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Statistical Study on Properties of High-Performance Recycled Aggregate Concrete

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ABSTRACT: The engineering properties of high-performance recycled aggregate concrete (HPRAC) using the crushed brick, tile and hardened mortar to replace the coarse aggregate of concrete were studied. Three placement ratios by volume are 0%, 10% and 20%, respectively. Experimental results show that, basically, the more the amount of recycled aggregate replacement is, the lower the corresponding engineering properties of concrete will be. The maximum reductions occur in compressive strength and surface electrical resistance where 27.5% and 37.7% reduction, respectively, were observed as compared with the control normal concrete specimens. On the other hand, the statistical analyses on the experimental results, including three-factor ANOVA and multiple regression analysis were also carried out. According the result of statistical study, the brick, tile and hardened mortar replacement are the significant factors on the performance of concrete, respectively. From the results of weight analysis, the brick aggregate replacement is the most significant factor influencing the performance of HPRAC due to it lower specific weight and higher water apportion.

1 INTRODUTION

There are about 198×10^6 m^3 of demolition waste produced from the construction activities during the years from 2004 to 2008 in Taiwan in which about 15 percent of the waste belongs to the deposed plastics, wood, metal, paper, glass, etc., while the rest of 85 percent belongs to the deposed concrete debris, brick pieces, broken roof tile, broken ceramics of sanitary wares, broken porcelain of kitchen ware, etc. Without a proper measure for solution, they would cause a severe issue of site pollution and other related environmental problems. Some of the solid demolition wastes such as brick, tile and hardened mortar, etc., have been commonly recycled and/or reused in construction sites as either partial or total replacement of coarse aggregates and shown the satisfactory engineering properties (Rahal 2007, Etxeberria et al. 2007, Rao et al. 2007).

On the other hand, the high performance concrete (HPC) has high workability, compressive strength and durability which has been widely used in many construction projects. This study aims at investigating the engineering properties of the high performance recycled aggregate concrete (HPRAC) by using three types of recycled coarse aggregates (broken pieces of brick, tile and hardened mortar) to replace 10% and 20% by volume of the normal coarse aggregate in the original HPC. The densified mixture design algorithm (DMDA) was adopted (Hwang et al. 1996) to proportion the concrete mix of HPRAC. Due to a wide range variation of material properties of these recycled coarse aggregate, it is anticipated that their effects on the resulting HPRAC would be profound too. On account for a deeper investigation into various extent of effects on the type of recycled aggregate, the amount of replacement and their mutual interaction on the HPRAC, the statistical methods of three-factor ANOVA and multiple regression analysis were carried out. Detailed experimental work and analysis will be given in the following sections.

2 EXPERIMENT WORK

2.1 *Materials*

1. Cement: Portland cement Type I manufactured by Taiwan Cement Corporation.
2. Normal coarse and fine aggregates: The normal coarse and fine aggregates came from the river of Taiwan. The basic characteristics of two aggregates are shown in Table 1. The maximum aggregate size is 20 mm.
3. Recycled brick, tile and hardened mortar aggregates: Three types of recycled coarse aggregate were manufactured from the domestic deposal plant of construction debris as shown in Figs. 1 to 3, respectively. Broken brick and tile aggregates are flat with various irregular shapes. The shape of hardened mortar is similar to the normal coarse

aggregate. The basic propertied of these recycled aggregates are also shown in Table 1.

Table 1 Properties of various aggregate

	Specific weight	Water absorption*	Fineness modulus
Normal coarse aggregate	2.72	1.3	6.69
Normal fine aggregate	2.71	0.7	3.05
Recycled brick	1.6	13.1	6.72
Recycled tile	2.27	10	7.14
Recycled hardened mortar	2.3	10	6.71

* 24 hours after aggregate submerged in the water.

Figure 1 Recycled brick aggregate


Figure 2 Recycled tile aggregate


Figure 3 Recycled hardened mortar aggregate

4. Fly ash: The F class was used in this study. It contained about 51.2% of SiO_2 and 24.3% of Al_2O_3. Its fineness and specific gravity were 311.0 m^2/kg and 2.17, respectively.
5. Slag: The industrial by-product from the domestic iron and steel plant of Taiwan contains about 64.9% of SiO_2 and 41.8% of CaO. Its fineness and specific gravity were 800 m^2/kg and 2.85, respectively.

