AN EXPERIMENTAL STUDY ON PROPERTIES OF HIGH-PERFORMANCE CONCRETE USING RECYCLED AGGREGATES

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Abtract - This study evaluates the properties of high-performance concrete (HPC) using recycled coarse and fine aggregates sourced from Taiwan. Densified mixture design algorithm is used to calculate the mix proportion of the HPC. The HPC samples are prepared with a constant water-to-binder ratio of 0.35, using either natural fine aggregate (NFA) or recycled fine aggregate (RFA) combined with natural coarse aggregate (NCA) and recycled coarse aggregate (RCA). The effect of replacing 0%, 30%, and 100% NCA by RCA in each group mixture is studied. Both fresh and hardened properties of the HPC are evaluated. Test results show that the compressive strength values of the HPC range from 31.7 to 56.7 MPa. Moreover, all of the HPC samples produced in this study exhibit the excellent anti-erosion ability and durability performance with electrical surface resistivity and ultrasonic pulse velocity values of above 20 kΩ.cm and 3660 m/s, respectively.

Key words - High-performance concrete; recycled aggregates; engineering property; compressive strength; durability

1. Introduction

In recent years, the urbanization level in the developing countries has been rapidly exploding. Consequently, a large number of old infrastructures are demolished for new ones. The demolition and the construction of new infrastructures generate a lot of construction wastes such as demolished concrete, brick, tile, wood, plastic, steel, etc. On the other hand, the use of natural resources in some areas is over exploited. The exploitation process and production of construction materials such as aggregate and cement from natural resources also generate a large amount of carbon dioxide (CO_2), causing greenhouse effect. For the sustainable development, it is necessary to reduce CO_2 and limit the use of natural resources by recycling industrial by-products and wastes such as silica fume, fly ash, slag, and recycled aggregate from building rubbles. The turning rubble from demolished buildings into fine and coarse aggregate used in concrete reduces both the consumption of natural resources and landfill for disposing of waste materials.

The performance of recycled aggregate concrete is generally not as good as that of conventional concrete made from natural aggregate [1–7]. It is noted that the properties of concrete made from recycled aggregate strongly depend on concrete mix proportion, sources, and quality of the recycled aggregate [1–2]. Tabsh and Abdelfatah [1] stated that the compressive and splitting tensile strength of recycled coarse aggregate concrete were 10–25% lower than that of the normal concrete. This was a similar trend when using recycled concrete coarse aggregate from different sources [2]. Etxeberria et al. [3] investigated the use of four different recycled coarse aggregates by crushed concrete to replace 0%, 25%, 50%, and 100% natural coarse aggregate in concrete mixtures. Their results showed that the compressive strength of concrete made from 100% recycled coarse aggregate was 20–25% lower than that of the conventional concrete. Xiao et al. [4] indicated that increasing the replacement level of recycled aggregate resulted in a reduction in elastic modulus and compressive strength of concrete. Casuccio et al. [5] studied the use of recycled coarse aggregate obtained by crushing a normal strength and high strength concrete. The compressive strength and modulus of elasticity of the recycled coarse aggregate concrete were about 1–15% and 13–18% lower than those of the conventional concrete, respectively. Chen et al. [6] recycled building rubble such as demolished concrete, brick, and tile into coarse aggregate used in concrete. The compressive strength of the concrete samples prepared with such recycled coarse aggregates was 25–40% below the strength of normal concrete. Furthermore, Khatib [7] examined the use of recycled fine aggregate made from demolished concrete and brick. Experimental results indicated that the compressive strength of recycled fine aggregate concrete was 10–30% lower than that of the conventional concrete. Kou and Poon [8] investigated the possible application of recycled concrete fine and coarse aggregate in self-compacting concrete. Test results proved the feasibility of utilization both recycled fine and coarse aggregate in self-compacting concrete.

In order to enhance both physical and engineering properties of the recycled aggregate concrete and reduce the amount of cement used, the additive materials such as silica fume, fly ash, slag, and metakaolin, which are the industrial by-products, were added into concrete mixtures. A previous study reported that the addition of 25% fly ash to concrete mixture reduced the drying shrinkage, enhanced the compressive strength, and increased the resistance to chloride ion penetration of the concrete [9]. Kou et al. [10] pointed out that the use of fly ash as cement substitution reduced the compressive strength, tensile strength, and elastic modulus, however, increased the resistance to chloride ion penetration and decreased the drying shrinkage and creep of recycled aggregate concrete. The use of a combination of mineral admixtures such as fly ash and silica fume [11], fly ash and slag [12], and silica fume, fly ash, slag and metakaolin [13] enhanced both physical and engineering properties of recycled aggregate concrete.

