Journal of Advanced Concrete Technology

Materials, Structures and Environment

Durability of recycled aggregate concrete: An overview

Jianzhuang Xiao, Deng Lu, Jingwei Ying

Journal of Advanced Concrete Technology, volume 11 (2013), pp. 347-359

Related Papers Click to Download full PDF!

Comparative Tests of Beams and Columns Made of Recycled Aggregate Concrete and Natural Aggregate Concrete

Andrzej B. Ajdukiewicz, Alina T. Kliszczewicz,

Journal of Advanced Concrete Technology, volume 5 (2007), pp. 259-273

Application of Conventionally Recycled Coarse Aggregate to Concrete Structure by Surface Modification Treatment

Masato Tsujino, Takafumi Noguchi, Tamura Masaki, Manabu Kanematsu

Journal of Advanced Concrete Technology, volume 5 (2007), pp. 13-25

Development of a Sustainable Concrete Waste Recycling System - Application of recycled aggregate concrete produced by aggregate replacing method

Yasuhiro Dosho

Journal of Advanced Concrete Technology, volume 5 (2007), pp. 27-42

Improving the Quality of Recycled Fine Aggregates by Selective Removal of Brittleness Defects

Hideo Ogawa, Toyoharu Nawa

Journal of Advanced Concrete Technology, volume 10 (2012), pp. 395-410

Click to Submit your Papers

Japan Concrete Institute <http://www.j-act.org>

Scientific paper

Durability of Recycled Aggregate Concrete: An Overview

Jianzhuang Xiao¹, Deng Lu² and Jingwei Ying³

Received 16 May 2012, accepted 12 December 2013

doi:10.3151/jact.11.347

Abstract

Recycled aggregate concrete (RAC) becomes a great concern for massive natural resource consumption and a huge construction waste. Many researchers have carried out numerous investigations on the durability of RAC. The purpose of this paper is to summarize the achievements and share them with researchers involved in the study on RAC. In this paper, the main durability index and test methods have been reviewed from worldwide literature. Secondly, the durability of RAC including chloride diffusion, freezing and thawing resistance, abrasion resistance, absorption, drying shrinkage and carbonation has been summarized based on literature study. Thirdly, the Grey Relational Analysis (GRA) has been applied to find the most critical factor determining the durability of RAC compared with that of natural aggregate concrete (NAC). At last, new types of recycled concrete have been discussed and compared with NAC.

1. Introduction

Recycling of concrete is needed based on environmental preservation and effective utilization of resources point of view (Ke *et al.* 2009). So far, there are a number of researches on mechanical properties of recycled aggregate concrete (RAC) at home and abroad (Ke *et al.* 2009; Poon *et al.* 2004; Xiao *et al.* 2005; Xiao *et al.* 2006a; Xiao *et al.* 2006b; Xiao and Falkner 2007). Some basic conclusions confirmed are for example: the compressive strength of concrete prepared with natural coarse aggregates (NCA) is higher than that of RAC and the interrelationships between the mechanical properties of RAC could be quite different from those of NAC. However, some hypothetical problems related to durability resulted in recycled aggregates being employed practically only as base filler for pavement construction (Etcheberria *et al.* 2007; Park *et al.* 2005; Vancura *et al.* 2009; Tam *et al.* 2006; Richardson and Jordan 1994). Engineers generally concern about the durability of RAC.

In comparison with natural coarse aggregates (NCA), recycled coarse aggregates (RCA) are more porous and old cement paste is attached on their surface. The microstructure of interfacial transition zone (ITZ) in RAC is different from that in NAC (Poon *et al.* 2004), and the total porosity and the average porosity diameter of the concrete increases as the RCA content increases (Kou and Poon 2006). In recent years, a wide range of ex-

perimental researches has led to significant advances in the understanding of RAC durability. For example, some investigators report that the chloride penetration resistance of RAC is slightly inferior to those of NAC (Otsuki *et al.* 2003) and decreases with the increasing of water-cement ratio (w/c) (Hu *et al.* 2009) and the RCA replacement ratio (Kou and Poon 2006), or even too low to protect the reinforcing steel bars from corrosion (Fraser 2008). Meanwhile some other literature conclude that chloride penetration of RAC can be intensified with the growth of the strength grade (Du *et al.* 2008; Hao and Jin 2008), mineral admixtures (Du *et al.* 2008) or mixing approaches (Tam *et al.* 2007; Kong *et al.* 2010). A research by Villagran *et al.* (2008) also indicates that RCA under marine exposure causes two opposed effects on RAC: it increases both its chloride penetration rate and chloride binding capacity.

In this paper, the main durability index and test methods are firstly reviewed, then the durability performance of RAC including (i) Chloride permeability, (ii) Freezing and thawing resistance, (iii) Abrasion resistance, (iv) Carbonation, (v) Absorption, and (vi) Drying shrinkage are analysed. In order to quantitatively analyze the influencing factor of RAC durability, the Grey Relational Analysis (GRA) is used. The GRA is useful for solving the complicated interrelationships among the behavior, posture, and boundary, even though the information is poor, incomplete, and uncertain (Deng 1985). At last, new types of recycled concrete have been proposed and compared with natural aggregate concrete (NAC).

2. Durability index and test methods

2.1 Chloride permeability

For reinforced concrete exposed to chlorine salt environments, chloride ingress is the major form of environment attack, which leads to corrosion of the reinforcing steel bars and deterioration of durability of rein-

¹Professor, Department of Building Engineering, Tongji University, Shanghai, P.R. China.

E-mail: jzx@tongji.edu.cn

²Graduate student, Department of Building Engineering, Tongji University, Shanghai, P.R. China.

³PhD student, Department of Building Engineering, Tongji University, Shanghai, P.R. China; Lecture, School of Civil Engineering and Architecture, Guangxi University, Nanning, P.R. China.

forced concrete. In order to measure chloride permeability of concrete, the commonly adopted tests include conventional chloride diffusion test and the accelerated chloride diffusion test. The conventional chloride diffusion test, including Salt Ponding Test (AASHTO T 259) and Bulk Diffusion Test (NTBuild 443), is the most primitive and easily acceptable method to determine the chloride diffusion coefficient. For the traditional method, specimens are exposed to a chloride solution for a long period, so that the chlorides penetrate the specimens due to the concentration gradient. Nevertheless, there are two disadvantages in this type of test: the first one is the fact that the minimum soak period is a very long time, especially for higher quality concrete. On the other hand, this kind of test is laborious as well as expensive since it must carry on the section or mortar powder and electrochemical titration to determine the chlorides (Stanish *et al.* 2000).

