RELIABILITY ESTIMATION OF RECYCLED AGGREGATE CONCRETE STRUCTURE SUBJECTED TO CARBONATION

T.M. KEA[1*] and M. AKIYAMA[1†]

[1]*Department of Civil and Environmental Engineering, Waseda University, Japan*

ABSTRACT

The life-cycle assessment of reinforced concrete structures through economic, environmental, and social impact across the whole service life is now gaining more and more interest in civil engineering. The mechanical properties and long-term performance of structures using recycled aggregate concrete (RAC) were reported to be weaker than those of structures using natural aggregate concrete (NAC) given the same mix proportion. However, the studies on the durability of RAC subjected to carbonation are scare and limited in the literature. The main purpose of this study is to present the computational procedure for the life-cycle reliability estimations of NAC and RAC structures exposed to carbonation. The experimental results of NAC and RAC under the diffusion of carbon dioxide (CO_2) are obtained from the literature reviews. A durability design factors and criterion for designing concrete structure using RAC that satisfy the target failure probability is presented. The effects of concrete properties (i.e. water to cement ratio) and concrete cover on the estimation of reliability of structures using natural and recycled aggregate are investigated in an illustrative example.

Keywords: Recycled aggregate concrete, carbonation, failure probability, concrete cover.

1. INTRODUCTION

It is very interesting to notice that concrete is the second most consumed material after water. China is well-known to be the most consuming concrete around the world. It is estimated that approximately 200 million tons of concrete waste are producing annually in China (Xiao et al. 2012) comparable with an estimated 900 million tons of construction and demolition waste in Europe, the US, and Japan (Klee 2009). If the concrete waste is not reused or recycled, it has to be thrown away in the landfill and therefore large amount of vacant space and energy will be required.

The sustainable development is the judicious use of natural aggregate (NA) by "3Rs" strategies: Reduce, Reuse, and Recycle. It is the sophisticated and cost-effectiveness methods to contribute to environmental protection and construction sustainability achievement. Once recycled aggregate

[*] Presenter: Email: theangmeng@asagi.waseda.jp

[†] Corresponding author: Email: akiyama617@waseda.jp

(RA) is widely available, the demand will gradually increase and cost will be comparatively lower. In addition, the demand of NA could be reduced.

The effects of RA on material properties (Padmini et al. 2009), on mechanical properties (Xiao et al. 2005), on structural properties (Sato et al. 2007), and on durability performance (Levy et al. 2004) have been investigated experimentally. It has been found that RAC properties were lower than those of NAC due to its lower density, higher water absorption, and higher porosity. The weaknesses could be improved by incorporating pozzolanics materials, by the treatments of recycled aggregate, and/or by new mixing methods. However, the application of RAC in structural application is still limited. For example, up to two-third of UK construction and demolition wastes were known to be recycled, but only 4% of them was used as RA for concrete production and the rest was used for landfill (Thomas et al. 2009). Researchers used their own methodologies to conduct experiments causing the difficulties in applying research outputs to the design of RAC structures. In order to meet the durability design requirement, RAC structures should have sufficient concrete quality and cover to resist harmful effects by carbonation. However, because of the presence of uncertainties associated with the prediction of carbonation, it is essential that long-term structural performance is treated based on reliability concepts and methods. Stochastic treatment of structural design problems takes into account the uncertain nature of long-term structural performance making a reliable design of concrete structures possible. This study aims to estimate (1) the failure probability of the NAC and RAC structures subjected to carbonation and (2) the appropriate concrete cover to meet the required service life of structures.

2. DURABILITY OF RECYCLED AGGREGATE CONCRETE

Durability of concrete is the capacity to resist the processes of deterioration when concrete is exposed to an aggressive environment. The Portland-cement concrete is highly crack-prone, porous, and permeable causing the embedded steel reinforcement to corrode with time resulting in the progressive deterioration of concrete structures. In addition, the RAC is even more porous than NAC. The incorporation of RA in concrete decreased the resistance of concrete to carbonation. It might prevent the practical application of RA in structural concrete (Kou et al. 2013). Durability plays significant roles in the life-cycle cost estimation of structures; for example, in Japan, it is estimated that the maintenance and renovation costs for infrastructures exceed 70% of the total public investment in 2010. In the United States, it is estimated that the necessary repairs and improvements to the infrastructure will amount to $3.3 trillion over a period of 19 years (Tam et al. 2007). Therefore, durability has gained more interest and become a common matter of social importance.

