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Optimal Design Criteria for Recycled Aggregate Concrete

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ABSTRACT
Based on the experimental work on recycled aggregate concrete (RAC) from different mix proportions, including recycled aggregate (RA) replacement ratios, water-to-cement ratios and aggregate-to-cement ratios, this project develops optimal design criteria for RAC. The optimal design criteria for RAC with five accurate prediction equations among compressive strength, tensile strength and flexural strength of the RAC was developed in this project by using linear regression analysis. The developed equations can be used to predict characteristic compressive, tensile and flexural strength by providing parameters of the mix proportions or from one of the characteristic strength or from the properties of the RA collected from the centralised recycling plants or construction and demolition sites with their designed mix proportions.

Keywords. Optimal design criteria, recycled aggregate concrete, recycled aggregate

INTRODUCTION
Environmental control is an increasingly pressing concern in the construction industry. Natural resources are consumed in its day-to-day operations and waste is generated. Construction activities thereby impose significant environmental impacts over the entire construction life cycle (Polster *et al.* 1996; Morledge and Jackson 2001). Waste management in the construction industry has not been successfully controlled, and it is challenging to initiate improvement. It has been thought that the reuse and recycling of materials will provide effective means to reduce the impact on limited landfill spaces and also improve waste management. This paper aims to study the use of RA from demolished concrete waste as RAC and develops optimal design criteria of RAC for structural applications.

RESEARCH METHODOLOGIES
RA samples collected from the south-eastern Australia centralised recycling plant were used for investigating the properties of RAC. The experimental work on RAC from different mix proportions, including replacement ratios of RA from 0% to 100%, water-to-cement ratios at 0.35, 0.40, 0.45, 0.50, 0.55 and 0.60, and aggregate-to-cement ratios at 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0, are investigated on strength behaviour.

OPTIMAL DESIGN CRITERIA FOR RECYCLED AGGREGATE CONCRETE
Data collected from the experimental work were analysed using the Statistical Package for Social Sciences (SPSS) Version 18.0 for Windows. It is clear that the relationship between different parameters of the RA, including RA replacement ratios, amount of water used, amount of cement used, amount of sand used, water-to-cement ratio and aggregate-to-cement ratio, and compressive, tensile and flexural strength are linear. The implication is that the higher RA replacement ratio will deteriorate the concrete strength.

Linear regression analysis is used for the development of the prediction equations for the RAC optimal design criteria. Table 3 shows the correlation among the characteristic strengths and quantities of different RA replacement, water, cement, sand, water-to-cement ratio and aggregate-to-cement ratio. The correlation between $f_{c'}$ and the replacement ratios of the 10 mm RA, 10 mm NA, 20 mm RA, 20 mm NA, water, cement, sand, RA replacement ratio, water-to-cement ratio and aggregate-to-cement ratio are 0.538, 0.512, 0.538, 0.512, 0.660, 0.646, 0.344, 0.528, 0.804 and 0.580 respectively. The significant value between the characteristic strengths and RA parameters in Table 3 are all less than 0.05, which means that all correlations are significant at the 95% confidence level. The sensibility analysis results for the data for RAC is 0.918, which shows that the data is suitable for analysis and the development of the optimal design criteria.

Table 1: Characteristic of compressive, tensile and flexural strength

Water-to-cement ratios	Aggregate-to-cement ratios	RA replacement ratios	Average compressive strength, (MPa)	Average tensile strength (MPa)	Average flexural strength (MPa)	Characteristic compressive strength, $f_{c'}$ (MPa)	Characteristic tensile strength, $f_{ct'}$ (MPa)	Characteristic flexural strength, f_{cf}' (MPa)
0.3	4.5	0	70.99	5.94	6.64	69.77	5.18	6.33
		30	63.92	5.23	6.08	63.60	4.78	5.80
		100	49.19	4.76	4.14	47.51	4.50	4.00
0.35		0	68.01	5.60	6.16	66.33	4.93	5.90
		30	56.21	4.92	5.51	53.95	4.58	5.17
		100	46.00	4.49	4.00	44.73	3.96	3.91
0.4		0	62.00	5.33	5.80	61.50	4.70	5.31
		30	53.73	4.85	5.00	52.14	4.46	4.47
		100	41.90	4.16	3.83	39.47	4.03	3.30
0.45		0	56.80	5.14	5.58	53.11	4.89	4.72
		10	55.40	5.03	5.00	54.52	4.78	4.82
		20	55.10	4.90	4.93	48.69	4.08	4.26
		30	52.40	4.73	4.55	49.07	4.40	3.99
		40	51.97	4.64	4.39	50.89	4.23	3.69
		50	50.00	4.51	4.05	42.22	4.20	3.83
		60	48.00	4.62	4.35	46.43	4.31	4.20
		70	46.80	4.37	4.20	43.73	3.78	3.83
		80	47.24	4.25	4.15	43.93	3.66	3.69
		90	44.20	4.09	4.06	41.09	4.00	3.51
		100	39.10	3.83	3.80	34.93	3.42	3.65
0.5		0	46.00	4.63	4.86	45.34	4.24	4.65
		30	43.40	4.37	4.33	41.20	3.89	3.89
		100	32.00	3.41	3.50	30.39	3.09	2.88