In order to overcome the time-consuming disadvantage of conventional chloride diffusion test, the accelerated chloride diffusion test was developed. The Rapid Chloride Penetration Test (RCPT) (ASTM C1202), originally developed by Whiting (1981), is the first method for accelerated chloride diffusion test. At present, this method is being used by a greater number of investigators (Du *et al.* 2006; Ann *et al.* 2008) to study the influence of pore size, curing condition, and aggregate fraction on the penetration of chloride ions, respectively. However, a series of investigations on the RCPT have been carried out, and the results of all researches reveal that the applied electrical potential of RCPT heats up the concrete specimen, which may affect the permeability (Andrade 1993; Feldman *et al.* 1999). The other disadvantage of the RCPT method is that the chloride penetration is not accurately determined as it only measures the total electrical charge passed through the cement-based material in the first 6 hours. Yang and Cho (2003) proposed a modified version of the RCPT that is called Accelerated Chloride Migration Test (ACMT). In ACMT, the current and the accumulative chloride ions penetrating through the test specimen are measured and the quantity of chloride ions in anode cell is taken periodically.

The Rapid Chloride Migration test (RCM) and NEL methods (put forward by Lu (1997) based on Nernst-

Einstein equation) are the accelerated chloride diffusion test. RCM method developed by Tang and Nilsson (1992) described in the guideline NT Build 492 (NT Build 492), is one of the popular accelerated test methods. NEL method is a new accelerated chloride diffusion test based on the Nernst-Einstein equation. The characteristic of this test is that it converts the chloride permeability determination to the conductivity measurement of the concrete saturated with a highly concentrated salt.

2.2 Freezing and thawing resistance

Freezing and thawing cycles is one of the most damaging actions affecting concrete, especially in cold climates (Medina 2013). The test methods used to evaluate freezing and thawing resistance of concrete have been recommended by several codes and standards, including GB50082-2009, ASTM C666, ASTM C672, RILEM TC176-IDC, etc. As listed in **Table 1**, although the test methods have some differences from country to country, the significant parameters of the experimental methods are temperature range, freeze-thaw cycle time, cooling rate, heat-transfer medium and surface conditions of specimen.

2.3 Abrasion resistance

Abrasion damage is a major problem resulting from the abrasion effects of waterborne gravel, rocks, and other debris circulated over a hydraulic structure and floors (Liu 1981). It can be found that several test methods directed by different countries are used to measure the abrasion resistance of concrete (Peng 2009). These abrasion tests can generally be divided as wear mass method and wear depth method, according to the index of abrasion resistance. The abrasion test, recommended by JTG E30, is a typical wear mass test method. For the first method, wear mass per unit area is used to indicate the abrasion resistance of concrete. Whereas, for the wear depth method, including the test directed by ASTM 779 and GB/T16925, represents the abrasion resistance with the depth of wear.

2.4 Carbonation

Carbonation is a chemical reaction that takes place between portlandite and CO₂ which destroys pH environ-

Table 1. Test methods of freezing and thawing resistance (Wu *et al.* 2009).

Test methods		Temperature range(°C)	Freeze-thaw cycle(h)	cooling rate(°C/h)	Heat-transfer medium	Test surface
GB 50082-2009	Rapid Freezing and Thawing	-18~5	2~4		Water	All
	Salt freezing method	-20~20	4	10	3% sodium chloride solution	One
ASTM	C666-97	-17.8~4.4	2~5	13	Water	All
	C672-2012	-17~23	22~26	2.5	4% sodium chloride solution	One
RILEM TC176-IDC2002		-20~20	12	10	3% sodium chloride solution	One

ment in concrete and results in steel bars corrosion. The test methods for the carbonization of concrete include the splitting method and the penetration method. The specimen should be split in the splitting method, which includes the normal carbonization method and the rapid carbonization method. In the penetration method, the carbonization resistance of concrete is indirectly characterized by the diffusion coefficient of gas in concrete (Du 2012). The method of CEN (European Committee for Standardisation) is a typical natural carbonization method. For this method, the specimens are respectively cured for 28, 91, 182, 273 and 364 days under specified curing conditions. Then the average value of the carbonation depth of five specimens measured by the method recommended by RILEM CPC is obtained (Jones *et al.* 2000). Nevertheless, the cycle of this test method is so long that much time and labor is needed.

So far, a unified international standard of the rapid carbonization method is not available. China's national standard GB/T50082-2009 specifies that specimens should be put in the carbonation box with the volume fraction of carbon dioxide of 20±3% so as to accelerate carbonation. Differently from the Chinese method, some scholars suggest the volume fraction of carbon dioxide to be lower than 10% to make the test condition closer to the ambient condition while the speed and effect of test are ensured (Lindvall 1998; Wu *et al.* 2008).

A series of investigations on the correlation between air permeability of concrete and its depth of carbonation have also been carried out (Basheer *et al.* 2001). Basheer (1991) reported that a linear relationship could be established between the depth of carbonation and the gas permeability values. Zhao and Li (2002) revealed that the carbonation of concrete can be correlated with the permeability and the correlation coefficient is 0.9373, 0.9914 and 0.9368 in the ages of 30, 60 and 120 days, respectively. Therefore, penetration method is feasible to determine the carbonation of concrete.

2.5 Absorption

Water absorption is a significant index to properly determine the durability of concrete (Safiuddin *et al.* 2011). Not only because the deterioration due to freezing and thawing is related to the water absorption of concrete

Fig. 1. Procedure of water absorption test.

(Hooton 1993), but also because the water absorption links to the transport of chloride, oxygen, and carbon dioxide, which are dominant factors which lead to corrosion of reinforcing steel bars in concrete (McCarter *et al.* 1992). ASTM C 642 and BS 1881-122, recommended by ASTM and BS respectively, are the commonly applied methods to measure the water absorption of concrete. The main procedure of the two methods is broadly shown in Fig. 1.

3. Analysis of influence parameters on durability of RAC

Most of the results found in literature cannot be directly comparable due to different experimental conditions, parent concrete, raw materials and related testing specification or standard. In order to summarize the common regulation, especially from different test specifications, this paper makes a comparison of the durability index with an RCA replacement ratio of r to that with an RCA replacement ratio of zero: defined as $f(r)/f(0)$. In which $f(r)$ means concrete durability of RCA with a replacement ratio of r , such as relative chloride penetrability, relative freeze-thaw resistance parameter, relative abrasion depth, relative depth of carbonation, the relative water absorption, and relative drying shrinkage.

3.1 Chloride permeability

In the environment of chlorine salt, chloride ion is not only the main impact factor of the reinforcements corrosion, but also one of the major impact factors of the popularization and application of recycled aggregate concrete. In an attempt to reveal the chloride diffusion characteristic in realistic recycled aggregate concrete (RAC) against that of natural aggregate concrete (NAC), the diffusivity variation of NAC and RAC with different water to cement ratio (w/c) has been summarized and shown in Fig. 2 (Hu *et al.* 2009; Du *et al.* 2008; Hao and Jin 2008; Stanish and Thomas 2003; Yang *et al.* 2004; Thomas and Bamforth 1999; Vedalakshmi *et al.*

Fig. 2 Diffusion coefficients of NAC and RAC.

Fig. 3 Variation of relative chloride penetrability with RCA replacement percentage.

