting and Drying Test:

This test was conducted using 100 mm cubic specimens. The specimens were subjected to wetting and drying cycles as follows: a full 24-hrs cycle consists of immersion in potable water for 16 hrs, followed by oven-drying at 60 °C for 8 hrs. After 30 cycles, the specimens were visually inspected and the change in weight and compressive strength were determined relative to the initial values before exposure to the cycles.

Alkali-Aggregate Reaction Test:

This test was performed according to ASTM C1260 using three 25 x 25 x 275 mm mortar bars cast from each mix. After demolding, the specimens were preconditioned in water at 80±2°C for 24 h. After measuring the initial lengths of the specimens, the mortar bars were immersed in 1N NaOH solution maintained at 80±2°C for 14 days and the lengths of the specimens were recorded during immersion in the solution.

Scanning Electron Microscope (SEM) Test:

This test was conducted to investigate the effect of using silica fume on the microstructure of concrete. The microstructure of the selected specimens was observed using samples with a size of 10 x 10 x 10 mm cut from the concrete.

3. Results and Discussions

3.1 Phase I: Selection of the Optimum Percentage of Recycled Aggregates

The 28-days compressive strength of concrete mixes containing either RCA or ACS as a function of replacement percentage of coarse aggregate is shown in Fig. 4. The compressive strength of concrete series containing RCA decreased with increasing the replacement percentage of coarse aggregate. The compressive strength decreased by about 3% for 25% replacement percentage of coarse aggregate compared to the control mix, while the reduction was about 15% for 100% replacement percentage. **Pani *et al.*, 2011**, found that the reduction in compressive strength was 5% and 21%, for 20% and 100% replacement percentage, respectively. The reduction in the strength is due to the inferior mechanical properties of RCA compared to natural coarse aggregate and the presence of weaker bond areas between RCA particles and mortar (**Mandal and Chakraborty, 2002; Pani *et al.*, 2011**).

On the contrary, the compressive strength of concrete containing ACS increased with increasing the replacement percentage of coarse aggregate by ACS. The compressive strength increased by about 18% for 100% replacement percentage of coarse aggregate. **Demirboğa and Gül, 2006**, found that coarse blast furnace slag aggregate (BFSA) can be utilized in making high strength concretes as the compressive strength of BFSA concretes were approximately 60–80% higher than control concretes for different w/c ratios and the compressive strength of BFSA concrete at 0.5 w/c ratio was nearly equal to that of the control concrete at 0.3 w/c ratio. From the above, it can be concluded that the optimum percentage of RCA is 25% which had a slight effect on the compressive strength of concrete, while ACS can be used to entirely replace coarse aggregate.