The previous studies have demonstrated the possibility of recycling all building rubbles into the useful fine and coarse aggregates used in concrete. The properties of concrete made from such the recycled aggregates were normally lower than properties of the conventional concrete; however, the concrete properties were improved with the inclusion of mineral additives. In order to enhance not only the mechanical properties but also the durability of concrete, Hwang and Hung [14] have proposed the Densified Mixture Design Algorithm (DMDA) method to design concrete mixture proportion. This method has been considered as a green design method for high-performance concrete (HPC) with increasing the physical density and reducing the amount of cement used. Thus, the primary objective of this study is to evaluate the properties of HPC designed by the DMDA method with the incorporation of recycled aggregates.

2. Materials and test methods

2.1. Materials

A mixture of type-I ordinary Portland cement (OPC), class-F fly ash (FA), and ground granulated blast furnace slag (GGBFS) are used as binder materials for producing concrete samples. All of the binder materials used in the present study are sourced from Taiwan with characteristics as presented in Table 1. Table 2 shows the sieve analysis and fineness modulus (FM) of both natural and recycled aggregates, while their physical and mechanical properties are shown in Table 3. It is noted that the recycled fine and coarse aggregates are provided by a local construction material company in Taiwan, which was made from a mixture of demolished crushed concrete, brick, and tile. As shown in Table 3, the recycled aggregates have properties that are not as good as those of natural aggregates. This is attributable to the high porosity of recycled aggregates compared with natural aggregates. In other words, the quality of the recycled aggregates is not as good as that of the natural aggregates. In order to reduce the amount of water, but keep the desired workability of the fresh concrete mixture, type-G superplasticizer (SP) with a specific gravity of 1.1 is used.

Table 1. *Characteristics of binder materials*

Materials		OPC	FA	GGBFS
Specific gravity		3.15	2.29	2.90
Chemical composition (wt.%)	SiO_2	20.0	64.0	35.6
	Al_2O_3	4.2	22.1	11.2
	Fe_2O_3	3.1	5.6	0.5
	CaO	62.4	2.7	41.0
	MgO	4.1	0.9	6.4
	SO_3	2.9	0.6	0.9
	Others	1.4	1.1	2.1

Table 2. *Sieve analysis and fineness modulus of the aggregates*

Sieve size (mm)	Percentage of passing, (%)		Sieve size (mm)	Percentage of passing, (%)	
	NFA	RFA		NCA	RCA
4.75 (#4)	99.3	98.7	19 (3/4 in)	100	100
2.36 (#8)	76.1	77.8	12.5 (1/2 in)	75.0	94.1
1.18 (#16)	53.4	55.8	9.5 (3/8 in)	46.6	64.4
0.6 (#30)	38.2	36.9	4.75 (#4)	11.0	13.5
0.3 (#50)	23.8	20.5	2.36 (#8)	3.9	4.1
0.15 (#100)	14.3	11.7	FM	6.2	5.8
FM	3.1	3.0			

Note: *NFA = Natural fine aggregate; RFA = Recycled fine aggregate; NCA = Natural coarse aggregate; RCA = Recycled coarse aggregate; FM= Fineness modulus.*

Table 3. *Physical and mechanical properties of the aggregates*

Physical properties	NFA	RFA	NCA	RCA
OD density (kg/m^3)	2640	2540	2646	2589
Absorption capacity (%)	1.5	5.6	0.7	3.2
Crushing strength (MPa)	NA	NA	61.5	44.3

Note: *OD = Oven dry condition; NA= Not available.*

2.2. Mix proportions and test methods

In this study, all of the mix proportions are designed using the DMDA method with the same water-to-binder ratio of 0.35. The design concept and the design procedures of DMDA method were previously published by Hwang and Hung [14]. In this method, concrete mix proportions are divided into two phases as aggregate and paste. The aggregate phase consists of coarse aggregate, fine aggregate, and fly ash, which forms the major skeleton of the concrete structure. The void among coarse particles is filled by fine aggregate and fly ash to minimize the porosity. Meanwhile, the paste phase includes cement, slag, water, and superplasticizer, which is for lubricating and filling pores to achieve concrete workability. The key point of DMDA method is to determine the optimized amount of concrete ingredients by experimental work so that concrete samples have the highest density as well as good quality. It also means that the amount of each concrete ingredient is different from a mixture to another mixture even they have the same a water-to-binder ratio.