2008; Erdogdu *et al.* 2004). It can be seen from **Fig. 2** that most of the diffusion coefficients of NAC vary in the range of $(1\sim10)\times10^{-12}$ m²/s, and that the upper limit of chloride diffusivities of NAC increases with w/c. Whereas most of the diffusion coefficients of RAC vary in the range of $(1\sim16)\times10^{-12}$ m²/s showing larger discreteness than that of NAC. This may be due to the influence of old attached mortar and old ITZ, which varies in a larger range than that of new mortar and new ITZ.

Kou *et al.* (2007), Nassar (2010), and Du *et al.* (2006) have conducted experiments on the chloride permeability of recycled aggregate concrete (RAC). The results reveal that the recycled coarse aggregate (RCA) replacement percentage has remarkable influence on the chloride permeability of RAC. **Figure 3** illustrates the relationship between the relative chloride penetrability of RAC and the RCA replacement percentage, which indicates that the chloride penetrability linearly increases with the increase of replacement percentage of RCA. It also shows that the line slope is different because of the different experiment conditions, including mineral admixtures, w/c ratio, curing age, and so on. Using recycled aggregates can slightly increase coefficient of permeability and chloride diffusion coefficient. However the values remain acceptable for durable concrete (Berndt 2009).

Besides RCA replacement percentage, many investigators have studied several other affecting factors on chloride permeability of RAC, such as admixtures, curing age, water cement ratio, and mixing method. Kou *et al.* (2007) found that the application of fly ash as a partial replacement of cement improved the resistance of chloride ion penetrability. Nassar (2010) revealed the similar conclusion that the use of class-F fly ash resulted in 38% reduction of the resistance of chloride ion penetrability in RAC. Du *et al.* (2006) observed that the resistance of chloride ion penetrability of recycled ag-

gregate concrete increased with the growth of the curing age. Hu *et al.* (2009) and Nassar (2010) found that reducing the w/c ratio could also improve the chloride impermeability. Otsuki *et al.* (2003) observed that the resistance of chloride ion penetrability of RAC could be intensified by selecting the double mixing method.

In addition, Xiao *et al.* (2012c) proposed a model to describe the effect of recycled aggregate on the chloride penetration in RAC and new theoretical equations to calculate the effective chloride diffusivity in the modeled RAC. Xiao *et al.* (2012b) revealed that the distribution of chloride concentration is not uniform within modeled RAC and the chloride concentration in modeled RAC decreases wavelike along the diffusion depth by simulating the chloride penetration characteristics in modeled RAC to study the chloride penetration characteristics of RAC.

3.2 Freezing and thawing resistance

Cao *et al.* (2012), Dai (2007), Zou *et al.* (2010), and Limbachiya *et al.* (2000) have investigated the freezing and thawing resistance of recycled aggregate concrete (RAC). **Figure 4** gives the relationship between the relative freezing and thawing resistance of RAC and the RCA replacement percentage. The freezing and thawing resistance of RAC is similar to the corresponding NAC for a similar strength and can be used for building structures in cold areas (Cao *et al.* 2012; Limbachiya *et al.* 2000). Richardson *et al.* (2011), Medina *et al.* (2013), and Ajdukiewicz and Kliszczewicz (2002) had shown similar conclusion. However, Dai *et al.* (2007) demonstrated that the strength loss rate of RAC is higher than that of NAC, and the main reason is that the RCA has lower freeze-thaw resistance because of its high water absorption. Zou *et al.* (2010) studied the basic mechanical properties of RAC after freeze-thaw, and the results represented that freeze-thaw resistance of RAC is lower than that of NAC and could be reduced with the increasement of RCA content and the freeze-thaw frequency.

Fig. 4 Variation of relative freeze-thaw resistance parameter with RCA replacement percentage.

Furthermore, Hosokawa *et al.* (1997) studied the influence of adhered mortar content of RCA on the freeze-thaw resistance of RAC. The result proved that the process to reduce adhered mortar was not an effective method for the freeze-thaw resistance of RAC. Richardson *et al.* (2011) discovered that the use of air entrainment and polypropylene fiber in RAC was equally effective for providing the freeze-thaw resistance. Salem *et al.* (2003) reported that lowering the w/c ratio to a certain level was helpful but not acceptable to the development of the freeze-thaw resistance of RAC and the use of entrained air was effective on improving it. Salem and Burdette (1998) proposed that the use of air entrainment and fly ash in RAC resulted in a significant improvement in the freeze-thaw resistance.

3.3 Abrasion resistances

Nassar and Soroushian (2012), Limbachiya *et al.* (2000), Peng (2009), and Sagoe *et al.* (2001) have studied the abrasion resistances of recycled aggregate concrete (RAC). The results show that the recycled coarse aggregate (RCA) replacement percentage has significant influence on the abrasion resistance of RAC. **Figure 5** illustrates the relationship between the relative abrasion resistance of RAC and the RCA replacement percentage, which indicates that the abrasion resistance decreases with the increase of replacement percentage of RCA. The concrete containing RCA reduced the abrasion resistance by about 12% compared to the natural aggregate concrete (NAC) (Sagoe *et al.* 2001). However, Limbachiya *et al.* (2000) studied the effects of RCA replacement percentage on the abrasion resistance of high-strength RAC and revealed that a given design strength RAC had similar abrasion resistance to the corresponding NAC.

Fig. 5 Relative abrasion depth or mass loss versus RCA replacement percentage.

Besides the RCA replacement percentage, many investigators have studied other affecting factors on abrasion of RAC, including admixtures, water cement ratio, and mixing method. Liu *et al.* (2012) reported that the abrasion resistance of the recycled concrete for pavement increases by 18%-36% compared with normal pavement concrete when the double mixing technique, high quality fly ash and high efficiency admixture is applied. Sagoe *et al.* (2001) pointed out that the abrasion resistance of RAC reduced with the increase of water-binder ratio and adding slag and fly ash improved the abrasion resistance of RAC. Mei and Zheng (2012) also reported that the interface modification of RCA and the mixture of fly ash and polymer emulsion improved the abrasion resistance of RAC.

3.4 Carbonation

Levy and Helene (2004) presented that the carbonation depth decreased when the RCA replacement was 20% or 50% in the RAC. If the coarse recycled masonry aggregates replace the RCA, this better behavior can also be found when the RCA replacement percentage is 100%. However, many investigators revealed that the carbonation resistance of RAC is lower than that of NAC. Kou and Poon (2012) and Limbachiya *et al.* (2012) found that the carbonation depth of concrete increased with the increase in recycled aggregate content. The carbonation depth of the RAC increases with the increase of RCA content when the RCA replacement percentage is less than 70%, and it decreases with the increase of the RCA content when the RCA replacement exceeds 70% (Lei and Xiao 2008). Zhang and Yan (2009b) indicated that the microstructure of RAC became more complicated and the interface increased with the admixture of RCA, which brought about a negative influence to the carbonation resistance. Yuan *et al.* (2010) found that the carbonation depth increased with the increase of the RCA replacement percentage, for the RCA porosity is higher and with more slight cracks. **Figure 6** illustrates

Fig. 6 Variation of relative depth of carbonation with RCA replacement percentage.

the relationship between the relative depth of carbonation and the RCA replacement percentage at 28 days.