Most of the experimental results of recycled aggregate and conventional concrete in the literature subjected to the carbonation are not comparable due to the heterogeneity of RAs, water to cement ratios (*w/c*), cement types, experiments procedure, and different curing conditions. It could be difficult to estimate the long-term performance of concrete structures exposed to CO_2. The extra alkaline reserve of RAC due to the presence of the attached old mortar plays a role in decreasing the carbonation rate. In order to obtain the same compressive strength, RAC requires lower *w/c*. Reducing the effective *w/c* in concrete production can improve the mechanical and durability properties of RAC (Kou et al. 2013).

3. CARBONATION TEST OF RECYCLED AGGREGATE CONCRETE

The carbonation depth of concrete is one of the parameter to evaluate the resistance of the concrete to CO_2 diffusion. Although the specimens could be cured in the real outdoor environment, it takes longer time to investigate. The specimens are able to be kept in the humidity chamber with high CO_2 concentration with constant temperature and relative humidity. In the real atmosphere, CO_2 concentration is about 0.0392% (Tans and Keeling 2012). After particular curing period, specimens are removed and carbonation depths are measured by spraying a 1% phenolphthalein solution dissolved in 70% ethylic alcohol and 30% distilled water and by checking the carbonated (white color) and non-carbonated (pink color) areas (Lovato et al. 2012). Assuming that carbonation depths vary linearly through square root of time (Evangelista et al. 2010), carbonation depths could be estimated by

$$d = k\sqrt{t} \tag{1}$$

where d (mm) is the carbonation depth, k is the carbonation velocity coefficient, and t (years) is the exposed time of concrete to carbonation. Therefore, the carbonation depth of NAC and RAC at particular lifetime could be obtained readily from the experimental results of the previous researches as shown in Figure 1.

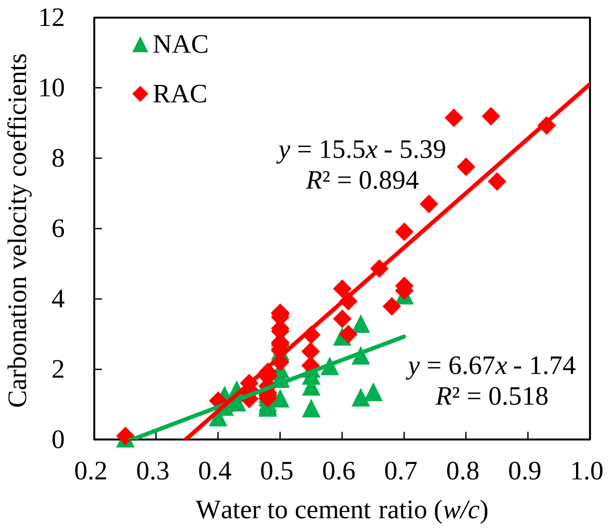

Figure 1: Carbonation velocity coefficients of NAC and RAC.

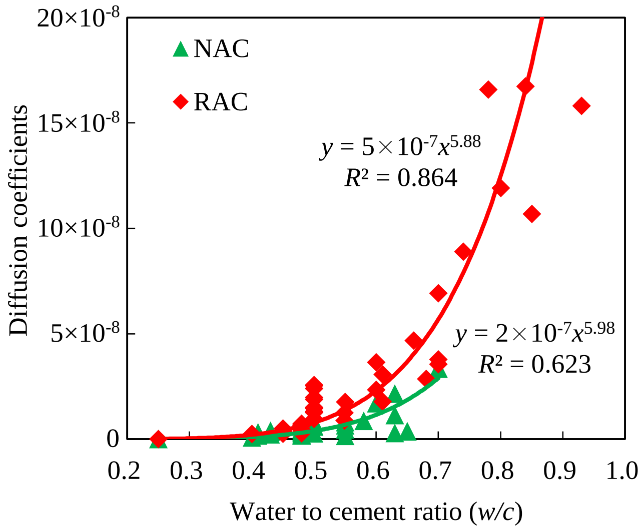

Figure 2: Diffusion coefficient of CO_2 of NAC and RAC from the Equation (3).

