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Review on Recycled Aggregate Concrete in the Past 15 Years in China

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Abstract:
A large number of investigations on the mechanical properties, durability and structural performances of recycled aggregate concrete (RAC) have been carried out in the past 15 years in PR China. Studies on the production process and properties of recycled aggregates are introduced. Typical approach for the mix design of RAC is presented. The researches on mechanical properties of RAC are introduced from the compressive strength, elastic modulus and stress-strain relationship. Studies on the failure mechanism of RAC from the view of micro and meso structure are presented. The research on durability of RAC is introduced from the aspect of chloride diffusion. Studies on structural performance of RAC are introduced from the seismic performance of RAC frame under cyclic and earthquake loading. The last part presents some applications of RAC. These results reveal that with proper design and construction, it is feasible to apply RAC as a structural material.
Keywords: Recycled aggregate concrete (RAC), Mechanical property, Failure mechanism, Chloride diffusion, Seismic performance.

INTRODUCTION

In China, with the rapid development of construction industry which is based on the cost of excessive natural resource consumption and the deterioration of the environment, the contradiction between the sustainable development of the construction industry and the shortage of resources will become more and more serious. At the same time, a large amount of solid waste is produced in the process of the construction of new buildings and demolition of old buildings every year. According to the statistics, approximately 15.5 million tons of construction waste was produced annually in China. Moreover, some natural disasters such as *Wenchuan* earthquake in 2008, *Yushu* earthquake in 2010 and *Yunnan* earthquake in 2011 in China have resulted in a great quantity of waste concrete. Today, the reuse of the construction waste has become a common concern issue in China and deserves deep researches. It can be foreseen that the RAC as a method of reuse and recycling of the construction waste will bring considerable economic and environmental benefit to China.

In the past 15 years (1996-2012), many Chinese scholars have engaged in the study of RAC and covered nearly all aspects of mechanical property and structural performance. Up to today, three national symposiums on RAC and two international conferences on waste concrete recycling and management have been held in China. This paper aims to introduce these achievements from some main aspects.

CRUSHING AND SIEVING TECHNOLOGY OF WASTE CONCRETE

Hou *et al.*(2002) designed one cycled aggregate production process with a set of wind grading equipment, which can sieve out the recycled aggregate with 0.15~5mm in diameter, and it laid a good foundation to use recycled fine aggregate in China. Li *et al.*(2001) proposed a production process to establish a practical continuous production line, which can produce clean recycled aggregate with different materials and diameters. Xiao *et al.* (2005) compared and analyzed different production processes for recycled aggregate in different countries and proposed a new production process according to the situation in China. It used manual method to remove reinforced bars and wood in waste concrete because the labor cost in China is relative low and processing big concrete block with machine is difficult. The recycled aggregate with diameter less than 0.5mm is considered as micro-powder because recycled fine aggregate has not been studied in-depth. Ferromagnetic separator and separation desk are used to improve the purity of recycled aggregate. Sieving machine is applied to produce recycled aggregate with different diameters. The recycled aggregate with 5~31.5mm in diameter is often washed at last.

PROPERTIES OF RECYCLED COARSE AGGREGATE (RCA)

Xu *et al.* (2006) compared and analyzed the test results of many scholars, and found that for RCA, the apparent density and stacking density are between 2.31~2.62 (kg/m^3) and 1.29~1.47 (kg/m^3), water absorption is 4%~10%, crush index is 14.2%~23.1%. Xiao (2008) and Li (2005) investigated on the RCA from primary concrete with different strength, and found that the apparent density of RCA increases with the increase of primary concrete strength. Shen (2006) found that the water absorption for some RCA can be as much as 15%. Li (2004) investigated the properties of RCA systematically and it showed that the bulk density, apparent density and soundness of RCA are lower than that of natural coarse aggregate, while the water absorption, crush index and sediment percentage of RCA are also higher. However, the properties of RCA can still meet the requirement in Chinese code.

MIX RATIO OF RAC

Xiao (2008) investigated the approach for the mix design of recycled aggregate concrete (RAC). It is proposed that the proportion of cement, sand and aggregate in RAC can be calculated based on the mix design code for conventional concrete, but the high water adsorption of waste concrete aggregates should be considered and the water should be added together with water content calculated according to the approach for conventional concrete. RAC using this method can meet the requirement of national code on workability and strength. Shi (2001) proposed an approach for the mix design of RAC based on free water-cement ratio to solve the problem of high water adsorption of waste concrete aggregate. Total water of RAC comprise of two parts. One part of water all absorbed by RCA is called additional water. The other part of water used for the mortar is called free water. Both of the two methods are used to consider the effect of high water adsorption in waste concrete aggregates.