Moreover, other investigators focused on the influence of water-cement ratio, mineral admixtures, mixing techniques and properties of the parent aggregate on the carbonation resistance of RAC. Otsuki *et al.* (2003), Thomas *et al.* (2013) and Gastaldini *et al.* (2007) indicated that the carbonation depth increases with the increase of water-cement ratio. Xiao *et al.* (2012a) proposed that the mineral admixture replacing cement partially (10% by mass of the cement) seems to accelerate the carbonation. Kou and Poon (2012) reported the use of fly ash as a partial replacement of cement and an addition of cement increased the carbonation depth of the concrete. The experiment conducted by Limbachiya *et al.* (2012) tends to indicate that combining fly ash with RCA in concrete may enhance the long-term resistance to carbonation, for the fly ash decreases the initial content of CaO in the cement matrix. Ryu (2002) revealed that the properties of RCA, including the quality and the content of mortar attached to the RCA, have no clear effects on the RAC carbonation. Tamura *et al.* (2001) reported that the double-mixing method reduced the carbonation depth of RAC by about 30%. Amnon (2003) found that the properties of the RCA crushed at different ages had no significant effect on the carbonation resistance of RAC.

3.5 Absorption

One of the major problems with the use of RCA in structural concrete is their high water absorption capacity which leads to difficulties in controlling the properties of fresh concrete and consequently influences the strength and durability of hardened concrete (Poon *et al.* 2007). Kou and Poon (2012), Thomas *et al.* (2013), and Olorunsogo and Padayachee (2002) investigated the absorption of RAC with different contents of RCA. The

Fig. 7 The relative water absorption versus RCA replacement percentage.

test results, given in Fig. 7, indicated that an increase of the RCA led to an increase of absorption of RAC. When the RCA replacement percentage was 100%, the absorption was increased by 70% compared to that of NAC with similar composition. This is due to the high absorption capacity of the RCA itself, which has created higher osmosis pressure within the concrete (Kwan *et al.* 2012).

Besides, the influence of mineral admixtures on the water absorption in RAC has been studied by many researchers. Limbachiya *et al.* (2012) found that the partial replacement of Portland cement by fly ash can effectively reduce the initial surface absorption. For the same concrete design strength, the fly ash concrete has shown lower water absorption compared to Portland cement concrete, especially for mixtures made with solely RCA. Kou and Poon (2012) also revealed that the mixture of fly ash as a partial replacement of cement decreased the water absorption of RAC.

3.6 Drying shrinkage

Drying shrinkage causes an increase in tensile stress, which may lead to cracking, internal warping, external deflection, and deterioration of RAC's durability. Several studies have been carried out to investigate the influence of RCA replacement percentage on the drying shrinkage, e.g., Kou *et al.* (2007), Nassar and Soroushian (2012), Hansen and Boegh (1985), Domingo *et al.* (2009), and Gomez (2002). Figure 8 illustrates the relationship between the relative drying shrinkage of RAC and the RCA replacement percentage (Kou *et al.* 2007; Nassar and Soroushian 2012), which shows that the drying shrinkage linearly increases with the increase of RCA replacement percentage. Hansen and Boegh (1985), and Domingo *et al.* (2009) found RAC had 40% to 60% higher shrinkage than the corresponding NAC. Gomez (2002) indicated that a higher absorption of RCA leads to the increase in shrinkage and creep of

Fig. 8 Relative drying shrinkage versus RCA replacement percentage.

RAC, and the higher the percentage of RCA added, the greater the shrinkage and creep increase.

Several affecting factors on drying shrinkage, such as age, original aggregate, water cement ratio and admixtures have been studied by many investigators. Sagoe *et al.* (2001) found that the drying shrinkage of RAC increased with time and stabilized at about 91 days, and it displayed about 25% higher than that of NAC. Sun (2006) revealed that the drying shrinkage of RAC increased with time, which increased rapidly at the early 56 days and slowly at the late period. Ravindrarajah and Tam (1985) pointed out that the shrinkage of RAC with aggregate from higher-grade parent concrete was greater than that of RAC with aggregate from lower-grade parent concrete. Limbachiya *et al.* (2012) and Zhu and Wu (2010) found that the drying shrinkage deformation of RAC increased with the raising of water cement ratio. A number of investigations (Limbachiya *et al.* 2012; Kou *et al.* 2007; Zhang *et al.* 2009a) point out the use of fly ash as a partial replacement for cement was able to reduce the drying shrinkage of RAC. Eguchi *et al.* (2003) studied the drying shrinkage of RAC based on the viewpoint of composite theory. The drying shrinkage of RAC increases because of the recycled aggregates with low Young's modulus and large drying shrinkage. Most of the water loss is from cement paste in conventional concrete, while recycled aggregates also lose water in RAC. The RCAs lose much water at the early period of drying, but the contribution of the lost water to drying shrinkage is small. The water loss from the recycled aggregate pores contributes to drying shrinkage after the early period. Fathifazl *et al.* (2011) investigated the creep and drying shrinkage of RAC mixes proportioned by method of mixture proportioning (EMV method). The results show that RAC by the EMV method experienced lower drying shrinkage compared with conventional concrete mixes.

4. Grey relational analysis on the durability of RAC

The durability of RAC depends on many factors. Some factors are primary, whereas some are secondary. At present, researches identify them through qualitative analysis. Thus in this paper the grey system theory is used to identify them through quantitative analysis. In this method, a Grey Relation Analysis (GRA) is conducted on the change rate of RAC's durability versus the RCA replacement percentag, after which the influence of different factors can be evaluated quantitatively based on the grey correlation degree.

