Civil Engineering and Architecture 2(4): 176-180, 2014
DOI: 10.13189/cea.2014.020404 http://www.hrpub.org

Experimental Investigation into the Freeze-Thaw Resistance of Concrete Using Recycled Concrete Aggregates and Admixtures

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Abstract This work investigates the effects of recycled concrete aggregates on the freeze-thaw resistance of the concrete. Taguchi orthogonal optimization technique was used in this investigation in order to minimize the number of samples required for each experiment. Therefore, only a few combination values of control factors required were chosen. Orthogonal table with three levels and four factors was used to prepare the mixing proportions. The results were analysis to check interaction among the factors. The results showed that in saturated Recycled Aggregate Concrete (RAC), the recycled aggregate has negative effects on its durability performance, therefore their use in structures exposed to severe climate is not strongly recommended. However, with the use of mineral and chemical admixtures, particularly air-entraining admixtures and fly ash, the recycled aggregate concrete could exhibit some level of durability.

Keywords Recycled Concrete Aggregates, Freeze-thaw Resistance, Air-Entraining Agent, Fly-ash

1. Introduction

Recycled concrete aggregates are aggregates obtained from recycled concrete, produced by the crushing of original concrete; such aggregates can be fine or coarse recycled aggregates. Fine recycled aggregate is sometimes referred to as crushed concrete fines. Recycled concrete aggregates may be also referred to as recycled aggregates [1].

Recycling old concrete has economic and environmental benefits. Economically, quality aggregates are in short supply in many places where concrete technology is needed, making it necessary to import aggregates from distant locations. Importing such aggregates can be very expensive because of cost of transportation, which can significantly increase the overall budget of a project. Environmentally, recycling may reduce the amount of construction debris disposed in landfills, and also the rate of natural resource depletion and environmental disturbance, thus having the potential to provide energy and save cost. Various benefits and challenges of using recycled materials in concrete have been extensively studied by many researchers [2-12].

Freeze-thaw resistance in concrete is very important in order to avoid excessive cracking, scaling and crumbling. If not properly taken care of, it can lead to substantial repair or replacement of any structure affected even before its life expectancy is reached. This work looks into the option of using recycled concrete aggregates as partial replacement for the conventional aggregates in concrete subjected to free-thaw resistance.

1.1. Mechanisms of Freeze-Thaw Damage.

Several theories have been proposed by different researchers to explain concrete damage due to freezing and thawing. Powers [13] (as contained in the United Stage Department of Transportation, Federal highway Administration (FHWA) Publication[14] was the first to put forth the hydraulic pressure theory, which states that damage from freezing is caused by a buildup of hydraulic pressure from the resistance to flow of unfrozen water in cement paste capillaries. When water begin to freeze in capillary pores, if the cement paste does not expand to accommodate it, unfrozen water will be pushed through the capillary pores, away from the sites of freezing, like water through a pipe. Powers applied Darcy's Law to illustrate the factors influencing the pressure generated by this flow also known as pressure gradient equation:

$$\Delta h = \frac{n}{k} Q \frac{l}{A} \tag{1}$$

Where,
Δh =pressure gradient
n =fluid viscosity
k =permeability
Q =flow rate
l = length of the flow path
A =flow area

1.2. Freezing and Thawing Resistance of Recycled Aggregates

Buck [15], in his work reported that the freeze-thaw resistance of original and recycled aggregate concrete was not significantly different. Strand [16] also reported results of tests on concrete specimens cast with coarse recycled aggregate and natural sand which indicate that recycled aggregate concrete is as durable as concrete made with virgin aggregates. Many of the recycled mixes tested exhibited better durability than concrete made with virgin materials. Hendriks [17] reports no significant difference in frost resistance of cores drilled from two concrete pavements near Helmond in the Netherlands. One pavement was made with conventional concrete and the other from recycled aggregate concrete. By visual inspection, Hasaba et al. [18] observed that it was the cement mortar adhering to the original aggregate particles in the recycled aggregates which deteriorated due to freezing and thawing.