COMPRESSIVE STRENGTH OF RAC

Li *et al.* (2006), Tang (2007) and Jin *et al.* (2008) had conducted experimental investigations on the compressive strength of RAC. The results show that the RCA content has obvious influence on the compressive strength of RAC. The relationship between the RCA replacement percentage and the relative compressive strength, which is defined as the ratio of the compressive strength of RAC to that of RAC with 0% replacement percentage (namely conventional concrete), is shown in Fig.1. It indicates that the compressive strength of RAC decreases with the increase of the RCA replacement percentage. However, the effect

on the compressive strength is not obvious when the RCA replacement percentage is less than 30%. A special phenomenon was found by Li *et al.* (2006) that the compressive strength of RAC with 50% replacement percentage is larger than that of 30%. It needs to further studied to demonstrate it is the real property of RAC or just because the randomicity of the test. Li *et al.* (2006) also pointed out that it is quite possible to obtain RAC with a desirable compressive strength by adjusting the waster/cement ratio.

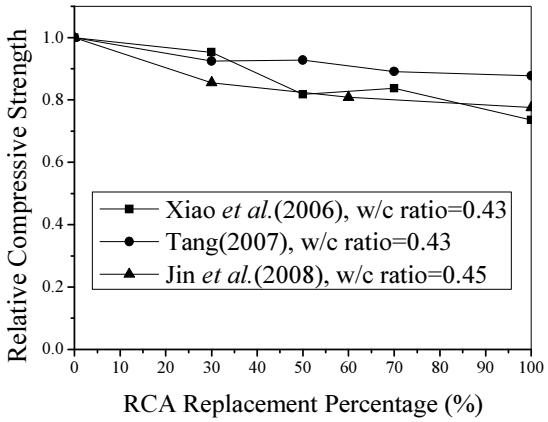


Fig.1. Influence of RCA replacement percentage on RAC compressive strength

ELASTIC MODULUS OF RAC

Xiao (2007) found that the elastic modulus of RAC decreases with the increase of the RCA replacement percentage and the elastic modulus of RAC with 100% RCA is 45% lower than that of conventional concrete. Zhou *et al.* (2010) indicated that the elastic modulus of RAC is 15% to 26% lower than that of conventional concrete, depending on the qualities of the parent concrete and the properties the RCA as well, and the formula of recycled concrete elastic modulus was also presented. Kou *et al.* (2007) found that the elastic modulus of RAC decreased with the increase of the RCA replacement percentage and the elastic modulus of RAC with 100% RCA was about 40% lower than that of conventional concrete. The relationship between the RCA replacement percentage and the relative elastic modulus, which is defined as the ratio of the elastic modulus of RAC to that of namely conventional concrete, is shown in Fig.2.

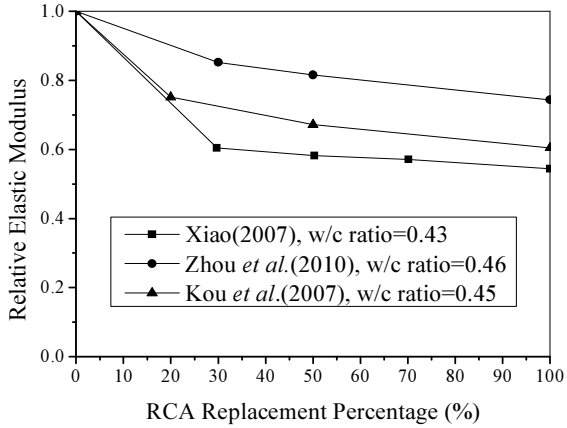


Fig.2.Influence of RCA replacement percentage on RACof elastic modulus

STRESS-STRAIN RELATIONSHIP OF RAC

Prisms are commonly used to test the concrete stress-strain relationship in China. Xiao (2007) has investigated the influence of RCA replacement percentage on the complete stress-strain curves of RAC, shown in Fig.3. The results show that the shape of the complete stress-strain curves of RAC is similar to that of conventional concrete. The equations were also proposed for the complete stress-strain curve of RAC with different RCA replacement percentages. Du *et al.*(2010 a) have experimentally investigated on the complete stress-strain curve under uniaxial compression loading. The results show that the peak stress, peak strain, secant modulus increase with increase of the strength grade of RAC. The constitutive model of stress-strain model of RAC was also proposed and the results from the constitutive model of stress-strain can meet the experiment results well. Besides, a variety of models for the stress-strain relationships of RAC under uniaxial compression have been proposed, e.g. by Xiao (2007) and Wang *et al.*(2010).

