Overview of recycled concrete research through development years (2004-2018)

Xiao J¹, Singh A D¹, Duan Z¹, Pan Y², Qin J³
1. College of Civil Engineering, Tongji University, Shanghai 200092, China
2. China Construction Eighth Bureau Second Construction Co. LTD, Jinan, 250033, China
3. Linyi Lantai Environmental Protection Technology Co. LTD, Linyi, 276000, China

jzx@tongji.edu.cn

Abstract. Along with the urbanization process, large amount of construction and demolition (C&D) waste during the construction, reconstruction, expansion or demolition of buildings is generated. Meanwhile, the impact on environment due to natural aggregate mining has become increasingly significant. These factors have driven the building industry to look for environmentally friendly materials and focusing on sustainable construction. Through nearly a decade of research, recycled concrete (RC) made with recycled aggregates manufactured from construction and demolition (C&D) waste has shown a competitive performance compared to natural materials and has already achieved industrial application. Researches on sustainably recycled concrete have become an essential part of sustainable development and continue to play a vital role for future research.

This paper engages in the discussion and the overview of research done by the Research Group for Recycled Concrete Structures and Construction at Tongji University, Shanghai. The first part discusses the necessary mechanical and durability properties of recycled concrete with recycled aggregate as well as recycled powder focusing on workability, strength, Poisson’s ratio, stress-strain behaviour along with carbonation, chloride penetration shrinkage and creep. The second part throws light on the elements and structures made with recycled aggregate concrete (RAC), discussing the behaviours of RAC components and structures.

1. Introduction
In recent years, large upscale of the construction sector and increasing requirement of advance and new habitats, caused by population growth and migration from rural to urban, have exploited a large number of construction materials. Environmental regulations and depletion of high-quality aggregates along with urgent need make natural aggregate the last option for the construction industry. Moreover, increase the cost of haulage from one place to another adds up to the increased cost of final construction materials along with explosive urbanization and increase modernization for alternate materials for construction. To reduce the impact on the environment and reduce the landfill space, it is of the dire need of finding an alternative for the construction materials in a friendlier and economical way. Moreover, to have a sustainable concrete industry, the attention should be paid to the conserve energy, resources, and environment protection.
In last decade, China has witnessed the significant degradation of natural resources. There has been a massive generation of C&D waste, which accounts for the 500 million tons of waste generated annually [1,2] as shown in Figure 1. Recycled aggregate concrete (RAC) being a sustainable material on one side, also helpful in saving the ecology by reducing the use of natural aggregates (NA). Literature suggests that the mechanical properties of recycled aggregate (RA) may be lower than those of normal concrete (NC) generally, but can be utilized in practical application for the structural purpose [3–5]. Studies prove that there are differences between the properties of recycled coarse aggregate (RCA) and natural coarse aggregate (NCA), due to some physical properties like rough and porous surface, reduced bulk and apparent density, increased porosity and adhered mortar on aggregates. These properties impact on the crushing value, soundness, and water absorption of aggregates, which are bases for the strength indexes of any concrete [5–9]. At present, implementing RAC is still at a demonstration phase, but our group has focused the research from 2004 onwards on RAC studies, thru micro-, meso- and full-scale structure.

2. RAC materials

2.1. Strength indexes

The compressive strength is one of the most essential mechanical property, which is the basis for the differentiation of RAC as compared to natural aggregate concrete (NAC). Due to difference in the physical properties between RCA and NCA compressive strength is the most important mechanical property. Based on the overall analysis of the results at early stage the compressive strength of RAC follows a similar pattern with NAC when undergoing curing.