2.2 *Mix proportion*

In this study, 81 cylinder specimens of $\phi 100 \times 200$ mm were mixed. All cylinder specimens were divided into two groups, the group of normal concrete (NC) and the group of high performance recycled aggregate concrete (HPRAC). Based on the mixing algorithm of DMDA, the mix proportions of NC using the normal coarse aggregate are shown in Table 2. Based the proportion values in Table 2, the mix proportions of two kinds of HPRAC were obtained by replacing the amount of normal coarse aggregate with 10% and 20% by volume of the crushed recycled brick, tile and hardened mortar, respectively. In order to increase the flowablity of concrete, a small amount of superplasticizer was used. The resulting slumps and slump flows for all the specimens are in the ranges of 220 and 260 mm, and 520 and 600 mm, respectively.

Table 2 Mix proportion of NC (unit: kg/m^3)

Water	Cement	Fly ash	Slag	F.A.*	C.A.*	S.P.*
174.7	316.0	128.9	316.0	945.0	879.0	7.4

* F.A. = fine aggregate, C.A. = coarse aggregate, S.P. = superplasticizer.

2.3 *Specimen preparation and testing*

After curing for 28 days under lime water, the cylindrical concrete specimens were tested for the compressive strength (f'_c), dynamic elasticity modulus (E_d), ultrasonic pulse velocity (V_p) and surface electrical resistance (R) at room temperature (T=25±1^{o}C) according to ASTM C215, C39, C496 and C1202, respectively.

3 RESULTS AND DISCUSSION

3.1 *Experimental Results*

From Table 3, the compressive strength of NC is 45.4 MPa and the compressive strengths of HPRAC are in the range of 32.9 and 43.8 MPa. It shows that the decrease of compressive strength of concrete results from the increase of the amount of replacement with the recycled coarse aggregate. The reductions of compressive strength were observed as compared with NC and shown as Table 4 with a maximum reduction of of 27.5% in the compressive strength.

Table 3 Compressive strength of NC and HPRAC (unit: MPa)

Brick Replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	45.4*	43.2	40.0
	10% (C2)	43.8	41.6	39.0
	20% (C3)	42.8	40.2	36.4
10% (A2)	0% (C1)	43.8	41.4	39.4
	10% (C2)	42.0	39.8	37.0
	20% (C3)	42.0	37.8	34.4
20% (A2)	0% (C1)	38.4	38.0	36.9
	10% (C2)	37.2	36.2	35.5
	20% (C3)	37.1	35.8	32.9

*: NC

Table 4 Reduction of compressive strength (unit: %)

Brick replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	−	4.8	11.9
	10% (C2)	3.5	8.4	14.1
	20% (C3)	5.7	11.5	19.8
10% (A2)	0% (C1)	3.5	8.8	13.2
	10% (C2)	7.5	12.3	18.5
	20% (C3)	7.5	16.7	24.2
20% (A2)	0% (C1)	15.4	16.3	18.7
	10% (C2)	18.1	20.3	21.8
	20% (C3)	18.3	21.1	27.5

The shape of a typical broken HPRAC specimen is given in Figure 4 which shows the failure plane passing through the recycled brick aggregate as expected.

Figure 4 Recycled hardened mortar aggregate

Table 5 shows the results of dynamic elastic modulus. The dynamic elastic modulus of NC is 40.4 GPa. For HPRAC, the dynamic elastic moduli are in the range of 33.2 and 39.3 GPa. The dynamic elastic moduli of HPRAC are lower than that of NC due the lower rigidity of three recycled aggregates. By comparing with NC, the reductions of dynamic elastic modulus were listed in Table 6 which shows a maximum reduction of the dynamic elastic modulus of 17.8%.