The method of GRA makes up the drawback caused by adopting mathematical statistics method to conduct system analysis (Deng 1985). Regression Analysis and GRA are widely adopted in multi-factor statistical analysis. Regression Analysis requires that the sample is large enough and obeys canonical distribution (Draper 1998). Compared with Regression Analysis, GRA can

be applied no matter how many samples there are and whether the sample is regular or not. What's more, the amount of calculation is very small, thus the method is very convenient (Tan 1995). The basic idea of GRA is judging whether the correlation of sequence curves is close enough according to the level of similarity of their geometric shapes. The more similar are the curves, the closer correlation between relative sequences is. The correlation of different sequences is analyzed by the grey correlation degree based on comparing the similarity degree of different sequences. The detailed counting process is as follows (Liu and Xie 2008), assuming the arrays are as follows:

$$\begin{aligned} X'_0 &= \{x'_0(1), x'_0(2), \dots, x'_0(n)\} \\ X'_1 &= \{x'_1(1), x'_1(2), \dots, x'_1(n)\} \\ X'_2 &= \{x'_2(1), x'_2(2), \dots, x'_2(n)\} \\ &\dots\dots\dots \\ X'_m &= \{x'_m(1), x'_m(2), \dots, x'_m(n)\} \end{aligned} \quad (1)$$

The normalization process

$$x_i(j) = x'_i(j) / \max_j(x'_i(j)) \quad (2)$$

The normalized arrays are as follows:

$$\begin{aligned} X_0 &= \{x_0(1), x_0(2), \dots, x_0(n)\} \\ X_1 &= \{x_1(1), x_1(2), \dots, x_1(n)\} \\ X_2 &= \{x_2(1), x_2(2), \dots, x_2(n)\} \\ &\dots\dots\dots \\ X_m &= \{x_m(1), x_m(2), \dots, x_m(n)\} \end{aligned} \quad (3)$$

The grey correlation coefficient:

$$\begin{aligned} r(x_0(j), x_i(j)) &= \frac{\min_i \min_j |x_0(j) - x_i(j)| + \beta \max_i \max_j |x_0(j) - x_i(j)|}{|x_0(j) - x_i(j)| + \beta \max_i \max_j |x_0(j) - x_i(j)|} \end{aligned} \quad (4)$$

β is a recognition coefficient and generally defined as 0.5 (Liu and Xie 2008).

The grey correlation degree of X_0 and X_i :

$$r(X_0, X_i) = \frac{1}{n} \sum_{j=1}^n r(x_0(j), x_i(j)) \quad (5)$$

In this paper, chloride permeability, abrasion, absorption and drying shrinkage of RAC are chosen to be analyzed through the grey relational analysis to identify the primary factors and secondary factors, providing theoretical basis for further durability improvement of RAC. In Fig. 9, the four arrays X_0, X_1, X_2, X_3 are the normalized slope, water cement ratio, admixtures and curing age, respectively, based on Eq.(2).

Figures 9 (a)-(d) show the normalized experiment data from Fig. 3, Fig. 5, Fig. 7 and Fig. 8, respectively. For example: $x'_1(8) = 0.45$ respects the water cement ratio is 0.45 according to Fig. 3's 8-Nassar, w/c=0.45, F=20, 56d, $\max x'_1(j) = 0.55$, so the $x_1(8) = 0.82$ shown

(a) chloride permeability, (b) abrasion, (c) absorption, (d) drying shrinkage.

Fig. 9 Normalized experiment data.

Fig. 10 Grey correlation degree.

in Fig. 9(a).

Based on the grey system theory, the calculation result of grey correlation of water cement ratio, admixtures and curing age on slopes is obtained, as shown in Fig. 10. The result indicates that water cement ratio has more correlation with RAC's durability, including chloride permeability, abrasion, absorption and drying shrinkage, than admixtures and curing age. During the mixture ratio design, the control of water cement ratio is the most important.

5. New types of RAC

The new conception of RAC contain aggregate as well as any kind of materials recycled in society, i.e., fiber, polymer, waste latex paint (WLP), recycled ceramics and so on.

Most fibrous residuals can be selected to improve the durability of concrete (Chun and Naik 2004). Fiber reinforcement can effectively improve the roughness, shrinkage, and durability characteristics of concrete. The use of recycled fibers from industrial or postconsumer waste offers additional advantages of waste reduction and resources conservation (Wang *et al.* 2000).

The use of recycled polyethylene terephthalate (PET) in polymer concrete helps in reducing the cost of the material, solving some of the solid waste problems caused by plastics, and saving energy (Jo *et al.* 2006). A wide range of properties could be obtained from polymer concrete using resins based on recycled PET. These properties are comparable to those obtained from polymer concrete using 100% virgin materials (Rebeiz and Fowler 2001). The prepared polymer concrete (PC) shows low apparent porosity, low water absorption, and small open pores (Tawfik and Eskander 2006). A new methodology for production of concrete impregnated with polystyrene (CIP) can reduce the permeability of pre-cast concrete surfaces, thereby, reducing the rate of degradation and increasing overall durability (Amianti and Botaro 2008). Carpet recycled (CR) with both containing polyamide (PA) and polypropylene (PP) fibers form a strong and water-resistant bond with concrete (Schmidt and Cieslak 2008).

Concrete mixtures incorporating Waste Latex Paint (WLP) can improve workability, higher flexural strength, lower chloride ion penetrability, better resistance to deicing salt surface scaling and can be more economic because they require less water-reducing and

air-entraining admixtures (Nehdi and Sumner 2003; Nehdi 2004). The durability of concrete can also be significantly enhanced due to WLP addition, and no significant emission of toxic substances was detected in leaching tests of WLP concrete specimens subjected to 300 freezing-and-thawing cycles (Mohammed *et al.* 2008).

As to the effects on concrete durability of using recycled ceramic aggregates related to long-term concrete durability (Correia *et al.* 2006), marble and granite waste aggregates can be used to improve the mechanical properties, workability and chemical resistance of the conventional concrete mixtures (Binici *et al.* 2008). The recycling of steel slag will become an important measure for the environment protection and therefore will be of significance (Li 2009).

6. Conclusions

This paper reviews the relevant studies and researches on the durability of RAC and analyzes the influencing factors according to the grey relational analysis. The main conclusions can be summarized in the following:

- (1) The chloride penetrability resistance and abrasion resistance of RAC linearly reduce with the increase of replacement percentage of RCA. Nevertheless, the use of fly ash, double mixing method and lower water cement ratio can increase the chloride penetrability resistance and abrasion resistance of RAC. What's more, the resistance of chloride ions penetrability of RAC with mineral admixtures can meet the engineering code.
- (2) Both freeze-thaw resistance and carbonation resistance of RAC decrease with the increase of the RCA replacement percentage and water cement ratio, but they decrease when an amount of fly ash and air entrainment are applied in the RAC. Besides, the double-mixing method can reduce the carbonation depth of RAC.
- (3) Both absorption and drying shrinkage of RAC linearly increase with the increase of replacement percentage of RCA, but decrease when an amount of fly ash is mixed in the RAC.
- (4) The water cement ratio, admixtures and curing age all have effects on the durability of RAC. The Grey Relational Analysis (GRA) has been applied to find that, compared to admixtures and curing age, water cement ratio has more correlation with chloride permeability, abrasion, absorption and drying shrinkage of RAC.
- (5) The new conception of RAC containing aggregate as well as any kind of materials recycled in society, i.e., fiber, polymer, waste latex paint, recycled ceramics and so on, is a feasible conception which needs to be further studied.

Acknowledgements

The authors wish to acknowledge the financial support

from the National Natural Science Foundation of China (NSFC) (Project No: 51325802).