For the evaluation of factors influencing the strength indexes and research has been carried out a test on more and 635 cube specimens in the concrete materials research laboratory, Tongji University, China. During the research phase of concrete with RA, various mixes were made using the different replacement ratio. This paper represents the review of the work done by the research team in Tongji University. Mixes with the different water-cement ratio (w/c) and the obtained results are shown in Figure 2, which shows the relative cube compressive strength at 28 days concrete strength of RAC which was cured in fog room (20±2 °C, 95% relative humidity). Figure 2 shows that the development of compressive strength coefficient before 28 days curing of RAC is higher than that of NAC. Whereas, the strength development coefficient after 28 days of curing of RAC is less than that of NAC. The reason being that additional water absorption of RA tends to provide additional internal curing in RAC than NAC. Another factor influencing the compressive strength is the weak bonding between the recycled concrete aggregate (RCA) and the new and old mortar. At the same time, higher w/c ratio leads to excess water in the pores of RCA [1,10].

![Figure 1: C&D waste generation in China [1,2]](image1)

![Figure 2: Relative cube compressive strength at 28 days](image2)
The results were analysed using a statistical approach to compare the outcome of RAC with NAC, which followed a normal distribution. The analysis showed that the coefficient of variance (COV) of compressive strength is not very large as compared to NAC, proving that the RCA replacement does not influence the RAC’s compressive strength variation coefficient. Furthermore, to check the feasibility of a normal distribution model, Monte Carlo simulation was used for evaluation of strength distribution of RAC and probability density function (π(σ)) for concrete compressive strength of RAC was obtained:

\[ \pi(\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\sigma-\mu)^2}{2\sigma^2}} \]  \hspace{1cm} \text{Eq. 1}

Where, the average value of the standard deviation of compressive strength \( \mu = 4.31 \) MPa, and the standard deviation \( \sigma = 1.1141 \) MPa. Furthermore, the Bayes estimation was used to get the SD for the various strength grade as shown in Table 1, but considering the situation the mixing plants, SD of RAC30 was kept at 5.0 MPa, which is closely identical to that of NAC but only applicable to the RCA from a single source which can control the quality of RCA.

Table 1: The Bayes estimation results of the standard deviation for RAC C30 compressive strength

| r (%) | 0 | 30 | 50 | 100 |
|------|---|----|----|-----|
| \( \sigma \) (MPa) | 4.31 | 4.5 | 3.95 | 3.2 |

On further analysis, after the comparison between the experimental and simulation data, the following relationships between the splitting tensile strength and the compressive strength, flexural strength and the compressive strength of the RAC are shown in Eq. 2 and Eq. 3 respectively [11].

\[ f_{sp} = 0.24 f_{cu}^{0.65} \]  \hspace{1cm} \text{Eq. 2}

\[ f_f = 0.75 \sqrt{f_{cu}} \]  \hspace{1cm} \text{Eq. 3}

Where, \( f_{cu} \) is the compressive strength in MPa, \( f_{sp} \) is splitting tensile strength in MPa and \( f_f \) is the flexural strength in MPa.

2.2 Constitutive relationship
For the constitutive relationship between various parameters of concrete, with an investigation on a stress-strain curve with/without confinements [12], axial loading [13], shear loading [14] and impact loading [15] along with shear transfer behavior and compressive behavior of RAC under high strain rate. During testing, strain rate of the test specimens was kept constant to \( 44 \times 10^6 /s \) and Eq. 4 [16] was used to represent the axial loading constitutive model for the linear analysis of the RAC structure and members:

\[ y = \begin{cases} \frac{ax + (3-2a)x^2 + (a-2)x^3}{b(x-1)^2 + x} & \text{if } 0 \leq x < 1 \\ x & \text{if } x \geq 1 \end{cases} \]  \hspace{1cm} \text{Eq. 4}

The values attained \( a \) and \( b \) using the statistical data are:

\[ a = 2.2(0.748r^2 - 1.231r + 0.975) \]
\[ b = 0.8(7.6483r + 1.142) \]

![Figure 3: Normalized stress-strain curve for recycled aggregate](image-url)
Where, \( x = \varepsilon / \varepsilon_0 \), \( y = \sigma / f_c \) from a normalized recycled concrete stress-strain curves as shown in Figure 3, \( a \) is the initial gradient line non-dimensional curve, it reflects RAC’s initial modulus of elasticity, \( b \) the value is related to the non-dimensional dropping stage of the curve area, representing the ductility of concrete and \( r \) is the replacement ratio of RCA.