Table 5 Dynamic elastic modulus of NC and HPRAC (unit: GPa)

Brick replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	40.4*	38.8	37.1
	10% (C2)	39.3	37.8	36.2
	20% (C3)	38.5	37.0	34.4
10% (A2)	0% (C1)	38.9	38.2	36.6
	10% (C2)	36.5	36.5	35.9
	20% (C3)	37.0	36.4	34.4
20% (A2)	0% (C1)	37.0	36.9	36.2
	10% (C2)	36.0	35.5	34.7
	20% (C3)	35.3	34.6	33.2

*: NC

Table 6 Reduction of dynamic elastic modulus (unit: %)

Brick Replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	-	4.0	8.2
	10% (C2)	2.7	6.4	10.4
	20% (C3)	4.7	8.4	14.9
10% (A2)	0% (C1)	3.7	5.4	9.4
	10% (C2)	9.7	9.7	11.1
	20% (C3)	8.4	9.9	14.9
20% (A2)	0% (C1)	8.4	8.7	10.4
	10% (C2)	10.9	12.1	14.1
	20% (C3)	12.6	14.4	17.8

The results of ultrasonic pulse velocity testing are shown as Table 7. The ultrasonic pulse velocities of NC and HPRAC are 4655 m/s and in the range of 4625 and 4360 m/s, respectively. The reductions of ultrasonic pulse velocity were listed in Table 8 which shows an insignificant effect of recycled coarse aggregates on the wave speed of concrete specimens.

Table 7 Ultrasonic pulse velocity of NC and HPRAC (unit: m/s)

Brick replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	4655	4615	4595

	10% (C2)	4625	4585	4550
	20% (C3)	4575	4560	4425
10% (A2)	0% (C1)	4615	4540	4515
	10% (C2)	4565	4485	4450
	20% (C3)	4535	4485	4390
20% (A2)	0% (C1)	4535	4475	4455
	10% (C2)	4470	4430	4385
	20% (C3)	4415	4385	4360

Table 8 Reduction of ultrasonic pulse velocity (unit: %)

Brick Replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	-	0.9	1.3
	10% (C2)	0.6	1.5	2.3
	20% (C3)	1.7	2.0	4.9
10% (A2)	0% (C1)	0.9	2.5	3.0
	10% (C2)	1.9	3.7	4.4
	20% (C3)	2.6	3.7	5.7
20% (A2)	0% (C1)	2.6	3.9	4.3
	10% (C2)	4.0	4.8	5.8
	20% (C3)	5.2	5.8	6.3

The results of surface electrical resistance testing are shown as Table 6. The surface electrical resistance of NC and HPRAC are 22.8 kΩ-cm and in the range of 14.2 and 19.9 kΩ-cm, respectively. Table 10 shows the ratios of reduction of the surface electrical resistance with a maximum value of 37.7%.

Table 9 Surface electrical resistance of NC and HPRAC (unit: kΩ-cm)

Brick Replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	22.8*	19.9	17.7
	10% (C2)	18.9	17.6	17.2
	20% (C3)	17.6	16.9	16.0
10% (A2)	0% (C1)	19.3	18.4	16.4
	10% (C2)	17.1	16.1	15.6
	20% (C3)	16.4	15.9	14.7
20% (A2)	0% (C1)	17.9	17.1	15.9
	10% (C2)	15.7	15.1	14.7
	20% (C3)	14.7	14.4	14.2

Table 10 Reduction of Surface electrical resistance (unit: %)

Brick Replacement (A)	Hardened mortar replacement (C)	Tile replacement (B)		
		0% (B1)	10% (B2)	20% (B3)
0% (A1)	0% (C1)	-	12.7	22.4
	10% (C2)	17.1	22.8	24.6
	20% (C3)	22.8	25.9	29.8
10% (A2)	0% (C1)	15.4	19.3	28.1
	10% (C2)	25.0	29.4	31.6
	20% (C3)	28.1	30.3	35.5
20% (A2)	0% (C1)	21.5	25.0	30.3
	10% (C2)	31.1	33.8	35.5
	20% (C3)	35.5	36.8	37.7

3.2 *Analysis of variance (ANOVA)*

The analysis of variance (ANOVA) is a statistical model which uses of the Fisher's F-distribution as part of the test of statistical significance or p-value to assess the collection of variance and object (Walpole R.E. & Myers R.H. 1993). The experimental results given in the Section 3.1 clearly show that there exists a strong dependence of the replacement of normal coarse aggregate with different types and amount of recycled coarse aggregate of brick, tile and hardened mortar on the compressive strength, dynamic elastic modulus, ultrasonic pulse velocity and surface electrical resistance of concrete, respectively. Therefore, three-way ANOVA for repeated measurements was used to obtain the further confirmation.