Table 2: Characteristic of compressive, tensile and flexural strength

Water-to-cement ratios	Aggregate-to-cement ratios	RA replacement ratios	Average compressive strength, (MPa)	Average tensile strength (MPa)	Average flexural strength (MPa)	Characteristic compressive strength, $f_{c'}$ (MPa)	Characteristic tensile strength, $f_{ct'}$ (MPa)	Characteristic flexural strength, f_{cf}' (MPa)
0.55	4.5	0	40.00	4.14	4.40	37.24	3.97	4.01
		30	37.22	3.89	3.98	34.74	3.28	3.72
		100	29.00	3.09	3.12	27.38	2.94	2.90
0.6		0	32.21	3.80	4.20	30.35	3.51	3.72
		30	32.30	3.57	3.60	30.56	2.65	3.12
		100	25.26	2.95	3.02	21.78	2.81	2.76
0.45	3.0	0	80.40	6.24	6.67	78.67	6.07	6.55
		30	74.01	5.55	5.79	72.66	4.83	5.08
		100	55.46	4.52	4.75	54.47	4.32	3.88
	3.5	0	73.10	5.76	6.20	72.22	4.95	5.96
		30	65.94	5.24	5.34	63.59	4.70	5.02
		100	51.82	4.33	4.22	50.22	4.09	4.03
	4.0	0	66.12	5.40	5.85	64.39	4.99	5.51
		30	57.13	4.97	4.79	56.18	4.61	4.46
		100	45.62	4.13	3.92	44.12	3.67	3.72
	5.0	0	52.20	4.92	4.89	49.49	4.57	4.56
		30	47.60	4.55	4.27	47.24	4.48	3.73
		100	34.35	3.64	3.42	33.39	3.43	3.28
	5.5	0	50.42	4.60	4.40	49.28	4.02	3.35
		30	42.91	4.26	3.87	40.45	3.23	3.58
		100	32.30	3.43	3.08	31.90	3.22	2.69
	6.0	0	42.93	4.26	4.00	41.45	3.88	3.08
		30	34.92	3.72	3.64	34.09	3.34	3.21
		100	27.13	2.92	2.84	24.34	2.28	2.09

Table 3: Correlation between characteristic strengths and quantity of mix proportions by proportional