4. FAILURE PROBABILITY OF RAC STRUCTURE SUBJECTED TO CARBONATION

For durability design of reinforced concrete structures, it is important to ensure that the embedded steel has enough concrete cover to protect reinforcing steel from excessive moisture or chemical corrosion throughout its design service life, especially when the concrete structures are exposed to the aggressive environment. Concrete is the porous material so that CO_2 is able to diffuse more deeply into the concrete at a rate proportional to the square root of time as shown in Equation (1). In the estimation of time to steel corrosion initiation, the corrosion of steel is assumed to start when the carbonation depth reaches 80% of concrete cover (Hussain et al. 2009). In the reliability analysis, the probabilities $P_f(t)$ of the initiation of steel corrosion in reinforced concrete structures at time t could be evaluated by

$$P_f(t) = P\left\{0.8\chi_1 c - d_c(D_{CO_2}, w/c, RH, T, t_e, \Re) \le 0\right\} < PF_{target} \tag{2}$$

where χ_1 is the model uncertainty associated with concrete cover c (mm), D_{CO2} (m/sec^2) is the diffusion coefficient of CO_2, d_c (mm) is the carbonation depth calculated from D_{CO2} (m/sec^2), RH is the relative humidity, T (^oC) is the exposed temperature, t_e is the equivalent hydration period of curing at $RH = 1$, $\Re$ is the degree of chemical reaction, and PF_{target} is the target failure probability (0.1, 0.05, and 0.01). The diffusion coefficient of CO_2 through the carbonated concrete can be identified based on the previous experimental results using specimens exposed in a climatic room with temperature of 25±1^{o}C and relative humidity of 65±5% (Lovato et al. 2012).

$$d_c^2 = 2D_{CO_2}(w/c, RH, T, t_e, \Re)\frac{C_{CO_2}}{C_c}t \tag{3}$$

where C_{CO2} (kg/m^3) is the atmospheric CO_2 concentration, C_c (kg/m^3) is the amount of CO_2 required for the completion of carbonation of concrete, $C_{CO2}/C_c = 8\times10^{-6}$ for the normal weight concrete made of Portland cement and exposed to a standard environment (Telford 1993), and t (sec) is the exposed time. From Figure 2, the estimation equations of the diffusivities of NAC and RAC, Equations (4) and (5) could be obtained by Power regression equation.

$$D_{CO_2,exp,NAC}(w/c) = 2\times10^{-7}\chi_2(w/c)^{5.98} \tag{4}$$

$$D_{CO_2,exp,RAC}(w/c) = 5\times10^{-7}\chi_3(w/c)^{5.88} \tag{5}$$

where $D_{CO2,exp,NAC}(w/c)$ and $D_{CO2,exp,RAC}(w/c)$ are the diffusion coefficients of NAC and RAC from the experimental data, respectively, χ_2 is the model uncertainty associated with the estimation of $D_{CO2,exp,NAC}$, χ_3 is the model uncertainty associated with the estimation of $D_{CO2,exp,RAC}$. The diffusion rate of CO_2 depends not only the properties of concrete, but also the surrounding environment condition including CO_2 concentration, temperature, relative humidity, cement hydration process, and the chemical reactions between cementitious components and the aggressive species (Saetta et al. 1993; Saetta et al. 2004). In order to include these effects, the effective diffusion coefficient is modified by

$$D_{CO_2}(w/c, RH, T, t_e, \Re) = D_{CO_2,exp}(w/c) F_1(RH) F_2(T) F_3(t_e) F_4(\Re) \quad (6)$$