2. Materials and Methods

100 x 100 x 400 mm concrete prisms were used to test the freeze and thaw cycles. Entrapped air was intentionally introduced though the use of air entraining agent. Air entering agent used in this study was (MNC-AE1) classified according to Chinese standard [19]. Table 1 gives the properties of the air-entraining agent. Taguchi Orthogonal Array table with three levels and four factors (AO L9 3^4 series) was used to prepare the mixing proportions [20]. The main factors used were the changes in water-cement ratio, the percentage of recycled coarse aggregates replacement with natural aggregate, percentage replacement of cement by fly ash and percentage of total fresh air. Fresh air percentage variation was achieved through the addition of air-entraining agent in order to stabilize the air entrapped during the mixing in the form of very small, discrete bubbles known as entrained air. Table 2 gives the nine sets of mix proportions of concrete using L9 (3^4 series) orthogonal array. Analysis of Variance was used to check the existence of interaction among the factors. The summary of the test factors and their levels for OA L9 are given in Table 3. All specimens were cast into plastic moulds and compacted using a vibrating table. The freeze-thaw resistance of concrete determines the overall resistance of the concrete to freezing and thawing. This condition was reflected in the laboratory by controlling the temperature using automatic equipment capable of producing periodic cycling, then reporting durability factors. In this study, the freeze–thaw cycling test was performed according to Chinese standard [21]. After 23days of standard moist curing as specified by the test method, three specimens for each mix immersed in water for 4 days after which they were weighed and tested for Fundamental Transverse Frequency before being exposed to the freezing and thawing cycles; these specimens were then put into the freeze–thaw apparatus, and were used to measure resonant frequency, weight loss and RDME after each 25 cycles until RDME dropped to 60%, and or its loss of weight exceeds 5.0% before the 300th cycle. The temperature of the concrete samples was controlled by a Pt sensor embedded in the center of the concrete. In a single cycle, the temperature of the specimens cools from 6 °C to −15 °C and then warms to 6 °C all within approximately 3.5-4 h. The Relative Dynamic Modulus of Elasticity (RDME) was measured at every 25 freeze–thaw cycles

Table 1. Properties of the air-entraining agent

Test Items		Results	Standard requirements (GB8076-1997)
Water Reducing Rate (%)		8	≥6
Ratio of Bleeding Rate (%)		/	≤80
PH		8	8±1
Difference in Setting time	Initial Final	+40	-90 ~ +120
		+85	-90 ~ +120
Ratio of compressive strength (%)	3Day	114	≥80
	7Day	95	≥80
	28Day	100	≥80
Density(g/cm^3)		1.07	1.05-1.10
Solid Content (%)		40	43- 52
Cement Flowing Rate(mm)		235	≥190
Air content (%)		5.6	>3
Addition Rate		0.005-0.015%of Cement	0.005-0.015%of Cement

Table 2. Nine sets of mix proportions of concrete using L9 (3^4 series) orthogonal array

Test No.	W/C[1]	RA[2] (kg/m^3)	FA[3] (kg/m^3)	NA[4] (kg)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	AEA[5] (L/100kg)
1	0.45	0	0	1160	153	340	650	0.008
2	0.45	559	68	580	153	8	650	0.033
3	0.45	1117	102	0	153	7	650	0.046
4	0.50	0	68	1160	170	8	650	0.043
5	0.50	559	102	580	170	7	650	0.002
6	0.50	1117	0	0	170	340	650	0.023
7	0.55	0	102	1160	187	7	650	0.020
8	0.55	559	0	580	187	340	650	0.040
9	0.55	1117	68	0	187	8	650	0.010

[1] W/C - Water-Cement ratio

[2] RA - Recycled aggregates

[3] FA-Fly-ash

[4] NA- Natural Aggregates

[5] AEA = Air-Entraining Admixture (Admixture dose is given in liters (L) per 100 kg of cement).