The results of ANOVA for compressive strength, dynamic elastic modulus, ultrasonic pulse velocity and surface electrical resistance of concrete with various types of aggregate replacement are shown as Tables 11 to 14, respectively. The level of significance has been set at 0.05. The symbols of A, B and C were used to indicate the recycled brick, tile and hardened mortar coarse aggregates, respectively. The symbols of A × B, B × C, A × C and A×B×C indicate the interactions between each individual factor, respectively. From Table 11, the replacement of recycled brick, tile and hardened mortar coarse aggregate is the significant factor on compressive strength of HPRAC since the P-value is less than 0.05, respectively. It shows that the interaction between the factors does not influence the compressive strength of HPRAC.

Table 11 ANOVA for compressive strength of concrete with various types of aggregate replacement

Source**	SS	df	MS	F-value	P-value	
A	242.24	2	121.12	20.72	3.53E-06	*
B	190.36	2	95.28	16.28	2.30E-05	*
C	94.48	2	47.24	8.08	1.78E-03	*
A × B	21.21	4	5.30	0.91	4.74E-01	
B × C	0.79	4	0.20	0.03	9.98E-01	
A × C	11.59	4	2.90	0.50	7.39E-01	
A×B×C	2.32	8	0.29	0.05	1.0E+00	
Error	157.86	27	5.85			
Sum	83358.7	54				

* the significant factor (P-value < 0.05)

** A: recycled brick, B: recycled tile, C: recycled hardened mortar replacement

Table 12 shows that the replacement of recycled brick, tile and hardened mortar is the significant factor on the compressive strength of HPRAC since the P-value is less than 0.05, respectively. The interaction between brick and tile replacement (A × B) also influences the dynamic elastic modulus of HPRAC.

Table 12 ANOVA for dynamic elastic modulus of concrete with various types of aggregate replacement

Source**	SS	df	MS	F-value	P-value	
A	44.48	2	22.24	67.05	3.37E-11	*
B	47.34	2	23.67	71.37	1.66E-11	*
C	41.43	2	20.71	62.45	7.45E-11	*
A × B	7.67	4	1.92	5.78	1.71E-03	*
B × C	1.24	4	0.31	0.93	4.59E-01	
A × C	2.58	4	0.65	1.95	1.32E-01	
A×B×C	1.40	8	0.18	0.53	8.26E-01	
Error	8.96	27	0.33			
Sum	72594.6	54				

*: the significant factor (P-value < 0.05)

**: A: brick, B: tile, C: hardened mortar replacement

Table 13 shows that the significant factor on the ultrasonic pulse velocity of HPRAC is the replacement of recycled brick, tile and hardened mortar, respectively. All the interactions between the factors do not significantly influence the ultrasonic pulse velocity of HPRAC.

Table 13 ANOVA for ultrasonic pulse velocity of concrete with various types of aggregate replacement

Source**	SS	df	MS	F-value	P-value	
A	180781.5	2	90391	76.39	7.67E-12	*
B	83137.0	2	41569	35.13	3.07E-08	*
C	841159.3	2	42080	35.56	2.72E-08	*
A × B	4729.6	4	1182	1.00	4.25E-01	
B × C	2440.7	4	610	0.52	7.25E-01	
A × C	6518.5	4	1630	1.38	2.68E-01	
A×B×C	5914.8	8	739	0.63	7.49E-01	
Error	31950	27	1183			
Sum	1.097E+09	54				

*: the significant factor (P-value < 0.05)

**: A: brick, B: tile, C: hardened mortar replacement

Table 14 shows that the replacement of recycled brick, tile and hardened mortar is the significant factor on the surface electrical resistance of HPRAC since the P-value is less than 0.05, respectively. The P-value of the interaction between recycled tile and hardened mortar replacement (B × C) and the interaction between brick and hardened mortar replacement (A × C) is 3.58×10^{-2} and 3.34×10^{-6}, respectively. Each of them is the major influencing factor for the surface electrical resistance of HPRAC.