		fc	fct	fcf	RA10	NA10	RA20	NA20	Water	Cement	Sand	RAtotal	WC	AC
fc	Pearson Correlation	1	.926**	.915**	-.538**	.512**	-.538**	.512**	-.660**	.646**	-.344**	-.528**	-.804**	-.580**
	Sig. (1-tailed)		.000	.000	.000	.000	.000	.000	.000	.000	.009	.000	.000	.000
fct	Pearson Correlation	.926**	1	.892**	-.557**	.537**	-.557**	.537**	-.628**	.566**	-.278*	-.550**	-.756**	-.529**
	Sig. (1-tailed)	.000		.000	.000	.000	.000	.000	.000	.000	.029	.000	.000	.000
fcf	Pearson Correlation	.915**	.892**	1	-.616**	.594**	-.616**	.594**	-.575**	.565**	-.303*	-.610**	-.730**	-.551**
	Sig. (1-tailed)	.000	.000		.000	.000	.000	.000	.000	.000	.019	.000	.000	.000
RA10	Pearson Correlation	-.538**	-.557**	-.616**	1	-.997**	1.000**	-.997**	-.005	-.033	.036	.999**	.012	.029
	Sig. (1-tailed)	.000	.000	.000		.000	.000	.000	.486	.412	.404	.000	.469	.423
NA10	Pearson Correlation	.512**	.537**	.594**	-.997**	1	-.997**	1.000**	-.010	-.033	.038	-.999**	.015	.038
	Sig. (1-tailed)	.000	.000	.000	.000		.000	.000	.474	.414	.400	.000	.459	.400
RA20	Pearson Correlation	-.538**	-.557**	-.616**	1.000**	-.997**	1	-.997**	-.005	-.033	.036	.999**	.012	.029
	Sig. (1-tailed)	.000	.000	.000	.000	.000		.000	.486	.412	.405	.000	.469	.423
NA20	Pearson Correlation	.512**	.537**	.594**	-.997**	1.000**	-.997**	1	-.010	-.033	.038	-.999**	.016	.038
	Sig. (1-tailed)	.000	.000	.000	.000	.000	.000		.475	.414	.400	.000	.459	.400
	Pearson Correlation	-.660**	-.628**	-.575**	-.005	-.010	-.005	-.010	1	-.272*	-.198	.001	.827**	.188
	Sig. (1-tailed)	.000	.000	.000	.486	.474	.486	.475		.032	.091	.497	.000	.103
	Pearson Correlation	.646**	.566**	.565**	-.033	-.033	-.033	-.033	-.272*	1	-.889**	-.005	-.748**	-.974**
	Sig. (1-tailed)	.000	.000	.000	.412	.414	.412	.414	.032		.000	.487	.000	.000
	Pearson Correlation	-.344**	-.278*	-.303*	.036	.038	.036	.038	-.198	-.889**	1	.004	.369**	.903**
	Sig. (1-tailed)	.009	.029	.019	.404	.400	.405	.400	.091	.000		.489	.005	.000
	Pearson Correlation	-.528**	-.550**	-.610**	.999**	-.999**	.999**	-.999**	.001	-.005	.004	1	.000	.000
	Sig. (1-tailed)	.000	.000	.000	.000	.000	.000	.000	.497	.487	.489		.500	.500
	Pearson Correlation	-.804**	-.756**	-.730**	.012	.015	.012	.016	.827**	-.748**	.369**	.000	1	.707**
	Sig. (1-tailed)	.000	.000	.000	.469	.459	.469	.459	.000	.000	.005	.500		.000
	Pearson Correlation	-.580**	-.529**	-.551**	.029	.038	.029	.038	.188	-.974**	.903**	.000	.707**	1
	Sig. (1-tailed)	.000	.000	.000	.423	.400	.423	.400	.103	.000	.000	.500	.000	

** Correlation is significant at the 0.01 level (1-tailed). * Correlation is significant at the 0.05 level (1-tailed).

There are four methods – Stepwise, Remove, Backward and Forward – used in the linear regression analysis. Prediction equations will be developed if the correlation significant (sig. or α) of the models is less than 0.05, which leads to the development of Equation 1 and Equation 2.

$$f_c' = 105.118 - (111.411 \times WC) - (1.161 \times RA10)$$ **Equation 1**

$$f_c' = 324870 + (69.32 \times Water) - (26.148 \times Sand) - (0.175 \times RAtotal) - (132236 \times WC) + (131.455 \times AC)$$

Equation 2

where $f_{c'}$ is the characteristic compressive strength; *WC* the water-to-cement ratio; *RA10* the replacement ratios of 10 mm RA; *Water* the quantity of water by proportion of mix proportion (%); *Sand* the quantity of sand by proportion of mix proportion (%); *RATotal* the total RA replacement ratio; and *AC* aggregate-to-cement ratio.

The same procedure is also used for the development of the model for the characteristic tensile and flexural strength with the RA parameters, which leads to the development of Equation 3 and Equation 4 respectively.

$$f_{ct}' = 7.192 - (5.892 \times WC) - (0.01 \times RATotal)$$ **Equation 3**

$$f_{cf} = 8.246 - (7.648 \times WC) - (0.015 \times RATotal)$$ **Equation 4**

where $f_{ct'}$ is the characteristic tensile strength; and $f_{ct'}$ is the characteristic flexural strength.