Table 3. Summary of test factors and their levels for OA L9 (3^4 series)

Level	Factors			
	(W/C)	(RA)	Fly-Ash(FA)	Air Content (AC)
1	0.45	0%	0%	2.5%
2	0.50	50%	20%	3.5%
3	0.55	100%	30%	4.5%

The Relative Dynamic Modulus of Elasticity (RDME) was calculated as follows

$$P = (x_n{}^2/\ x_0{}^2)\ x100 \qquad (2)$$

Where,
P=percentage of relative dynamic modulus of elasticity after C cycles of freezing and thawing.
n = number of cycles at the time of testing
x_n = fundamental transverse frequency after n cycles of freezing and thawing
x_0 = fundamental transverse frequency at zero cycles, in Hertz.

The durability factor (DF) was then determined as follows:

$$DF = (Pn/N)x100 \qquad (3)$$

Where,
DF =durability factor of the test specimen
P =percentage of relative dynamic modulus of elasticity
n =number of cycles completed
N=the planned duration of testing (usually 300 cycles)

Durability factor's scale ranges from 0-100. The 100 stands for the best possible frost resistance performance and 0 stands for the worst possible performance. From literatures, there is no established rating of the durability factor, interpretations vary from user to user.

The change in weight due to freezing and thawing cycles was calculated as follows:

$$\Delta W = [\ (G_0\text{-}G_n)/G_0]\ x\ 100 \qquad (4)$$

Where,
ΔW =weight change of specimen at C cycles of freezing and thawing in percent
G_0 =weight change of specimen at the beginning of the test in Kg.
G_n =weight of specimen after C cycles in Kg.

The set up for the measurement of the freeze-thaw resistance is shown in Figure 1.

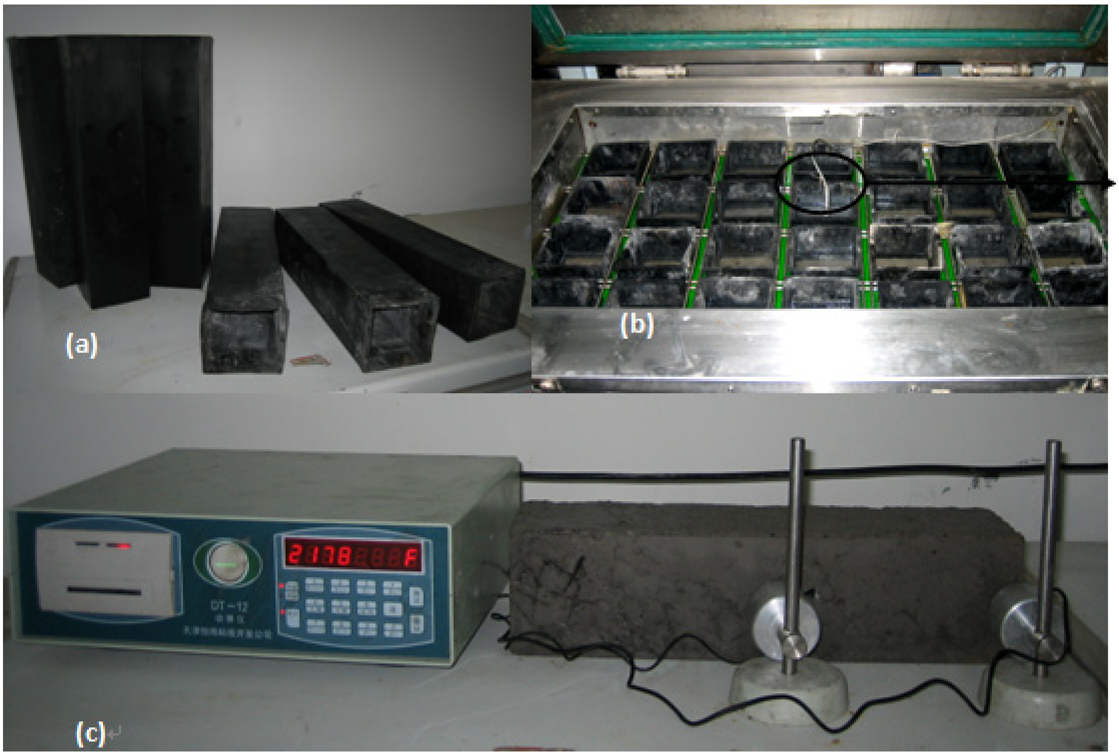

Figure 1. A freeze and thaw apparatus and set-up of the test. (a) Vertical containers for freeze-thaw concrete specimens (b) Freeze and thaw chamber showing the samples (c) Test set-up for resonant frequency. (x)Pt sensor