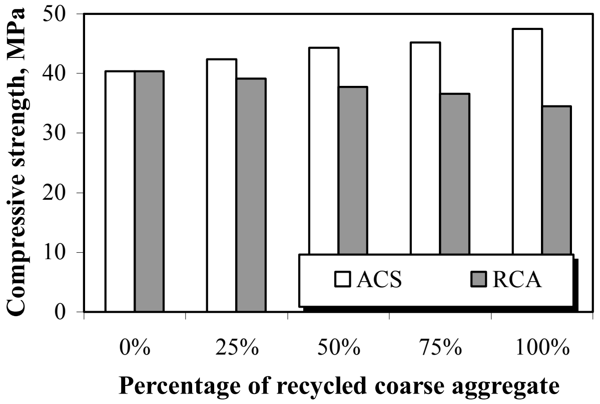

Figure 4. Effect of Recycled Aggregate Type on Compressive Strength

3.2 Phase II: The Behavior of Recycled Concrete Mixes

3.2.1 Compressive Strength

The compressive strength of concrete mixes is shown in Table 4. The compressive strength of concrete mix M2 (containing 25% RCA) was slightly lower than that of the control concrete, while the compressive strength of mix M3 (containing 100% ACS) was significantly higher than that of the control concrete. The compressive strength of mix M4 (containing a blend of RCA and ACS) was slightly higher than that of the control concrete. Thus, the use of ACS as coarse aggregate increases the compressive strength of concrete, while the use of RCA decreases the compressive strength of concrete. Furthermore, the use of ACS in combination with RCA eliminates the negative impact of RCA on concrete strength and offers a benefit of producing recycled concrete containing 50% of recycled coarse aggregates with comparable compressive strength to that of the control concrete without increasing the cement content. Concrete mix M5 (containing 10% silica fume) showed the highest compressive strength among all mixes and it had 25% higher compressive strength compared to the control concrete. This is due to the physical and chemical effects of silica fume as the silica fume with high fineness and high silica content provides a filler effect and a pozzolanic reaction, causing pore refinement and replacing the weaker component (i.e., calcium hydroxide "CH") with a stronger one (i.e., calcium silicate hydrate "C-S-H") (**Sabir, 1997; Zain *et al.,* 2000**). Thus, silica fume can be utilized beneficially as a supplementary cementing material to improve the performance of concrete containing a blend of recycled aggregates.

Table 4. Hardened Concrete Properties

Mix ID	Coarse aggregate type	Compressive strength, MPa	Average loss of thickness due to abrasion, mm	Permeability coefficient, cm/s
M1	100%NA	56.2	0.72	3.54
M2	75%NA+ 25%RCA	55.4	0.71	4.10
M3	100%ACS	64.1	0.61	3.88
M4	50%NA+ 25%RCA+ 25%ACS	56.8	0.67	3.96
M5	50%NA+ 25%RCA+ 25%ACS	70.3	0.26	3.05

3.2.2 Concrete Microstructure

The mechanical behavior and durability of concrete are thought to be affected by the microstructure of the concrete. At the macroscopic level, concrete is considered as a two-phase material, consisting of aggregate particles of varying sizes and shapes dispersed in a binding medium, which consists of an incoherent mass of the hydrated cement paste. At the microscopic level, there is a third phase, the interfacial transition zone (ITZ), which represents the interfacial region between the particles of coarse aggregate and the hydrated cement paste. The interfacial zone is generally weaker than either of the two main components of concrete. Thus, it has a significant effect on the performance of concrete.

As illustrated previously that RCA particle is composed of original coarse aggregate and attached mortar. Thus, the microstructure of the concrete containing RCA is more complicated than that of the conventional concrete. Concrete containing coarse RCA possesses two interfacial transition zones; one between original coarse aggregate and the old attached mortar (old ITZ) and the other one between RCA and new mortar matrix (new ITZ), while conventional concrete has only one type of ITZ between natural aggregate and mortar matrix. Thus, two concrete mixes were selected for examination under microscope; mix M4 and mix M5, in order to investigate the effect of using silica fume on the ITZ of concrete especially that containing RCA.

The ITZ of mixes M4 and M5 is shown in Fig. 5. It can be observed that incorporation of silica fume results in a drastic change in the microstructure of the concrete. The SEM micrographs clearly show the positive effect of silica fume. It enhances the compressive strength of concrete by developing a stronger and denser ITZ in concrete compared to the poorer ITZ for mix M4 (without silica fume). The thickness of the ITZ between RCA and mortar in mix M4 was much greater than that in mix M5 (Fig. 5a) which generates a weak bond between coarse aggregate and mortar matrix. This is probably due to the high water consumed by RCA to compensate its high absorption. This high water content may cause internal bleeding under the aggregate surface leading to the formation of voids in the vicinity of RCA and thus porous ITZ will be formed. On the other hand, the ITZ between RCA and new mortar in concrete mix M5 containing silica fume cannot be distinguished easily (Fig. 5b). This is due to filler effect and pozzolanic activity of silica fume as it acts as a microfiller, filling the ITZ and the microcracks formed on RCA surface, followed by the pozzolanic reaction to form additional C-S-H which improves the aggregate-matrix bond associated with the formation of a strengthened and less porous transition zone.

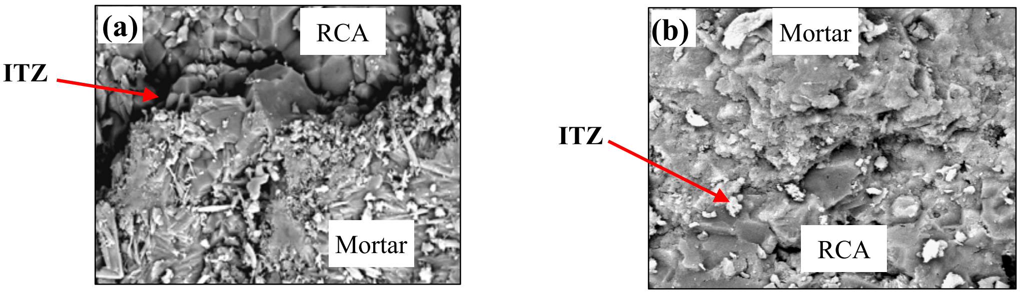

Figure 5. ITZ between RCA and New Mortar in Mixes M4 (Left) and M5 (Right) (1500x)