Table 4 shows the mix proportions for all concrete mixtures, which includes two groups. The first group is designed with natural fine aggregate, while the second group was designed with recycled fine aggregate. In each group, recycled coarse aggregate content is 0%, 30% and 100% of the total coarse aggregate amount. The M1, M2, and M3 mixtures denote concrete designed with 100% natural fine aggregate and 0%, 30%, and 100% recycled coarse aggregate, respectively. Meanwhile, M4, M5, and M6 mixtures denote concrete designed with 100% recycled fine aggregate and 0%, 30%, and 100% recycled coarse aggregate, respectively. It is noted that the total binder amount increases with increasing the recycled aggregates content. In details, the total binder amount of group II mixtures is higher than those of corresponding group I mixtures. Due to the high porosity of recycled aggregate, all of the concrete mixtures reach the highest density incorporating a high amount of binder.

Table 4. *Mixture proportion for preparing concrete samples*

Mixture		Concrete ingredient proportions (kg/m^3)						
		OPC	Slag	FA	CAg	FAg	Water	SP
Group I	M1	220.2	55.1	117.1	786.8	1123.5	133.4	4.1
	M2	322.6	80.6	105.2	453.2	1250.5	174.8	3.3
	M3	363.4	90.8	60.2	813.7	879.3	177.5	2.4
Group II	M4	293.6	73.4	190.2	665.4	894.4	191.1	4.1
	M5	433.6	108.4	115.9	398.2	998.2	227.0	3.2
	M6	363.1	90.8	121.0	763.1	775.1	197.5	3.5

Note: *CAg = Coarse aggregate; FAg = Fine aggregate*

2.3. Test programs

Cylinder concrete samples with 10 cm in diameter and 20 cm in height are prepared. The properties of fresh and hardened concrete such as workability, compressive strength, water absorption, thermal conductivity, ultrasonic pulse velocity, and electrical surface resistivity are tested. The concrete compressive strength is measured at 7, 14, and 28 days, while other properties of the samples are measured at 28 days. The values presented herein are the average value of three concrete samples.

3. Results and discussion

3.1. Fresh concrete properties

The designed workability of the fresh HPC mixtures is controlled in the range of 22 ± 2 cm by using various dosages of SP. Thus, right after mixing, the fresh HPC mixtures are checked for the slump, slump flow spread, and flow time with the results as provided in Table 5. It is noted that the workability of fresh concrete is tested in accordance with ASTM C143. As a results, the slump, slump flow spread, and flow time of all concrete mixtures are in the ranges of 21–23 cm, 32–36 cm, and 5–10 seconds, respectively. Thus, all of these mixtures show good fresh properties.

***Table 5.** Properties of fresh concrete mixtures*

Mixture		Slump (cm)	Slump flow (cm)	Flow time (sec.)	% SP
Group I	M1	21	36	10	1.09
	M2	23	34	5	0.64
	M3	21	32	7	0.45
Group II	M4	23	35	10	0.86
	M5	23	36	5	0.48
	M6	22	32	7	0.64

3.2. Compressive strength development

Compressive strength is a very important property of hardened concrete. Figures 1 and 2 show the compressive strength development of the HPC samples in group I and group II, respectively. It is observed that the compressive strength of all concrete mixtures increases with curing ages, with the strength values ranging from 31.7 to 56.7 MPa.