References

- Ajdukiewicz, A. and Kliszczewicz, A., (2002). "Influence of recycled aggregates on mechanical properties of HS/HPC." *Cement Concrete Composites*, 24(2), 269-279.
- Amianti, M. and Botaro, V. R., (2008). "Recycling of EPS: A new methodology for production of concrete impregnated with polystyrene (CIP)." *Cement Concrete Composites*, 30(1), 23-28.
- Amnon, K., (2003). "Properties of concrete made with recycled aggregate from partially hydrated old concrete." *Cement and Concrete Research*, 33(5), 703-711.
- Andrade, C., (1993). "Calculation of chloride diffusion coefficients in concrete from ionic migration measurements." *Cement and Concrete Research*, 23, 724-742.
- Ann, K. Y., Moon, H. Y., Kim, Y. B. and Ryou, J., (2008). "Durability of recycled aggregate concrete using pozzolanic materials." *Waste Management*, 28, 993-999.
- Basheer, P. A. M., (1991). "Clam' permeability tests for assessing the durability of concrete." PhD Thesis, *The Queen's University of Belfast*, 438.
- Basheer, L., Kropp, J. and Clelan, D. J., (2001). "Assessment of the durability of concrete from its permeation properties: a review." *Construction and Building Materials*, 15, 93-103.
- Berndt, M. L., (2009). "Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate." *Construction and Building Materials*, 23(7), 2606-2613.
- Binici, H. F., Shah, T., Aksogan, O. and Kaplan, H., (2008). "Durability of concrete made with granite and marble as recycle aggregates." *Journal of Materials Processing Technology*, 208(1-3), 299-308.
- Cao, W. L., Liang, M. B., Dong, H. Y. and Zhang, J. W., (2012). "Experimental study on basic mechanical properties of recycled concrete after freeze-thaw cycles." *Journal of Natural Disasters*, 21(3), 184-190. (in Chinese)
- Chun, Y. M. and Naik, T. R., (2004). "Repulping fibrous residuals from pulp and paper mills for recycling in concrete." *Tappi Journal*, 3(12), 7-10.
- Correia, J. R., de Brito, J. and Pereira, A. S., (2006). "Effects on concrete durability of using recycled ceramic aggregates." *Materials and Structures*, 39(2), 169-77.
- Dai, W. Y., Sun, W. M. and Miu, H. L., (2007). "Experimental study on freeze-thaw durability of recycled concret." *Concrete*, 8, 69-71. (in Chinese)
- Deng, J. L., (1985). "The grey control system." *Hua Zhong Engineering College Press*, Wuhan, China. (in Chinese)
- Domingo-Cabo, A., Lázaro, C., López-Gayarre, F.,

- Serrano-López, M.A., Serna, P. and Castaño-Tabares, J. O., (2009). "Creep and shrinkage of recycled aggregate concrete." *Construction and Building Materials*, 23 (7), 2545-2553.
- Draper, N. R. and Smith, H., (1998). "Applied regression analysis." Wiley Interscience.
- Du, T., Li, H. Q., Guo, T. P. and Zhou, Z. Q., (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., Fang, L. B., Liu, Z. X., Zhou, Z. Q. and Liu, J., (2008). "The chloride ion penetrability in recycled aggregate concrete with mineral admixtures." *Proceedings of the Tenth International Symposium on Structural Engineering for Young Experts*, 1, 1835-42. (in Chinese)
- Du, S. C., (2012). "Concrete continuous non-destructive carbonation test and carbonation comprehensive evaluation." *Dalian University of Technology*. (in Chinese)
- Eguchi, K., Teranishi, K. and Narikawa, M., (2003). "Study on mechanism of drying shrinkage and water loss of recycled aggregate concrete." *Journal of Structural and Construction Engineering*, 573, 1-7. (in Japanese)
- Erdogdu, S., Kondratova, I. L. and Bremner, T. W., (2004). "Determination of chloride diffusion coefficient of concrete using open-circuit potential measurements." *Cement and Concrete Research*, 34(4), 603-609.
- Etxeberria, M., Mari, A.R. and Vazquez, E., (2007). "Recycled aggregate concrete as structural material." *Materials and Structures*, 40(5), 529-41.
- Fathifazl, G., Razaqpur, A. G., Isgor, O. B., Abbas, A., Fournier, B. and Foo, S., (2011). "Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate." *Cement and Concrete Composites*, 33(10), 1026-1037.
- Feldman, R., Prudencio Jr, L.R. and Chan, G., (1999). "Rapid chloride permeability test on blended cement and other concretes: Correlations between charge, initial current and conductivity." *Construction and Building Materials*, 13(3), 149-154.
- Fraser, J. B., (2008). "Accelerated testing protocol for durability of roller compacted recycled aggregate concrete (RCRAC)." *Florida Atlantic University*, 115.
- Gastaldini, A., Isaia, G. C., Gomes, N. S. and Sperb, J. E. K., (2007). "Chloride penetration and carbonation in concrete with rice husk ash and chemical activators." *Cement and Concrete Composites*, 29(3), 176-180.
- Gomez-Soberón, J. M. V., (2002). "Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study." *Cement and Concrete Research*, 32(8), 1301-1311.
- Hansen, T. C. and Boegh, E., (1985). "Elasticity and drying shrinkage of recycled aggregate concrete." *ACI Journal*, 82(5), 648- 652.
- Hao, W. and Jin, W., (2008). "Experimental study on the chloride permeability of recycled aggregate concrete." *Advances in Concrete Structural Durability, Proceedings of Icdcs2008*, 1-2, 254-60. (in Chinese)
- Hooton, R. D., (1993). "Influence of silica fume replacement of cement on physical properties and resistance to sulfate attack, freezing and thawing, and alkali-silica reactivity." *ACI Materials Journal*, 90(2), 143-151.
- Hosokawa, Y., Maeda, N. and Hayasaka, T., (1997). "Influence of the time of removing mortar from recycled coarse aggregate on the properties of concrete products using recycled coarse aggregate from waste concrete." *Proceedings of CSCE/JSCE International Conference on Engineering Materials*, Canada, 775-788.
- Hu, B., Liu, B. K. and Zhang, L.L., (2009). "Chloride ion permeability test and analysis for recycled concrete." *Journal of Hefei University of Technology*, 32(8), 1240-1243. (in Chinese)
- Jo, B. W., Park, S. K. and Kim, C. H., (2006). "Mechanical properties of polyester polymer concrete using recycled polyethylene terephthalate." *ACI Structural Journal*, 103(2), 219-225.
- Jones, M. R., Dhir, R. K., Newlands, M. D. and Abbas, A. M. O., (2000). "A study of the CEN test method for measurement of the carbonation depth of hardened concrete." *Materials and Structure*, 33(2), 135-142.
- Ke, Y., Beaucour, A. L., Ortola, S., Dumontet, H. and Cabrilac, R., (2009). "Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete." *Construction and Building Materials*, 23(8), 2821-2828.
- Kong, D. Y., Lei, T., Zheng, J. J., Ma, C. C. and Jiang, J., (2010). "Effect and mechanism of surface-coating pozzalanic materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete." *Construction and Building Materials*, 24(5), 701-708.
- Kou, S. C. and Poon, C. S., (2006). "Compressive strength, pore size distribution and chloride-ion penetration of recycled aggregate concrete incorporating class-F fly ash." *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, 21(4), 130-136.
- Kou, S. C., Poon, C. S. and Chan, D., (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.
- Kou, S. C. and Poon, C. S., (2012). "Enhancing the durability properties of concrete prepared with coarse recycled aggregate." *Construction and Building Materials*, 35, 69-76.
- Kwan, W. H., Ramli, M., Kam, K. J. and Sulieman, M. Z., (2012). "Influence of the amount of recycled coarse aggregate in concrete design and durability