3.2.3 Concrete Durability

Durability of concrete is defined as "Its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration", and hence to retain its original shape, dimension, quality and serviceability in the working environment during its anticipated service life (**ACI 201.2R-01, 2001**). Durable concrete should sustain the physical and chemical causes affecting its performance adversely.

Abrasion Resistance

Deterioration of concrete surface may be caused by forms of wear due to various exposures such as erosion and abrasion. Abrasion is the wearing due to repeated rubbing and friction of objects on concrete surface. Abrasion resistance of concrete is of crucial importance in pavements, floors, and hydraulic structures. Excessive abrasion leads to an increase in accidents as the floor becomes polished reducing its skid resistance. Therefore, abrasion resistance of concrete should be known when it is used in places that are exposed to wear.

The average loss of thickness of concrete mixes due to abrasion is shown in Table 4. In general, the abrasion resistance of concrete containing ACS, RCA or a combination of them as coarse aggregate was higher than that of the control concrete entirely made with natural aggregate. The average loss of thickness of concrete mixes M2, M3, and M4 decreased by 1.11%, 15.28%, and 6.94%, respectively compared to mix M1. **Limbachiya *et al.*, 2007**, reported that concrete containing coarse RCA shows a satisfactory performance to abrasion resistance, irrespective of RCA content, provided that the concrete mixes are of similar design strengths. It should be mentioned that the enhancement in the abrasion resistance by using RCA as coarse aggregate was trivial compared to ACS, indicating the superior behavior of ACS compared to RCA. Furthermore, the abrasion resistance of concrete mix M5 (containing 10% silica fume) was significantly higher than that of the control concrete. Hence, the use of ACS, RCA or a blend of them as coarse aggregate as well as using of silica fume as a supplementary cementing material is beneficial in enhancing the abrasion resistance of concrete.

Permeability

The transport of deleterious agents can occur through permeability of gas, air, liquid or water. Nevertheless, the transport properties are key indicators of the durability of concrete, and therefore they relate to the risk of acid, chloride and sulfate attacks, alkali-aggregate reaction, and freeze-thaw deterioration. Table 4 demonstrates the permeability coefficient of concrete mixes. The permeability of mixes M2 to M4 was higher than that of the control concrete. Among these mixes, concrete mix M2 (containing 25% RCA) had the highest permeability, while mix M3 (containing 100% ACS) had the lowest one, which implies that the concrete containing ACS has a denser microstructure compared to concrete containing RCA. The increase in the permeability of concrete containing RCA is due to the high porosity of RCA in addition to the microcracks and fissures formed in RCA during the crushing process of old concrete (**Olorunsogo and Padayachee, 2002**), while the increase in the permeability of ACS concrete is due to the vesicular surface of ACS aggregate. The use of 10% silica fume significantly improved the permeability of concrete containing a blend of RCA and ACS. It decreased the permeability of concrete by about 23% compared to concrete without silica fume (mix M4). Furthermore, concrete mix M5 had the lowest permeability coefficient among all concrete mixes. This is due to the physical and chemical effects of the silica fume as it enhances the microstructure of concrete and provides a barrier against water penetration. Hence, the use of ACS as coarse aggregate will rather eliminate the negative impact resulted from using RCA with respect to the permeability of concrete. Moreover, the permeability of concrete can be significantly improved by using 10% silica fume as a supplementary cementing material.