3. Results and Discussions

The weight change of the concrete specimens over the freezing and thawing cycles were also investigated and included in Appendix B while the summary is also presented in Table 4. The weight change was an indication of the deterioration of the concrete specimen and also provided the idea of moisture absorbed due to the cracking of specimen due to an expansion of the cement paste. Tables 5 gives the Orthogonal analysis for the final relative dynamic modulus of elasticity (RDME), durability factor (DF) mass change for all the mixes, all in percentages. From the table, the final relative dynamic of elasticity depends largely on the percentage of air content and the percentage volume of recycled aggregate contents. The water-cement ratio (within the range tested) does not appear to play a significant role on the on the final RDME. Final durability factors (DF) also follow the same trend. From the results one can conclude that addition of recycled aggregates might have adverse effect on the properties of concrete exposed to freezing and thawing particularly the RDME and DF. Also, the introduction of air by the use of an air entraining agent also improve the relative dynamic modulus of elasticity and durability factors of the samples

On the other hand, addition of fly-ash played a significant role on the final weight changes for the samples, followed by percentage volume of recycled aggregates. The significant role played by fly-ash in the final weight change might be due to the fact that fly-ash is known to be finer than cement, thereby resulting in more cementious particles per unit volume thus, allowing a greater packing density and resulting in a more refined cement paste. Consequently, this would have reduced the amount of capillary pores in the concrete mixes, thereby resulting in a less porous paste.

Table 4. Summary of freeze-thaw test results for the nine mixes.

Test no.	W/C	AC (%)	Cycles	Final RDME[5] (%)	DF[6] (%)	Final mass change (%)
1	0.45	2.5	200	58.19	38.79	0.300
2	0.45	3.5	200	62.61	41.74	0.500
3	0.45	4.5	200	65.74	43.83	5.300
4	0.50	4.5	200	86.42	57.61	1.167
5	0.50	2.5	200	60.07	40.05	1.800
6	0.50	3.5	200	57.76	38.51	1.300
7	0.55	3.5	200	65.30	43.53	2.833
8	0.55	4.5	200	53.76	35.84	1.500
9	0.55	2.5	150	49.94	24.97	1.733

[5] RDME- Relative Dynamic Modulus of Elasticity

[6] DF- Durability Factor

Table 5. L9 (3^4 Series) Orthogonal analysis for final RMDE and DF of the freeze-thaw samples

	Factors	***E1**	***E2**	***E3**	****R**
Final RMDE	W/C	62.18	68.08	56.33	11.75
	RA	69.97	58.81	57.81	12.16
	FA	56.57	66.32	63.70	9.75
	AC	56.07	61.89	68.64	15.57
Final DF	W/C	41.45	45.39	34.78	10.61
	RA	46.64	39.21	35.77	10.87
	FA	37.71	41.44	42.47	4.76
	AC	34.60	41.26	45.76	11.16
Final Weight Change	W/C	2.03	1.42	2.02	0.61
	RA	1.43	1.27	2.78	1.51
	FA	1.03	1.13	3.31	2.28
	AC	1.28	1.54	2.66	1.38

*E1, E2, E3, - Average effect of three factors at level 1, 2 or 3.

**R –Rank of significance among the factors.

4. Conclusions

The use of recycled aggregates resulted in reduced freeze-thaw resistance due to the saturation of the aggregates during the test. This conclusion is valid for recycled aggregate concrete tested when air entraining admixture was used.

Lower water-cement ratio was beneficial to the development of the freeze-thaw durability of the concrete tested.

Use of fly ash resulted in significant improvement of the freeze-thaw durability and caused no significant reduction in their corresponding properties.

Acknowledgements

Nigerian Scholarship Board and China Scholarship Council are acknowledged for the bilateral educational agreements scholarship programme that afforded the opportunity to carry out this research.

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