$$F_1(RH) = (1 - RH)^{2.5} \quad (7)$$

$$F_2(T) = \exp\{Q/R[1/T_0 - 1/(T + 273)]\} \quad (8)$$

$$F_3(t_e) = \chi + (1 - \chi)(28/t_e)^{0.5} \quad (9)$$

$$F_4(\Re) = 1 - \zeta\Re \quad (10)$$

where $D_{CO2,exp}$ (*w/c*) is the diffusion coefficient of CO_2 from Equations (4) and (5), $F_1(RH)$ takes into account the decrease in CO_2 diffusivity as the relative humidity increases; for example, it could be said that the carbonation depth of outdoor concrete is lower than that of indoor concrete, $F_2(T)$ is the semi-empirical expression, $F_3(t_e)$ slows the diffusion as the degree of cement hydration increases, $F_4(\Re)$ weakens the CO_2 diffusivity capacity due to the reduction of porosity in the concrete by carbonation process, *Q* is the activation energy, *R* is the gas constant, *Q/R* is the activation temperature defined by Saetta et al. (1993), T_0 (K) is the reference temperature, *T* (°C) is the exposed temperature, $\chi = D_\infty/D_{28}$ is the ratio of diffusion at infinity time and at 28 days (Saetta et al. 2005), t_e (days) is the equivalent hydration period at *RH* = 1 which can be seen in Equation (11) (Saetta et al. 1993), ζ is the parameter varying between 0 and 1, and $\Re = [CaCO_3]/[CaCO_3]_{max}$ is the degree of chemical reaction (Saetta et al. 2004). In this study, it is assumed that *Q/R* = 4700K, T_0 = 298K, χ = 0.8, ζ = 0.8, and $\Re$ = 0.1.

$$t_e = \int_0^t \beta_T \beta_h dt \quad (11)$$

where $\beta_T = \exp\{U_R/R[1/T_0 - 1/(T+273)]\}$ and $\beta_h = [1+(\alpha - \alpha RH)^4]^{-1}$ is the effect of temperature and humidity on the rate of cement hydration reaction, respectively, U_h is the activation energy of hydration, and α is the value for computational calculation in Saetta et al. (1993). In this study, it is assumed that $U_h/R = 4600[30/(T+10)]^{0.39}$ and α = 5. The failure probabilities of NAC and RAC subjected to carbonation with the random variables as shown in Table 1 are estimated by Monte Carlo Simulation.

Table 1: Radom variables

Variable	*Symbol*	*Unit*	*Mean*	*COV*	*PDF*	*Reference*
Relative humidity	*RH*	-	0.65	0.2	Normal	Lovato et al. 2012
Temperature	*T*	°C	25	0.04	Normal	Lovato et al. 2012
	χ_1	mm	-	0.2	Normal	Enright and Frangopol (1998)
	χ_2	mm	1.64	0.66	Normal	
	χ_3	mm	1.09	0.61	Normal	

5. RESULTS AND DISCUSSION

5.1. Failure probability of recycled aggregate concrete

The failure probabilities of various NAC and RAC due to the carbonation ingression in a relationship with structure lifetime are shown in Figure 3. The prefixes “N” and “R” indicate the natural and recycled aggregate concrete respectively, the following numbers “65”, “55”, and “45” show the water to cement ratio, and the suffixes “C10”, “C25”, and “C40” represent the concrete cover of 10mm, 25mm, and 40mm, respectively. It can be clearly seen that the failure probabilities of all types of RAC are comparatively higher. The failure probabilities of NAC and RAC are proportional to *w/c* but inversely proportional to concrete cover. As either the *w/c* increases or concrete cover decreases, the failure probabilities increase. For example, with the same 25mm concrete cover, the failure probabilities of NAC and RAC with *w/c* of 45% and 65% increase from 0.046 to 0.55 and from 0.12 to 0.69 at 100 years after construction, respectively. However, with the same *w/c* of 55%, the failure probabilities of NAC and RAC with 10mm and 40mm concrete cover decrease from 0.74 to 0.074 and from 0.84 to 0.17, respectively. Therefore, if the concrete cover becomes 4 times larger, the failure probabilities diminish about 10 times for NAC and 5 times for RAC. And, if *w/c* is 30% lower, the failure probabilities drop 12 and 6 times for NAC and RAC, respectively.

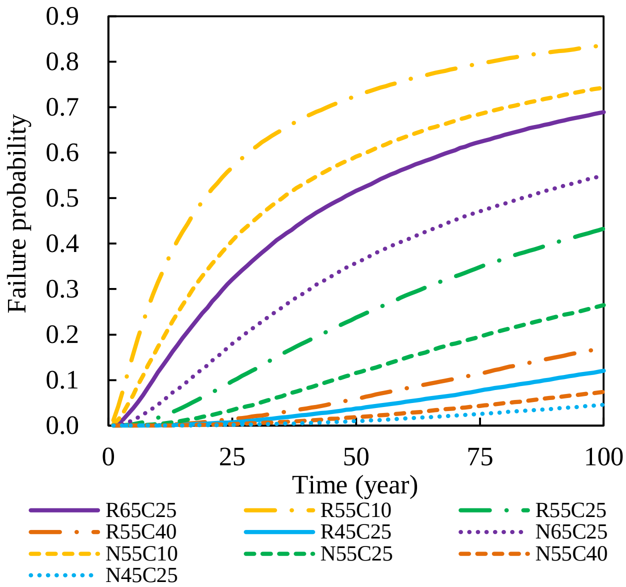

Figure 3: Failure probabilities of NAC and RAC from Equation (2).