Wetting and Drying

Table 5 shows the average change in weight and compressive strength of the specimens after exposure to wetting-drying cycles. There was a loss of weight and compressive strength in all mixes; however, the differences in the behavior between the mixes were not excessive. In comparison between concrete mixes M1 to M3, it can be found that concrete mix containing 25% RCA had the highest weight and strength losses indicating the sensitivity of RCA to wetting and drying, while concrete mix containing ACS had the lowest losses. Furthermore, the use of ACS improved the performance of concrete containing RCA, and the use of silica fume had a significant effect on increasing the resistance of concrete to wet and dry compared to the mixes without silica fume. The behavior of 25% RCA concrete was not expected as the porous structure of RCA is considered to be effective in releasing the pressure occurring during the evaporation of free water. The explanation of this behavior may be that concrete containing RCA is weak and susceptible to tensile stresses developed during drying as the damage due to wetting-drying is produced by two combined effects: thermal dilation and contraction (i.e., shrinkage due to variations in humidity occurring due to evaporation of absorbed free water with respect to temperature change during drying-wetting cycles).

Table 5. Properties of Concrete Mixes after Wetting and Drying Cycles

Mix ID	Coarse aggregate type	Surface appearance	Weight change, %	Change in compressive strength, %
M1	100%NA	Good	-0.95	-3.4
M2	75%NA+ 25%RCA	Acceptable	-1.39	-6.0
M3	100%ACS	Good	-0.41	-3.2
M4	50%NA+ 25%RCA+ 25%ACS	Good	-1.28	-4.1
M5	50%NA+ 25%RCA+ 25%ACS	Good	-0.09	-2.6

Sulfate Attack

The compressive strength of concrete mixes after exposure to magnesium sulfate solution as a function of time is presented in Fig. 6. A nearly similar trend was observed in all mixes. In general, up to 3 months of exposure to sulfate attack, there was a slight increase in compressive strength. Thereafter, the compressive strength decreased with increasing the exposure period. This is due to "magnesium sulfate attack" which is generally accepted as the most detrimental of all the sulfates. The main damaging effect of magnesium sulfate solution is the disintegration of C-S-H gel to non-cementitious magnesium silicate hydrate gel (M-S-H) at high sulfate concentration. This alteration results in softening of the material and strength loss (**Mehta, 1986; Mangat and Khatib, 1993**). However, the compressive strength of the produced concrete mixes remained higher than 50 MPa even after exposure to magnesium sulfate attack, indicating the possibility of manufacturing high-performance green concrete, with recycled aggregates as coarse aggregate and silica fume as a supplementary cementing material, with high resistance to sulfate attack.

In comparison between concrete mixes, it can be observed that in general the behavior of mix M2 (containing 25% RCA) when exposed to sulfate attack was comparable to that of the control mix although its initial compressive strength before exposure to magnesium sulfate solution was slightly lower than that of the control concrete (Table 4), indicating the higher durability of RCA to magnesium sulfate attack compared to natural coarse aggregate. This finding confirmed the results obtained from the soundness test (see Table 2). **Mandal and Chakraborty, 2002,** reported that the durability of concrete containing coarse RCA under sulfate attack is equal or slightly inferior to that of natural aggregate concrete. On the other hand, the compressive strength of concrete mix entirely made with ACS (mix M3) was significantly higher than that of the control mix regardless of exposure period to sulfate attack. **Galal *et al.*, 2004**, reported that ACS has a good resistance to seawater attack up to one year. Furthermore, the compressive strength of mix M4 (containing a blend of RCA and ACS) was slightly higher than that of the control concrete. Hence, in general the compressive strength of recycled concretes after exposure to sulfate attack was higher or even comparable to that of the control concrete. This means that the use of ACS, RCA or a combination of them as coarse aggregate improves the resistance of concrete to sulfate attack compared to the control concrete entirely made with natural aggregates. On the other hand, concrete mix containing silica fume (mix M5) had higher compressive strength compared to concrete mix without silica fume (mix M4), regardless of immersion period although the difference in the strength decreased by increasing the exposure period to sulfate attack, indicating the sensitivity of silica fume to magnesium sulfate attack. The effect of magnesium sulfate on concrete containing silica fume can be explained in two stages. In the early stage, any detrimental effect of magnesium sulfate is not clear as silica fume reacts with CH and fills the micropores and the cement paste-aggregate interface, leading to a consumption of CH and a reduction in sulfate ingress depth (**Mehta, 1986; Mangat and Khatib, 1993**). At the later stage, when the magnesium sulfate attack is considered, the compressive strength of concrete incorporating silica fume shows a rapid deterioration and the disintegration of the C-S-H gel to M-S-H gel increases by the presence of silica fume as the additional C-S-H generated from the pozzolanic reaction is more susceptible to the magnesium sulfate attack than the C-S-H generated from the hydration of cement due to the differences in their atomic structure and arrangement (**Cohen and Mather, 1992; Biricik *et al.*, 2000**).