Equation 1, Equation 2, Equation 3and Equation 4 are provided to predict target characteristic compressive, tensile and flexural strength from mix proportions. The independent variables for Equation 1 are water-to-cement ratio and replacement ratios of 10 mm RA. The independent variables for Equation 3 and Equation 4 are water-to-cement ratio and total RA replacement ratios. Equation 1 is reanalysed using the same independent variables as in Equation 3 and Equation 4 in the linear regression analysis with the four methods, Equation 5 is deviated.

$$f_c' = 105.509 - (112.283 \times WC) - (0.175 \times RATotal)$$ **Equation 5**

CONCLUSION

The optimal design criteria for RAC with five accurate prediction equations was developed in this chapter by using linear regression analysis. The developed equations can be used to predict characteristic compressive, tensile and flexural strength by providing parameters of the mix proportions or from one of the characteristic strength.

REFERENCES

Acker, A. V. (1998). Recycling of concrete at a precast concrete plant. Proceedings of the International Symposium on Sustainable Construction: Use of Recycled Aggregate. London, UK, Thomas Telford**:** 321-332.

Ahmed, A. a. S., L. (1995). "Effects of microstructure of fracture behaviour of hardened cement paste." *Microstructure of Cement-Based Systems/Bonding and Interfaces in Cementitious Materials: Symposia*, Boston, Massachusetts, U.S.A.

Aitcin, P. C. and Neville, A. M. (1993). "High performance concrete demystified." *Concrete International*, 15(1), 21-26.

Ajdukiewicz, A. and Kliszuzewicz, A. (2002). "Influence of recycled aggregates on mechanical properties of HS/HPC." *Cement and Concrete Composites*, 24(2), 269-279.

Alexander, M. G. (1996). *The effects of ageing on the interfacial zone in concrete*. RILEM Report, Interfacial Transition Zone in Concrete: State-of-the-Art Report. London, E&FN Spon. **11:** 150-174.

AS1012 (1993). *Methods of testing Concrete*, Australian Standard.

AS 3600 (2001). *Concrete structure*. New South Wales, Standards Australia

Bakoss, S. L. and Ravindrarajah, R. S. (1999a). *Recycled construction and demolition materials for use in roadwork and other local government activities*, Institute of Municipal Engineering Australia (NSW Division), New South Wales Government, Sydney, Australia.

Bakoss, S. L. and Ravindrarajah, R. S. (1999b). *Recycled construction and demolition materials for use in roadworks and other local government activities*, Institute of Municipal Engineering Australia (NSW Division), New South Wales Government, Sydney, Australia.

Bentz, D. P. and Garboczi, E. J. (1991). "Simulation studies of the effects of mineral admixtures on the cement paste-aggregate interfacial zone." *ACI Materials Journal* September-October518-529.

Buch, N., Frabizzio, M. A. and Hiller, J. E. (2000). "Impact of coarse aggregates on transverse crack performance in jointed concrete pavements." *ACI Materials Journal*, 97(3), 325-332.

Carneiro, A. P., et al (2000). "Construction waste characterization for production of recycled aggregate - Salvador / Brazil." *Waste Materials in Construction: WASCON 2000: Proceeding of the International Conference on the Science and Engineering of Recycling for Environmental Protection*, Harrogate, England.

Coventry, S., Wolveridge, C. and Hillier, S. (1999). *The reclaimed and recycled construction materials handbook*, London: Construction Industry Research and Information Association.

Engineer Forum (2011). http://civil4m.com/showthread.php/55-Methods-of-proportioning-concrete, Engineer Forom.

Farran, J. (1956). "Contribution of microstructure of minerals and their bonding with Portland cement paste." *Rev, Material, Construction, Travel Publics*490-491.

Howard Humphreys and Partners (1994). *Managing demolition and construction wastes: report of the study on the recycling of demolition and construction wastes in the UK*, London: HMSO

Jia, W., Baoyuan, L., Songshan, X. and Zhongwei, W. (1986). "Improvement of paste-aggregate interface by adding silica fume." *Proceedings of the 8th International Congress on the Chemistry of Cement, Volume 3*, Rio de Janeiro, Brazil.

Kawano, H. (2000). "Barriers for sustainable use of concrete materials." *Concrete Technology for a Sustainable Development in the 21st Century*, Lofoten, Norway, E&FN Spon.