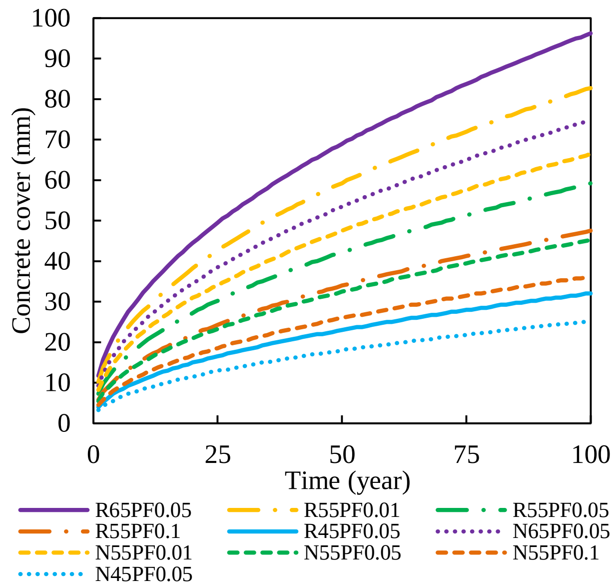

Figure 4: Relationship between concrete cover and structure lifetime.

5.2. Durability design method of RAC structure for its lifetime

To ensure the durability of RAC structures for the specific lifetime, the appropriate concrete cover have to be carefully selected to prevent the structural damage from carbonation-induced steel corrosion. The concrete cover with different concrete qualities and degrees of reliability could be chosen from Figure 4. For all types of concrete, the minimum concrete cover should be not less than 20mm in case that service life of structure is set to 100 years. Due to the lower material properties and durability performance, all types of RAC require larger concrete cover. Particularly, in case of *w/c* of 65%, the required RAC cover reaches almost 100mm; therefore, it is not applicable to use that type of concrete to ensure the specific durability of concrete structures during 100 years.

In order to simplify the design method of the RAC to ensure the target failure probability without any reliability analysis, the partial factor γ is introduced by

$$\gamma = \frac{0.8\chi_1 c}{d_c(D_{CO_2}, w/c, RH, T, t_e, \Re)} \geq 1.0 \tag{12}$$

Table 2 shows the minimum concrete cover (mm) and partial factors γ with different structural lifetime of 50, 75, and 100 years from the Equation (12). It can be observed that the partial factors for all concrete types are slightly changed. For the target failure probabilities of 0.1, 0.05, and 0.01, the corresponding partial factors are about 2.0, 2.5, and 3.5, respectively.

Table 2: Concrete cover (partial factor γ) of concrete structures subjected to carbonation

w/c	65%		55%		45%	
Concrete types	*NAC*	*RAC*	*NAC*	*RAC*	*NAC*	*RAC*
(a) Lifetime = 50 years						
PF_{target} = 0.1	43.0 (1.97)	57.3 (2.01)	26.0	34.0	14.5	19.0
PF_{target} = 0.05	53.5 (2.45)	69.0 (2.42)	32.5	42.3	18.0	23.0
PF_{target} = 0.01	75.3 (3.48)	95.8 (3.33)	47.5	59.3	25.0	33.5
(b) Lifetime = 75 years						
PF_{target} = 0.1	51.0	67.8	30.8 (1.90)	40.3 (1.90)	17.0	22.5
PF_{target} = 0.05	63.3	81.5	38.5 (2.41)	50.0 (2.34)	21.3	27.3
PF_{target} = 0.01	89.3	113	56.0 (3.49)	70.3 (3.28)	29.8	39.3
(c) Lifetime = 100 years						
PF_{target} = 0.1	60.3	80.3	36.3	47.5	20.3 (2.01)	26.8 (1.97)
PF_{target} = 0.05	74.8	96.3	45.3	59.3	25.3 (2.49)	32.0 (2.35)
PF_{target} = 0.01	105	134.0	66.5	82.8	35.0 (3.46)	46.3 (3.42)