- properties.” *Construction and Building Materials*, 26(1), 565-573.
- Lei, B. and Xiao, J. Z., (2008). “Research on carbonation resistance of recycled aggregate concrete.” *Chinese Journal of Building Materials*, 11(5), 605-611. (in Chinese)
- Levy, S. M. and Helene, P., (2004). “Durability of recycled aggregates concrete: a safe way to sustainable development.” *Cement and Concrete Research*, 34(11), 1975-1980.
- Li, Y. F., (2009). “Recycling of steel slag for energy saving and its application in high performance concrete.” *2009 Asia-Pacific Power and Energy Engineering Conference (Appeec)*, 1-7, 2786-2789.
- Limbachiya, M. C., Leelawar, T. and Dhir, R. K., (2000). “Use of recycled concrete aggregate in high-strength concrete.” *Materials and Structures*, 33(10), 574-580.
- Limbachiya, M., Meddah, M. S. and Ouchagour, Y., (2012) “Use of recycled concrete aggregate in fly-ash concrete.” *Construction and Building Materials*, 27(1), 439-449.
- Lindvall, A., (1998). “DuraCrete-Probabilistic performance based durability design of concrete structure”, 2nd Int. Ph.D. *Symposium in civil engineering*.
- Liu, T. C., (1981). “Abrasion resistance of concrete.” *ACI Journal Proceedings*, 78(5), 341-350.
- Liu, S. F. and Xie, N. M., (2008). “Grey system theory and its application.” 4th ed, *Beijing: Science Press*. (in Chinese)
- Liu, Q. T., Chen, F. N., Cai, L. C., Wu, Y. G., Wu, H. C., Chen, F. N., Huang, G. Q. and Zhu, Z. Y., (2012) “Properties and applications of recycled concrete for airport pavement.” *Journal of Central South University (Science and Technology)*, 43(8), 3263-3269. (in Chinese)
- Lu, X. Y., (1997). “Application of the Nernst-Einstein equation to concrete.” *Cement and Concrete Research*, 27(8), 293-302.
- McCarter, W. J., Ezirim, H. and Emerson, M., (1992). “Absorption of water and chloride into concrete.” *Magazine of Concrete Research*, 44(158), 31-37.
- Medina, C., de Rojas, M. and Frias, M., (2013). “Freeze-thaw durability of recycled concrete containing ceramic aggregate.” *Journal of Cleaner Production*, 40, 151-160.
- Mei, Y. J. and Zheng, J. H., (2012). “Technical approach to improve abrasion properties of recycled aggregate concrete.” *Chinese Concrete*, 2, 134-137. (in Chinese)
- Mohammed, A., Nehdi, M. and Adawi, A., (2008). “Recycling waste latex paint in concrete with added value.” *ACI Materials Journal*, 105(4), 367-374.
- Nassar, R. U. D., (2010). “Synergistic use of milled waste glass and recycled aggregate towards a sustainable concrete-based infrastructure.” *East Lansing: Michigan State University*.
- Nassar, R. U. D. and Soroushian, P., (2012). “Use of milled waste glass in recycled aggregate concrete.” *Proceedings of the ICE - Construction Materials*, 166(5), 304-315.
- Nehdi, M. and Sumner, J., (2003). “Recycling waste latex paint in concrete.” *Cement and Concrete Research*, 33(6), 857-863.
- Nehdi, M., (2004). “Recycled waste latex paint as an admixture in concrete sidewalks.” *ACI Special Publication*, 219, 131-144.
- Olorunsogo, F. T. and Padayachee, N., (2002). “Performance of recycled aggregate concrete monitored by durability indexes.” *Cement and Concrete Research*, 32(2), 179-185.
- Otsuki, N., Miyazato, S. and Yodsudjai, W., (2003) “Influence of recycled aggregate on interfacial transition zone, strength, chloride, penetration and carbonation.” *Journal of Materials in Civil Engineering*, 15(5), 443-451.
- Park, S. B., Seo, D. S. and Lee, J., (2005). “Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio.” *Cement and Concrete Research*, 35(9), 1846-1854.
- Peng, S. X., (2009). “Study on abrasion resistance of recycled aggregate concrete.” *Changsha: Central South University*. (in Chinese)
- Poon, C. S., Shui, Z. H. and Lam, L., (2004). “Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates.” *Construction and Building Materials*, 18(6), 461-468.
- Poon, C. S., Kou, S. C. and Lam, L., (2007). “Influence of recycled aggregate on slump and bleeding of fresh concrete.” *Materials and Structures*, 40(9), 981-988.
- Ravindrarajah, R. S. and Tam, C. T., (1985). “Properties of concrete made with crushed concrete as coarse aggregate.” *Magazine of Concrete Research*, 37(130), 29-38.
- Rebeiz, K. S. and Fowler, D. W., (2001). “An overview on polymer concrete using recycled PET.” *2001 Second International Conference on Engineering Materials*, 1, 215-222.
- Richardson, B. J. E. and Jordan, D. O., (1994). “Use of recycled concrete as a road pavement material within Australia.” *Australian Road Research Board*, 213-228.
- Richardson, A., Coventry, K. and Bacon, J., (2011). “Freeze/thaw durability of concrete with recycled demolition aggregate compared to virgin aggregate concrete.” *Journal of Cleaner Production*, 19, 272-277.
- Ryu, J. S., (2002) “An experimental study on the effect of recycled aggregate on concrete properties.” *Magazine of Concrete Research*, 54(1), 7-12.
- Safiuddin, Md., Mahmud, H. B. and Jumaat, M. Z., (2011). “Efficacy of ASTM saturation techniques for measuring the water absorption of concrete.” *Arabian Journal for Science and Engineering*, 36(5), 761-768.
- Sagoe-Crentsil, K. K., Brown, T. and Taylor, A. H., (2001). “Performance of concrete made with commercially produced coarse recycled concrete