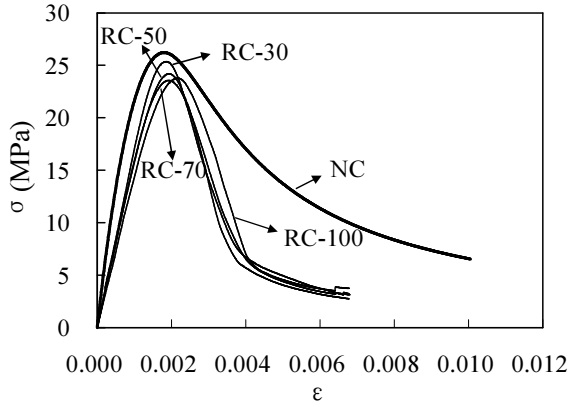


Fig.3. Stress-strain curves of RAC with different RCA replacement percentage under uniaxial compression loading (Xiao, 2007)

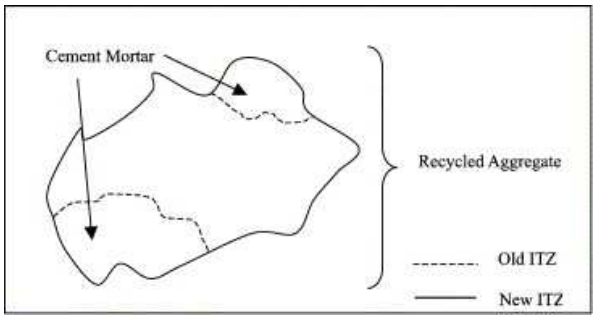


Fig.4. Meso-structure of RAC prepared with RCA (Tam *et al.*, 2005)

FAILURE MECHANISM

Du *et al.* (2010 b) investigated the micro-hardness of the interfacial transition zones (ITZ) and the interface between the old cement paste of recycled aggregate and new mortar matrix body of RAC with different strength grade by using digitalmicro-hardness meter. The results show that the micro-hardness of RCA was much higher than that of the ITZs in the RAC, and the micro-hardness of the interface between the RCA and the new mortar matrix

was the lowest. Tam *et al.* (2005) pointed out that the microstructure of RAC was much more complicated than that in conventional concrete, shown in Fig.4. RAC possessed two ITZs, one is between the RCA and new mortar matrix, and the other is between the RCA and the old mortar attached (old ITZ). The cement mortar remaining at the ITZ of RCA forms the weak link in RAC.

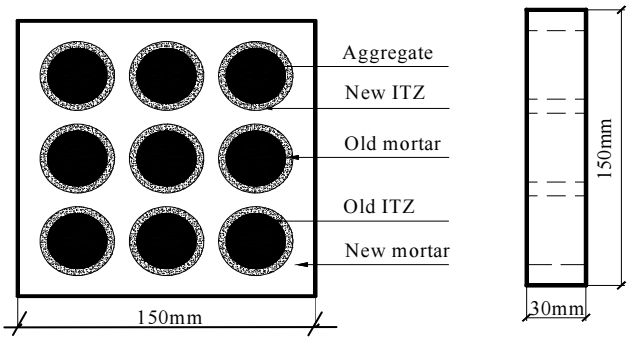


Fig.5. Diagram of modeled recycled aggregate concrete

Xiao *et al.* (2011) proposed the concept of modeled recycled aggregate concrete (MRAC) (shown in Fig.5) to investigate the failure of mechanism of RAC, and the influence of different parameters on the mechanical properties of MRAC under uniaxial compression was studied. The results show that the strength of the new and old hardened cement paste has a significant influence on the mechanical properties of MRAC. Li *et al.* (2012 a) studied the stress distribution characteristic of the MRAC under uniaxial compression by meso-level numerical analysis. The results prove that a concentration of tensile stress and shear stress produces at new and old ITZs, and the magnitude of concentration depends on the elastic modulus of natural aggregates. Li *et al.* (2012 b) investigated the cracking behavior of MRAC specimens under compressive loading using Digital Image Correlation (DIC) to study the failure processes of RAC. The results reveal that the first bond cracks appear around both the old ITZs and new ITZs, and then propagate into the old and new mortar matrix by connecting each other. It is also found that the relative strength of coarse aggregate and mortar matrix has remarkable influence on the failure process of RAC. Xiao *et al.*(2012a) have experimental studied the crack propagation of MRAC and RAC under uniaxial compressive loading. The results indicate that the failure process and crack pattern of MRAC are greatly influenced by the relative strength of new mortar and old mortar and the water-cement ratio (w/c) of the mixture.