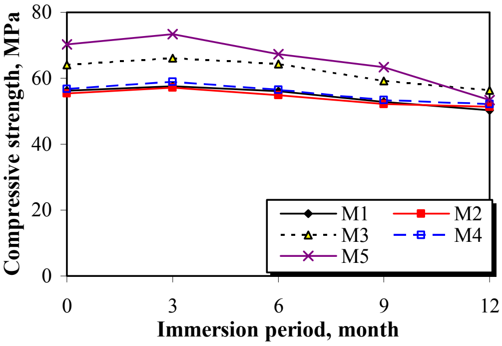

Figure 6. Compressive Strength of Concrete Mixes Exposed to Sulfate Attack

Fig. 7 shows the reduction in compressive strength after exposure to sulfate attack as a function of time. All mixes showed a continuous reduction in compressive strength with exposure to magnesium sulfate, but their amplitudes of reduction were different. The reduction in compressive strength ranged from 23.6% to 36.9% after 12 months of exposure to sulfate attack. There are two visible bundles of diagrams; the lower one for concrete mixes made without silica fume (i.e., M1 to M4 mixes) and the higher one for concrete containing silica fume (i.e., mix M5). The reduction in the compressive strength of mixes M2 to M4 were comparable to that of mix M1 entirely made with natural aggregate, regardless of coarse aggregate type or replacement percentage of natural coarse aggregate. Among these mixes and after 12 months of exposure to sulfate attack, concrete mix M2 (containing 25% RCA) showed the lowest strength loss, while mix M3 entirely made with ACS as coarse aggregate showed the highest strength loss. On the other hand, concrete mix containing silica fume (mix M5) showed the highest reduction in compressive strength due to sulfate attack compared to concretes made without silica fume, indicating the sensitivity of silica fume to magnesium sulfate attack. From the above it was found that the use of ACS, RCA or a combination of them improve the resistance of concrete to sulfate attack, while the use of silica fume negatively affects the resistance of concrete to sulfate attack especially at later ages due to the disintegration of the C-S-H gel to M-S-H gel.

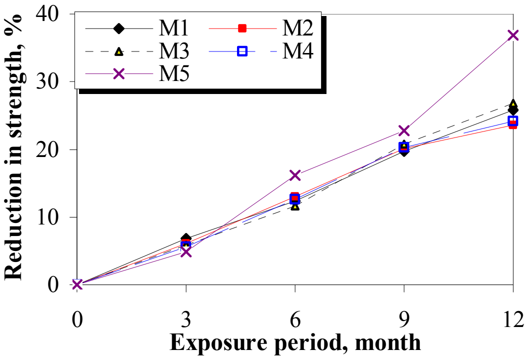

Figure 7. Reduction in Compressive Strength of Concrete Mixes Exposed to Sulfate Attack

Alkali-Aggregate Reaction

Alkali-aggregate reaction is one of the most challenging problems in concrete technology nowadays. Therefore, it is important to make sure that the proceeding alkali-aggregate reaction does not cause damages in the new structures especially in case of using new types of aggregates. Alkali-aggregate reaction (AAR) occurs in concrete when alkalis from the cement, or from an external source, react with certain aggregates the form products that are deleterious in some way to the concrete. Four forms of alkali-aggregate reaction have been recognized. They are alkali-silica reaction, alkali-silicate reaction, alkali-carbonate reaction, and other alkali-aggregate reactions. Alkali-silica reaction (ASR) is more widespread, and is more harmful to the mechanical properties of concrete (**West, 1996**). ASR occurs in concrete when alkalis from the cement, or from an external source, react with free silica present in certain aggregates to form alkali-silica gel [N(K)-S-H]. This gel has the property of taking water and expanding. This expansion can cause cracks, and ultimately can damage the concrete (**ACI 201.2R-01, 2001**).