- aggregate." *Cement and Concrete Research*, 31(5), 707-712.
- Salem, R. M. and Burdette, E. G., (1998). "Role of chemical and mineral admixtures on physical properties and frost-resistance of recycled aggregate concrete." *ACI Materials Journal*, 95(5), 558-563.
- Salem, R. M., Burdette, E. G. and Jackson, N. M., (2003). "Resistance to freezing and thawing of recycled aggregate concrete." *ACI Materials Journal*, 100(3), 216-221.
- Schmidt, H. and Cieslak, M., (2008). "Concrete with carpet recyclates: Suitability assessment by surface energy evaluation." *Waste Manage*, 28(7), 1182-1187.
- Stanish, K. D., Hooton, R. D. and Thomas, M. D. A., (2000). "Testing the chloride penetration resistance of concrete: a literature review." University of Toronto, Canada.
- Stanish, K. and Thomas, M., (2003). "The use of bulk diffusion tests to establish time-dependent concrete chloride diffusion coefficients." *Cement and Concrete Research*, 33(1), 55-62.
- Sun, H., (2006). "Study of coarse aggregate and admixtures on the properties of recycled concrete." Shanghai: Tongji University. (in Chinese)
- Tam, V. W. Y., Gao, X. F. and Tam, C. M., (2006). "Comparing performance of modified two-stage mixing approach for producing recycled aggregate concrete." *Magazine of Concrete Research*, 58(7), 477-484.
- Tam, V. W. Y. and Tam, C. M., (2007) "Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach." *Journal of Materials Science*, 42(10), 3592-3602.
- Tamura, H., Nishio, A. and Ohashi, J., (2001). "High quality recycled aggregate concrete (HiRCA) processed by decompression and rapid release." ACI Special Publications Rep. No. SP-200, American Concrete Institute (ACI), Detroit, 491-502.
- Tan, X. and Deng, J. L., (1995). "Grey relational analysis: New method of multivariable statistical analysis." *Statistical Research*, 3, 46-48.
- Tang, L. and Nilsson, L. O., (1992). "Chloride diffusivity in high strength concrete." *Nordic Concrete Research*, 11, 162-170.
- Tawfik, M. E. and Eskander, S. B., (2006). "Polymer concrete from marble wastes and recycled poly(ethylene terephthalate)." *Journal of Elastom Plast*, 38(1), 65-79.
- Thomas, M. D. A. and Bamforth, P. B., (1999). "Modelling chloride diffusion in concrete - Effect of fly ash and slag." *Cement and Concrete Research*, 29(4), 487-495.
- Thomas, C., Setien, J., Polanco, J. A. and Sanchez de Juan, M., (2013). "Durability of recycled aggregate concrete." *Construction and Building Materials*, 40, 105-1065.
- Vancura, M., Khazanovich, L. and Tompkins, D., (2009). "Reappraisal of recycled concrete aggregate as coarse aggregate in concretes for rigid pavements." *Transportation Research Board of the National Academies*, 2113, 149-55.
- Vedalakshmi, R., Devi, R. R., Emmanuel, B. and Palaniswamy, N., (2008). "Determination of diffusion coefficient of chloride in concrete: An electrochemical impedance spectroscopic approach." *Materials and Structures*, 41(7), 1315-1326.
- Villagran-Zaccardi, Y. A., Zega, C. J. and Di Maio, A. A., (2008). "Chloride penetration and binding in recycled concrete." *Journal of Materials in Civil Engineering*, 20(6), 449-455.
- Wang, Y. J., Wu, H. C. and Li, V. C., (2000). "Concrete reinforcement with recycled fibers." *Journal of Materials in Civil Engineering*, 12(4), 314-319.
- Whiting, D., (1981). "Rapid measurement of the chloride permeability of concrete." *Public Roads*, 45(3), 101-112.
- Wu, J. H., Zhang, Y. M. and Sun, W., (2008). "Concrete carbonation model and test method review and suggestion." *China Concrete and Cement Products*, 6, 1-7. (in Chinese)
- Wu, X. L., Zhang, W. P., Huang, Q. H. and Gu, X. L., (2009). "Overview on test methods of deterioration of concrete exposed to freeze-thaw and deicer." *Structural Engineers*, 25(2), 147-152. (in Chinese)
- Xiao, J. Z., Li, J. B. and Zhang, C., (2005). "Mechanical properties of recycled aggregate concrete under uniaxial loading." *Cement and Concrete Research*, 35(6), 1187-1194.
- Xiao, J. Z., Li, J. B. and Zhang, C., (2006a). "On relationships between the mechanical properties of recycled aggregate concrete: An overview." *Materials and Structures*, 39(6), 655-664.
- Xiao, J. Z., Sun, Y. D. and Falkner, H., (2006b). "Seismic performance of frame structures with recycled aggregate concrete." *Engineering Structures*, 28(1), 1-8.
- Xiao, J. Z. and Falkner, H., (2007). "Bond behaviour between recycled aggregate concrete and steel rebars." *Construction and Building Materials*, 21(2), 395-401.
- Xiao, J. Z., Lei, B. and Zhang, C. Z., (2012a). "On carbonation behavior of recycled aggregate concrete." *SCIENCE CHINA Technological Sciences*, 55(9), 2609-2616.
- Xiao, J. Z. and Ying, J. W., (2012b). "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, J. Z., Ying, J. W. and Shen, L. M., (2012c). "FEM simulation of chloride diffusion in modeled recycled aggregate concrete." *Construction and Building Materials*, 29, 12-23.
- Yang, C. C. and Cho, S. W., (2003). "An electrochemical method for accelerated chloride migration test of diffusion coefficient in cement-

- based materials.” *Materials Chemistry and Physics*, 81, 126-125.
- Yang, C. C., Wang, L. C. and Weng, T. L., (2004). “Using charge passed and total chloride content to assess the effect of penetrating silane sealer on the transport properties of concrete.” *Materials Chemistry and Physics*, 85(1), 238-244.
- Yuan, C. F., Luo, Z., Ding, T. F., Wang, H., Hao, Y. and Zhang, H. L., (2010). “Orthogonal experiment of carbonation resistance for recycled aggregate concrete.” *Journal of Wuhan University of Technology*, 21, 9-12. (in Chinese)
- Zhang, J., Du, H., Zhang, C. and Li, Q. Y., (2009a). “Influence of mineral admixture and recycled aggregate on shrinkage of concrete.” *Journal of Qingdao Technological University*, 34(4), 145-149,153. (in Chinese)
- Zhang, Z. and Yan, H. S., (2009b). “Carbonization of recycled aggregate concrete.” *Chinese Concrete*, 11, 34-36. (in Chinese)
- Zhao, T. J. and Li, S. J., (2002). “The permeability, carbonation and steel corrosion of concrete.” *China civil engineering society, high strength and high performance concrete and its application workshop*. (in Chinese)
- Zhu, L. and Wu, J., (2010). “The study on early drying shrinkage of recycled aggregate concrete.” *2nd International Conference on Waste Engineering and Management*, ICWEM 2010 RILEM Proceedings, 73, 568-575.
- Zou, C. Y., Fan Y. H. and Hu, Q., (2010). “Experimental study on the basic mechanical property of recycled concrete after freeze-thaw.” *Building Structures*, 40, 434-438. (in Chinese)