CHLORIDE DIFFUSION OF RAC

Zhang *et al.*(2009) studied the influences of mineral admixture and recycled aggregate on the chloride permeability of high-performance RAC. It is found that the impermeability of RAC with high-quality RCA is close to that of conventional concrete. Du *et al.* (2006) have experimental investigated the resistance of chloride ion penetration of RAC. The results indicate that the resistance of chloride penetration of RAC is lower than that of the conventional concrete but still sufficient and the minimal admixtures such as fly ash and granulated blast-furnace slag can effectively improve the chloride ion penetrability of RAC. Hu *et al.*(2009) found that the chloride ion permeability of RAC is lower than that of conventional concrete and the resistance to chloride ion permeability increases with the decrease of W/C. The relationship between the chloride ion penetration and the RCA replacement percentage is shown in Fig.6. It can be concluded that the resistance of chloride ion penetration of RAC is lower than that of conventional concrete, and it decreases with the

increase of RCA replacement percentage.

Besides, Xiao *et al*. (2012 b) numerically simulated the chloride diffusion characteristics in MRAC to study the chloride diffusion characteristics of RAC, the results show that the distribution of chloride concentration is not uniform within MRAC and the chloride concentration in RAC decreases wavelike along the diffusion depth. Xiao *et al.* (2012 c) proposed a model to describe the effect of recycled aggregate on the chloride diffusion in RAC and new theoretical equations to calculate the effective chloride diffusivity in the modeled RAC.