Figure 8 shows the expansion of the mortar bars due to alkali-silica reaction. The expansion ranged from 0.0288% to 0.071% after 14 days of curing under test conditions and therefore, it was within an acceptable limit of 0.1% according to ASTM C1260 Specifications. This indicates the innocuous behavior of the used aggregates and no potentially deleterious expansion due to alkali-silica reaction would be caused even by using recycled aggregates (i.e., RCA, ACS, or a blend of them) as coarse aggregate. However, the use of RCA increased the ASR expansion while the use of ACS decreased it. The use of 25% RCA increased the 14-days expansion by about 2.9% compared to that of the control mortar. This is not surprising because the primary composition of RCA is silica which is varied from 52% to 68% and thus the use of RCA might increase the alkali level in the system. So, the content of RCA in concrete should be limited to control the ASR and precautions should be taken for using RCA in concrete such as being used in combination with low-reactive aggregate and using low-alkali Portland cement and mineral admixtures to mitigate the reaction. The use ACS in combination with RCA enhanced the performance of mortar compared to mortar mix containing 25% RCA. The 14-days expansion decreased by about 22% by using ACS in combination with RCA compared to mix containing 25% RCA (mix M2).

The use of silica fume significantly decreased the expansion of mortar compared to the mix without silica fume, indicating the benefit of using silica fume to suppress the expansion due to alkali-silica reaction. The 14-days expansion decreased by about 48% in mortar mix containing silica fume (M5) compared to that of mortar mix without silica fume (M4). This is due to the pozzolanic reaction of silica fume which transforms the CH, released from the hydration of Portland cement, into a C-S-H. Thus, the OH^- ions concentration in the interstitial solution that controls the expansion is reduced. In addition, the use of silica fume produces a dense mortar matrix with reduced permeability, as discussed before, thus the penetration of alkalis and humidity from the outside will be inhibited and the alkali-silica reaction will be more difficult to develop (**Turanli *et al.*, 2003**).

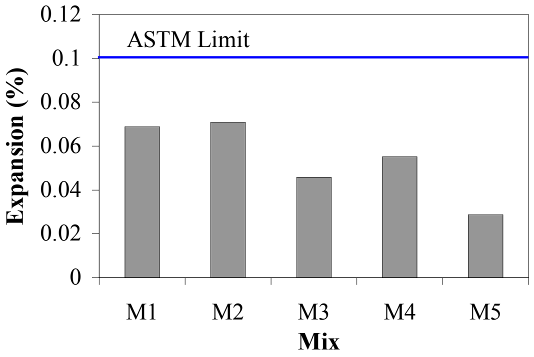

Figure 8. Expansion of the Mortar Bars due to Alkali-Aggregate Reaction

4. Conclusions

Recycled aggregates from demolished concrete and industrial wastes can be used as alternative sources of coarse aggregate especially where good aggregates are scarce. Furthermore, recycling of these wastes offers a feasible solution for waste management. Recycled concrete aggregate is inferior to natural coarse aggregate while air-cooled slag can be considered as a high quality aggregate with properties comparable to those of natural coarse aggregate and better microstructure compared to recycled concrete aggregate.

In general, the moisture content of the used recycled aggregates (i.e., recycled concrete aggregate and air-cooled slag) during mixing is a significant factor affecting the workability of concrete. To avoid difficulties with the batching and placing of concrete, recycled aggregates should be used in a saturated surface dry condition and appropriate percentage of superplasticizer should be used to compensate the higher water absorption of these aggregates compared to natural coarse aggregate. The content of recycled concrete aggregate in structural concrete should be limited to 25% of coarse aggregate or it will decline the strength of concrete, while air-cooled slag can be used to entirely replace natural coarse aggregate without negative impact on concrete as the performance of air-cooled slag concrete is superior or even comparable to that of control concrete in terms of its strength and durability. Furthermore, air-cooled slag aggregate can be beneficially used to attenuate the negative impacts of recycled concrete aggregate on concrete strength and durability. A blend of air-cooled slag and recycled concrete aggregate offers a benefit of producing recycled concrete with 50% of recycled aggregates with comparable strength and durability to that of the control concrete without increasing the content of cement. Moreover, silica fume can be used beneficially as a supplementary cementing material to produce more durable and sustainable concrete as it significantly improves the behavior of concrete. It is possible to manufacture high-performance green concrete, with compressive strength in excess of 50 MPa and high durability, using recycled aggregates produced from demolition and steel industry wastes as coarse aggregate and silica fume as a supplementary cementing material.

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