Table 14 ANOVA for surface electrical resistance of concrete with various types of aggregate replacement

Source**	SS	df	MS	F-value	P-value	
A	6.954	2	34.77	240.98	6.07E-18	*
B	35.85	2	17.93	124.23	2.41E-14	*
C	71.58	2	35.79	248.04	4.19E-18	*
A × B	4.13	4	1.03	7.16	4.57E-04	
B × C	1.73	4	0.43	3.01	3.58E-02	*
A × C	7.87	4	1.97	13.63	3.34E-06	*
A×B×C	2.43	8	0.30	2.11	7.06E-02	
Error	3.90	27	0.14			
Sum	15548.9	54				

*: the significant factor (P-value < 0.05)

**: A: brick, B: tile, C: hardened mortar replacement

3.3 *Regression analysis*

The application of regression equation is helpful and necessary for engineering design in order to predict the compressive strength, dynamic elasticity modulus, ultrasonic pulse velocity and surface electrical resistance of concrete with different types and replacement of recycled coarse aggregates. According Tables 3 to 6, the regression equations for predicting f'_c, E_d, V_p and R of HPRAC specimens with different types and replacement amounts of recycled aggregate were determined by using SPSS software, respectively, and given as following:

$$\begin{aligned} f'_C &= 45.674 - 0.489A - 0.222B - 0.151C \\ &\quad - 0.0087A^2 - 0.002B^2 + 0.00098C^2 \\ &\quad + 0.01AB + 0.004AC - 0.004BC \\ &\quad - 0.00022ABC \end{aligned} \tag{1}$$

$$\begin{aligned} E_d &= 40.214 - 0.146A - 0.090B - 0.134C \\ &\quad - 0.00091A^2 - 0.003B^2 + 0.002C^2 \\ &\quad + 0.006AB + 0.000044AC - 0.001BC \\ &\quad - 0.000054ABC \end{aligned} \tag{2}$$

$$\begin{aligned} V_P &= 4655.023 - 5.465A - 2.938B - 2.924C \\ &\quad - 0.036A^2 - 0.003B^2 + 0.022C^2 \\ &\quad - 0.09AB - 0.144AC - 0.235BC \\ &\quad + 0.014ABC \end{aligned} \tag{3}$$

$$\begin{aligned} R &= 22.180 - 0.274A - 0.214B - 0.346C \\ &\quad + 0.003A^2 - 0.000347B^2 + 0.006C^2 \\ &\quad + 0.006AB + 0.004AC + 0.0074BC \\ &\quad - 0.000244ABC \end{aligned} \tag{4}$$

where, the symbols of A, B and C indicates the replacement amount of recycled brick, tile and hardened mortar coarse aggregates, respectively.

According to equations (1) to (4), the factors of weighted influence of replacement amounts of various recycled coarse aggregate on the performance of HPRAC show that the replacement of brick aggregate is the most significant factor on the variations of the compressive strength, ultrasonic pulse velocity and surface electrical resistance of HPRAC.

4 CONCLUSIONS

(1) Major experimental results show that the compressive strength, dynamic elastic modulus, ultrasonic pulse velocity and surface electrical resistance of HPRAC concrete specimens decrease with the increase of the amounts of replacement with recycled coarse aggregate. By comparison with the NC, the maximum ratios of reduction occur in compressive strength and surface electrical resistance of 27.5% and 37.7%, respectively.

(2) According the results of statistical study, it confirms that the replacements of brick, tile and hardened mortar replacement are the significant factors on the performance of HPRAC concrete in all criteria of evaluations. Meanwhile, three regression equations are provided to predict the compressive strength, dynamic elasticity modulus, ultrasonic pulse velocity and surface electrical resistance of HPRAC concrete with different types and amount of replacements of recycled aggregate, respectively. From the analysis of weighted influence, the replacement of brick aggregate is the most significant influencing factor on the performance of HPRAC due to its lower specific weight and higher water apportion.

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