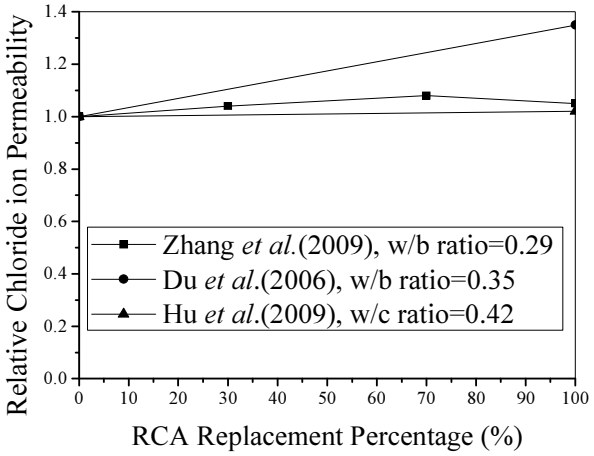


Fig.6.Influence of RCA replacement percentage on RAC Chloride permeability

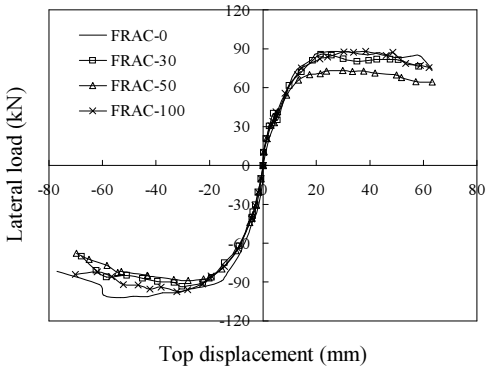
SEISMIC PERFORMANCE OF RAC FRAME

Xiao *et al.* (2006) have experimentally studied on the seismic performance of RAC frame structures under low-frequency cyclic lateral load with constant vertical actions. The results conclude that the seismic behavior of a frame structure with RAC decreases with the increase of the RCA replacement percentage, shown in Fig.7, while a frame structure with a higher content of RCA still has sufficient resistance under an earthquake attack. Cao *et al.* (2011) conducted experimental study on two 1/2.5 scaled two-story two-bay recycled concrete frames under cyclic loading action, the results show that the loading-carrying capacity of RAC frame is similar to that of conventional concrete frame, the ductility of RAC frame can meet the seismic requirements, and the failure processes can meet the principle of 'strong column and weak beam'. Xiao *et al.* (2012 d) investigated the seismic performance of the RAC frame structure by conducting the shaking table test on a 1/4-scale model of a two-bay, two-span, 6-story RAC frame structure. The model and failure pattern of the RAC frame structure is shown in Fig.8. The interstory drift, seismic force, interstory shear, hysteresis curves, capacity curve, ductility coefficient, and stiffness degradation were computed and analyzed. The results prove that the RAC frame structure with proper design and construction have good seismic performance to withstand earthquake strikes. The failure mode is typical 'Strong column and weak beam', and the RAC frame structure is able to withstand rarely occurring earthquakes of intensity 8.

APPLICATIONS OF RAC IN CHINA

A three story building 'Civil Engineering and Transportation Laboratory' in Beijing Architectural College was constructed using recycled concrete in 2007 under the technical support of Prof. JL Chen, shown in Fig.9. The recycled aggregates were produced from demolished concrete pavements and building waste.

(a) Test set up



(b) Skeleton curves

Fig.7. Test set up and skeleton curves of RAC frame structure (Xiao *et al.*, 2006)

(a) The model

(b) Beam

(c) Beam-column joint

Fig.8. Model and failure pattern of RAC frame structure (Xiao *et al.*, 2012 d)

Fig.9. A three-story building constructed with RAC in Beijing

On 12 May, 2008 a devastating earthquake struck the Sichuan province in China. It caused a large number of casualties and huge amount of construction and demolition waste in the earthquake-hit area. There were some demonstrative projects which used recycled aggregate concrete in the work of post-disaster reconstruction. Two of them which used RAC and RAC block respectively are located in Dujiangyan, shown in Fig.10(a) and (b).

The Shanghai Ecological House in the 2010 Shanghai World Expo Park was constructed by RAC, shown in Fig.11. It is called 'Ecological House' because it can save above 60% energy compared with similar buildings and can make the visitor feel at home.

(a) Constructed with RAC (b) Constructed with RAC block

Fig.10. Demonstrative projects with RAC structures in Dujiangyan, China

Fig.11. 'Shanghai Ecological House' in the 2010 Shanghai World Expo site

CONCLUSION:

This paper presents some main achievements made by Chinese scholars in past 15 years, the main conclusions are summarized as follows:

1) There are some mature techniques for crushing and sieving waste concrete which can match the national situation in China to produce recycled aggregates and the properties of recycled aggregates can still meet the requirement in Chinese code.

2) Some approaches for the mix design of RAC have been proposed considering the effect of high water adsorption in waste concrete aggregates.

3) The mechanical properties and durability of RAC are inferior to that of conventional concrete.

4) The failure mechanism of RAC has been discussed from the view points of micro and meso structure. It is found that the first bond cracks appear around both the old ITZs and new ITZs, and then propagate into the old and new mortar matrix by connecting each other.

5) Seismic performance of RAC frame is similar to that of conventional concrete and it is feasible to apply RAC frame to practical engineering.

6) There are some structures constructed with RAC in China, and it reveals that with proper design and construction, it is safe and feasible to apply RAC as a structural material in civil engineering.

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REFERENCE:

Cao WL, Yin HP, Zhang JW *et al.* (2011). Seismic behavior experiment of recycled concrete Frame structures. *Journal of Beijing University of Technology*, 37(2):191-198. [in Chinese]

Du T, Li HQ, Guo TP *et al.* (2006). Test study on the resistance of chloride ion penetration of recycled aggregate concrete. *Journal of Wuhan University of Technology*, 28(5): 33-36. [in Chinese]

Du T, Wang WH, Liu ZX *et al*. (2010 a).The complete stress-strain curve of recycled aggregate concrete under uniaxial compression loading. *Journal of Wuhan University of Technology-Materials Science Edition*, 25(5):862-865.

Du T, Wang WH, Lin HL *et al*. (2010 b). Experimental study on iInterfacial strength of the high performance recycled aggregate concrete. *ASCE Conference Proceedings*, 366:2821-2828.

Hou JP, Shi W, Song YP (2002). Development and application promoting of recycled concrete. *Architecture Technology*,33(1):15-17. [in Chinese]

Hu B, Liu BK, Zhang LL (2009). Chloride ion permeability test and analysis for recycled concrete. *Journal of Hefei University of Technology*, 32(8): 1241-1243.[in Chinese]

Jin C, Wang XP, Akinkurolere OO, Jiang CR (2008). Experimental research on the conversion relationships between the mechanical performance indexes of recycled concrete. *Chinese Concrete Journal* , (11): 37-39, 49. [in Chinese]

Kou SC, Poon CS, Dixon C (2007). Influence of fly ash as cement replacement on the properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 19(9):709-717.