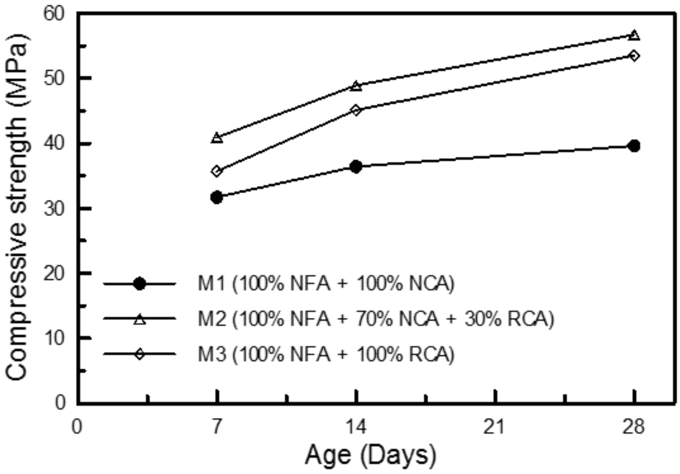

***Figure 1.** Compressive strength development of the HPC samples in group I*

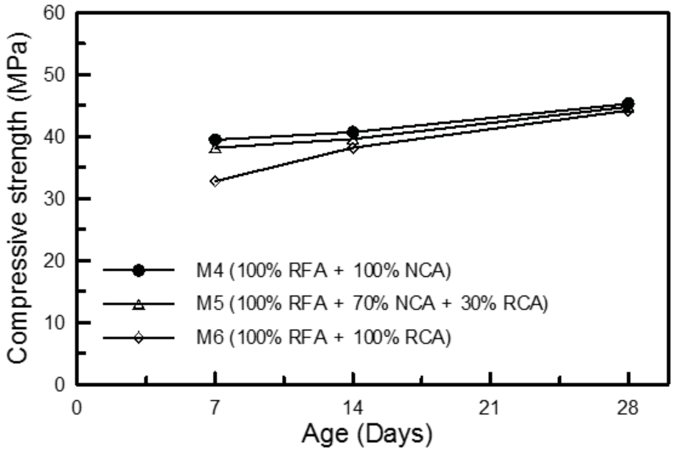

***Figure 2.** Compressive strength development of the HPC samples in group II*

As shown, the compressive strength of M5 and M6 mixtures were lower than that of the M2 and M3 mixtures, respectively. This phenomenon is due to the use 100% recycled fine aggregate in group II mixtures as compared to the use of 100% natural fine aggregate in group I mixtures. However, the compressive strength of M4 mixture was higher than that of M1 mixture because the total binder amount of M4 mixture is 42% higher than that of M1 mixture.

For group I, the HPC mixture with 30% recycled coarse aggregate content (M2) show the highest compressive strength, followed by mixture with 100% recycled coarse aggregate content (M3) and recycled coarse aggregate-free mixture (M1). It is noted that the total amount of binder of M2 and M3 mixtures is around 30% higher than that of control mixture (M1), which is used to minimize the porosity of recycled aggregate concrete structure. This is mainly attributable to the 43% and 35% higher compressive strength of M2 and M3 mixtures compared with the M1 mixture, respectively. It means that using DMDA method not only compensates the negative effects of the recycled coarse aggregate on concrete strength but also improves the strength of the recycled aggregate concrete. This finding is in line with the experimental results from a previous study [9]. With a similar amount of binder, M2 mixture with the use of 70% recycled coarse aggregate has the compressive strength value of around 6% higher than that of the M3 mixture with the use of 100% recycled coarse aggregate. It means that increasing the replacement level of recycled coarse aggregate results in a reduction in the concrete strength. This finding is in good agreement with previous studies [1–7].

For group II, all of the HPC mixtures are designed with 100% recycled fine aggregate and using recycled coarse aggregate to replace 0%, 30%, and 100% natural coarse aggregate. Among three mixtures in group II, M4 mixture has the highest compressive strength, followed by M5 and M6 mixtures. It reveals that compressive strength of the concrete samples reduced with increasing the content of recycled coarse aggregate. This phenomenon is associated with the high porosity of recycled aggregate [1–7]. However, all recycled aggregate concrete mixtures examined herein show similar compressive strength value of around 44.5 MPa at 28 days. Similar to the group I mixtures, this result is based on the fact that the total binder amount of M5 and M6 mixtures is higher than that of M4 mixture. This finding also proves the feasibility of using DMDA method to improve the properties of HPC made wfrom recycled aggregate.

3.3. Water absorption

Water absorption is an important parameter reflecting the permeable property of concrete. Concrete with low water absorption will have high resistance to the sulfate ions, chloride ions, alkali ions, and other harmful substance, which causes a chemical attack in concrete. The test result of the water absorption of the hardened concrete mixtures at 28-day ages is presented in Table 6. Generally, group II concrete mixtures show a higher water absorption rates than group I concrete mixtures. This is because the 100% recycled fine aggregate is used to replace natural fine aggregate in group II mixtures. For group I, the M1 and M3 mixtures have a similar water absorption level, whereas M2 shows the lowest water absorption rate. This is mainly due to the use of more binder amount and less recycled coarse aggregate content in M2 mixture as compared to those in M3 mixture. For group II, the water absorption increases with increasing the recycled coarse aggregate content.