Keru, W. and Jianhua, Z. (1988). "The influence of the matrix-aggregate bond on the strength and brittleness of concrete." *Bonding in Cementitious Composites, Materials Research Society*, 11429-34.

Kwan, A. K. H., Wang, Z. M. and Chan, H. C. (1999). "Microscopic study of concrete II: nonlinear finite element analysis." *Computers and Structures*, 71(5), 545-556.

Li, G., Xie, H. and G., X. (2001). "Transition zone studies of a new-tools concrete with different binders." *Cement and Concrete Composites*, 23(4-5), 381-387.

Lo, Y. T. (2000). Microstructure study of the aggregate/cement paste interfacial zone of lightweight concrete. Department of Building and Construction. Hong Kong, City University of Hong Kong

Metha, P. K. and Aitcin, P. C. (1990). "Microstructural basis of selection of materials and mix proportions for high strength concrete." *High Strength Concrete, Second International Symposium, ACI SP-121*265-286.

Mitsui, K., Li, Z., Lange, D. A. and Shah, S. P. (1994). "Relationship between microstructure and mechanical properties of the paste-aggregate interface." *ACI Materials Journal* 91(1), 30-39.

Mohamed, A. R. and Hansen, W. (1999). "Micromechanical modeling of crack-aggregate interaction in concrete materials." *Cement and Concrete Composites* 21(5-6), 349-359.

Morledge, R. and Jackson, F. (2001). "Reducing environmental pollution caused by construction plant." *Environmental Management and Health*, 12(2), 191-206.

Noguchi, T. and Tamura, M. (2001). "Concrete design towards complete recycling." *Structural Concrete*, 3(2), 155-167.

Olorunsogo, F. T. and Padayachee, N. (2002). "Performance of recycled aggregate concrete monitoring by durability indexes." *Cement and Concrete Research* 32(2), 179-185.

Polster, B., Peuportier, B., Sommereux, I. B., D., P. P., Gobin, C. and Durand, E. (1996). "Evaluation of the environmental quality of buildings towards a more environmentally conscious design." *Solar Energy*, 57(3), 219-230.

Popovics, S. (1987). "Attempts to improve the bond between cement paste and aggregate." *Materials and Structures* 20(115), 32-38.

Ravindrarajah, R. S. and Tam, C. T. (1988). *Methods of improving the quality of recycled aggregate concrete*. Demolition and reuse of concrete and masonry: reuse of demolition waste, London: Chapman and Hall**:** 575-584.

Sobhan, K. and Krizek, R. J. (1999). "Fatique behaviour of fiber-reinforce recycled aggregate base concrete." *Journal of Materials in Civil Engineering*, 11(2), 124-130.

Tasdemir, M. A., Tasdemir, C., Akyuz, S., Jefferson, A. D., Lydon, F. D. and Barr, B. I. G. (1998). "Evaluation of strains at peak stress in concrete: a three phase composite model approach." *Cement and Concrete Composites*, 20(4), 301-318.

Tech Data Sheet (1998). *Recycling spent sandblasting grit and similar wastes as aggregate in asphaltic concrete*, Naval Facilities Engineering Service Center, Port Hueneme, Falifornai 4370.

Tomasawa, F. and Noguchi, T. (2000). "New technology for recycling of concrete - Japanese experience." *Concrete Technology for a Sustainable Department in the 21st Century*, Lofoten, Norway, E & FN Spon.

Torring, M. (2000). *Management of concrete demolition waste*. Concrete technology for a sustainable development in the 21st century, London: New York: E & FN Spon**:** 321-331.

Wang, Z. M., Kwan, A. K. H. and Chan, H. C. (1999). "Microscopic study of concrete I: generation of random aggregate structure and finite element mesh." *Computers and Structures*, 70(5), 533-544.

Xiao, J., Li, J. and Zhang, C. (2005). "Mechanical properties of recycled aggregate concrete under uniaxial loading." *Cement and Concrete Research*, 35(6), 1187-1194.

Xueqan, W., Dongxu, L., Qinghan, B., Liqun, G. and Mingshu, T. (1987). "Preliminary study of a composite process in concrete manufacture." *Cement and Concrete Research*, 17(5), 709-714.