Li HQ, Du T,Wu XG (2001). Recycled aggregate concrete from construction debris. *J. Huazhong Univ. of Sci. & Tech*. 29(6):83-84. [in Chinese]

Li JB Xiao JZ, Sun ZP (2004). Properties of recycled coarse aggregate and Its Influence on Recycled Concrete.*Journal of Building Materials*, 7(4):390-395. [in Chinese]

Li K (2005). Research on the basic properties of recycled aggregate and recycled concrete[D]. DaLian: *Dalian University of Technology*. [in Chinese]

Li JB, Xiao JZ, Huang J (2006). Influence of recycled coarse aggregate replacement percentage on compressive strength of concrete. *Chinese Journal of Building Materials*, 9(3): 297-301. [in Chinese]

Li WG, Xiao JZ, Yuan JQ (2012 a). Stress distribution characteristics of modeled recycled aggregate concrete under uniaxial compression. *Journal of Tongji University (Natural Science)*, 40(6): 906-913. [in Chinese]

Li WG, Xiao JZ et al. (2012 b), Failure processes of modeled recycled aggregate concrete under uniaxial compression. *Cement and Concrete Composites*, 34(10): 1149-1158.

Shi W, Hou JP (2001). Technology and mix design on recycled concrete. *Building Technique Development*, 28(8):18-20. [in Chinese]

Shen DQ (2006). Study of recycled aggregate concrete[D].Beijing, Beijing Jiaotong University. [in Chinese]

Tam VWY, Gao XF, Tam CM (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research*, 35 (6):1195-1203.

Tang J (2007). Preliminary study on compressive strength of recycled aggregate concrete. *Sichuan Building Science*, 33(4): 183-186. [in Chinese]

Wang XT, Yang DJ (2010). Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. *Civil Engineering in China- Current Practice and Research Report*: 787-790.

Xiao JZ, Sun ZP *et al*. (2005). Study on crushing and regenerating technology of waste concrete. *Architecture Technology*, 36(2):141-144. [in Chinese]

Xiao JZ, Sun YD, Falkner H (2006). Seismic performance of frame structures with recycled aggregate concrete. *Engineering Structures*, 28(1):1-8.

Xiao JZ (2007). Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. *Journal of Tongji University (Natural Science)*, 35(11): 1445-1449. [in Chinese]

Xiao JZ (2008). Recycled Concrete [M]. Beijing, *China Building Industry Press*. [in Chinese]

Xiao JZ, Li WG (2011). Meso-level numerical simulation on mechanical properties of modeled recycled concrete under uniaxial compression. *Journal of Tongji University (Natural Science)*, 39(6): 791-797.[in Chinese]

Xiao JZ, Li WG et al. (2012 a). Crack propagation in recycled aggregate concrete under uniaxial compressive loading. *ACI Material Journal*, 109(4):451-462.

Xiao JZ, Ying JW (2012 b).Meso-level numerical simulation on two dimensional chloride diffusion in modeled recycled aggregate concrete. *Journal of Tongji University (Natural Science)*, 40(7): 1051-1057.[in Chinese]

Xiao, JZ, Ying JW *et al*. (2012 c). FEM simulation of chloride diffusion in modeled recycled aggregate concrete. *Construction and Building Materials*, 29: 12-23.

Xiao JZ, Wang CQ, Li J *et al.* (2012 d). Shaking table model tests on recycled aggregate concrete frame structure. *ACI Structural Journal*, 109(6): 777-786.

Xu YZ, Shi JQ (2006). Analyses and evaluation of the behaviour of recycled aggregate and recycled concrete. *Concrete*,7:41-46. [in Chinese]

Zhang J, Li QY, Du J *et al.* (2009). Experimental study on mineral admixture and recycled aggregates affecting the rapid chloride permeability of high-performance recycled concrete. *Chinese Concrete*, 2:94-97.

Zhou JH, He HJ, Meng XH *et al*. (2010). Basic mechanical properties of recycled concrete experimental study. *Journal of Shenyang Jianzhu University* (Natural Science), 26(3):464-468 [in Chinese]. [in Chinese]