Table 6. *Properties of hardened concrete at 28-day age*

Mixture	Hardened concrete properties			
	WA (%)	TC (W/mK)	UPV (m/s)	ESR (kΩ.cm)
M1	1.83	1.78	4481	32.1
M2	1.79	1.88	4741	36.9
M3	1.86	1.61	4452	32.3
M4	2.58	1.30	4420	30.5
M5	3.00	1.27	4370	35.0
M6	3.35	1.22	4297	38.9

Note: *WA = Water absorption; TC = Thermal conductivity; UPV = Ultrasonic pulse velocity; ESR = Electrical surface resistivity*

The water absorption strongly depends on the pore structure and the cracks in concrete. Recycled fine and coarse aggregates initially have higher porosity and water absorption capacity than natural fine and coarse aggregates (Table 3). Therefore, the concrete mixtures with higher recycled aggregate content exhibited higher water absorption level. However, the porosity of M2 and M3 mixtures is reduced by increasing the amount of binder, thus these mixtures have a good permeable quality as compared with the control mixture (M1).

3.4. Thermal conductivity

The results of thermal conductivity measurement for all HPC mixtures are shown in Table 6. In general, the thermal conductivity of all the examined concrete mixtures ranges from 1.22 to 1.88 W/mK. As a result, group II concrete mixtures have lower thermal conductivity values than that of group I concrete mixtures. The thermal conductivity is associated with the density of concrete and inversely related to water absorption. The increasing porosity of concrete samples due to the replacement of natural aggregate by recycled aggregate reduces the thermal conductivity of the concrete.

In group I, the M2 mixture show the highest value of thermal conductivity because of the highest amount of binder used as above mentioned. In group II, the thermal conductivity of the HPC decreases with the increase in recycled coarse aggregate content. The high porosity of the recycled aggregate as aforementioned is attributable to a lower thermal conductivity. However, the difference of thermal conductivity value among the mixtures in each group is insignificant due to the effectiveness of DMDA mix design method.

3.5. Ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) test is often used for assessing the uniformity and the relative quality of concrete, which relates to the presence of voids and cracks inside the concrete structure. The results of UPV test of the HPC samples are presented in Table 6. As shown, all of the concrete samples have UPV values of above 3660 m/s at 28-day ages, indicating a good durability as suggested by Malhotra [15]. In a similar trend to thermal conductivity, M2 mixture registers the highest UPV value, whereas M1 and M3 mixtures have similar UPV values. That is also due to the less porosity, as mentioned above, of M2 mixture in comparison with that of the other mixtures. With the use of recycled fine aggregate to replace natural fine aggregate, group II concrete mixtures exhibit lower UPV values than group I concrete mixtures.

3.6. Electrical surface resistivity

The electrical surface resistivity (ESR) of concrete is an important factor to evaluate the corrosion resistance of the concrete. The test results for the ESR of the HPC samples are shown in Table 6. As shown in the table, the ESR values of all concrete mixtures range from 30.5 to 38.9 kΩ.cm. Abdefatah and Tabsh [16] previously reported that concrete had excellent anti-erosion ability if its ESR value was above 20 kΩ.cm. This means that all of the recycled aggregate concrete mixtures used in this investigation exhibit excellent electrical resistivity. In other words, all concrete mixtures investigated herein demonstrate an excellent anti-erosion ability.

4. Conclusions

Properties of the HPC using recycled aggregates are evaluated in this study. The obtained results lead to the following conclusions:

- With the use of various SP dosages, all of the fresh concrete mixtures made from recycled aggregate exhibit a good workability with a less amount of water.

- All of the HPC samples show the good performance in terms of compressive strength, which ranges from 31.7 MPa to 56.7 MPa. The use of DMDA method to design recycled aggregate concrete mixtures is found to have a positive improvement of concrete strength.

- This study finds that increasing recycled aggregate content leads to increasing the water absorption capacity and electrical surface resistivity, but reducing the thermal conductivity and ultrasonic pulse velocity of the HPC samples. However, the addition of binder can compensate for or even improve properties of recycled aggregate concrete.

- All of the concrete samples examined in this study exhibit the good durability performance and excellent anti-erosion ability.

- The application of DMDA method for mix design of HPC with recycled aggregate effectively enhances both engineering properties and durability performance of the concrete.

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(The Board of Editors received the paper on 27/8/2017, its review was completed on 02/10/2017)