6. CONCLUSIONS

This study proposed minimum concrete covers for durability design of concretes incorporated with natural and recycled aggregate exposed to the carbonation based on reliability approach. From the calculation results, it was found that concrete qualities, water to cement ratios, concrete covers, and carbonation speeds have the great influences on the failure probability associated with carbonation depth threshold. Reliability estimation models of concrete structures exposed to the carbonation are established based on the experimental results in the literature. Most of previous researches of carbonation depth were conducted by the accelerated test with different curing conditions, types of RAs and RACs, and experimental methodologies. Further research is needed to investigate the effect of them on the long-term structural performance using RAs and RACs experimentally and analytically.

ACKNOWLEDGMENTS

This research was supported by Yoshida Scholarship Foundation (YSF) for funding support.

REFERENCES

Bažant ZP and Najjar LJ (1972). Nonlinear water diffusion in nonsaturated concrete. Journal of Matéraux et Constructions. 5(25).

Enright MP and Frangopol DM (1998). Probabilistic analysis of resistance degradation of reinforced concrete bridge beams under corrosion. Journal of Engineering Structures. 20(11), pp. 960-971.

Evangelista L and Brito JD (2010). Durability performance of concrete made with fine recycled concrete aggregates. Journal of Cement & Concrete Composites. 32, pp. 9-14.

Hussain RR and Ishida T (2009). Critical carbonation depth for initiation of steel corrosion in fully carbonated concrete and development of electrochemical carbonation induced corrosion model. Journal of Electrochemical Science. 4, pp. 1178-1195.

Klee H (2009). The cement sustainability initiative-Recycling concrete. Report, World Business Council for Sustainable Development, Switzerland.

Kou SC and Poon CS (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. Journal of Cement & Concrete Composites. 37, pp. 12-19.

Levy SM and Helene P (2004). Durability of recycled aggregates concrete-A safe way to sustainable development. Journal of Cement and Concrete Research. 34, pp. 1975-1980.

Lovato PS, Possan E, Molin DCCD, Masuero ÂB, and Ribeiro JLD (2012). Modeling of mechanical properties and durability of recycled aggregate concretes. Journal of Construction and Building Materials. 26, pp. 437-447.

Padmini AK, Ramamurthy K, and Mathews MS (2009). Influence of parent concrete on the properties of recycled aggregate concrete. Journal of Construction and Building Materials. 23, pp. 829-836.

Saetta AV and Vitaliani RV (2004). Experimental investigation and numerical modeling of carbonation process in reinforced concrete structures-Part I: Theoretical formulation. Journal of Cement and Concrete Research. 34, pp. 571-579.

Saetta AV and Vitaliani RV (2005). Experimental investigation and numerical modeling of carbonation process in reinforced concrete structures-Part II: Practical applications. Journal of Cement and Concrete Research. 35, pp. 958-967.

Saetta AV, Schrefler BA, and Vitaliani RV (1993). The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. Journal of Cement and Concrete Research. 23, pp. 761-772.

Sato R, Maruyama I, Sogabe T, and Sogo M (2007). Flexural behavior of reinforced recycled concrete beams. Journal of Advanced Concrete Technology. 5, pp. 43-61.

Tam VWY and Tam CM (2007). Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach. Journal of Materials Science. 42, pp. 3592-3602.

Tans P and Keeling R (2012). Trends in Atmospheric Carbon Dioxide. Report, Scripps Institution of Oceanography.

Telford T (1993). CEB-FIP model code 1990, Bulletins d'Information 203-205, Comité Euro-International du Béton, Switzerland.

Thomas A, Lombardi DR, Hunt D, and Gaterell M (2009). Estimating carbon dioxide emissions for aggregate use. Journal of Engineering Sustainability. 162, pp. 135-144.

Xiao JZ, Li J, and Zhang CH (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. Journal of Cement and Concrete Research. 35, pp. 1187-1194.

Xiao JZ, WenGui LI, and Poon CS (2012). Recent studies on mechanical properties of recycled aggregate concrete in China-A review. Journal of Science China Technological Sciences. 55, pp. 1463-1480.