2.3 Long term properties

In real conditions, the materials are usually exposed to prolong loading or cyclic loading during the design life of a structure. The first and far most important long-term property is shrinkage and creep. Test were carried out as per GB/T 50090-2002 [17]. The shrinkage and creep of RAC with four different replacements ratio of 33, 66 and 100% are 2.6, 15.4 and 26.9% and 28.7, 75 and 103% higher than that of NAC respectively, whereas environment has no drastic impact on the shrinkage and creep of RAC [18]. Mineral admixtures, water-reducing agents, bulking agents, etc. can reduce shrinkage deformation, whereas old adhering mortar cannot be ignored when calculating the creep of RAC because creep characteristics of RAC are influenced significantly by the content, elastic modulus, and creep behaviour of the old adhering mortar.

Evaluation of carbonation and chloride diffusivity are by Chinese codes GB/T50082-2009 [19] which are the second most long-term property. The porosity and attached mortar, which is higher in RCA than natural aggregate along with the same w/c ratio, can improve the carbonation resistance. Based on the existing formula from fib carbonation model [20], Chinese code’s model [21], Zhang and Jiang’s model [22], Xiao and Lei [23] represented two modified carbonation models, namely Xiao and Lei Model ‘a’ (Eq. 5) and Xiao and Lei Model ‘b’ (Eq. 6). These models are based on the factor, replacement percentage, which is an important factor in predicton of carbonation depth.

\[
x_c(t) = K_{CO_2} \cdot K_{x_1} \cdot K_{x_3} \cdot T^{0.25} \cdot RH^{1.5} \cdot (1 - RH) \left( \frac{230}{f_{cu}} + 2.5 \right) \cdot \sqrt{t} \quad \text{Eq. 5}
\]

\[
x_c(t) = 839 \cdot g_{RC}(1 - RH)^{1.5} \cdot \sqrt{\frac{W / \gamma_c C - 0.34}{\gamma_{HD} f_c C} \cdot n_0 \cdot \sqrt{t}} \quad \text{Eq. 6}
\]

where \( x_c(t) \) is the carbonation depth of concrete at time \( t \), in mm; \( W \) is the water content (kg/m\(^3\)); \( C \) is the cement content (kg/m\(^3\)); \( \gamma_c \) is the coefficient for cement type (1.0 for Portland cement); \( \gamma_{HD} \) is the coefficient of the degree of hydration (0.85 for 28 days’ curing, 1.0 for 90 days’ curing); and \( n_0 \) is the location factor, 1.4 for corner and 1.0 for another place; \( K_{x_1} \) is the stress factor, 1.0 for compression and 1.1 for tension; \( T \) is the temperature (°C); \( RH \) is the relative humidity; \( f_{cu} \) is mean value of RAC compressive strength; and \( g_{RC} \) equals to 1.0, while for RAC with a 100% replacement percentage of RCA, \( g_{RC} \) equals to 1.5. On the other hand, for chloride diffusivity, the experimental and theoretical data are generally in agreement with Fick’s second law similar having a deviation from NAC. Moreover, Xiao et al. [24] proposed a model that considered RAC as a five-phase composite model (Figure 4) [25] in order to describe the chloride diffusion coefficient (\( D_{cl} \)) in RAC (Eq. 7 and Eq. 8). Based on the residual mortars, which is the critical factor, the RAC will become NAC when the attached mortar value is less than the threshold value of 0.5.
\[ D_{\text{eff}} = \frac{x^2}{4 \left[ \text{erfc}^{-1} \left( \frac{C_{\text{mean}}}{C_s} \right) \right]^2 t} \]  
\text{Eq. 7}

\[ C_T = \int_{-5\text{mm}}^{+5\text{mm}} C(5, y) dy \]  
\text{Eq. 8}

where \( C_s \) is the boundary conditions of chloride concentration (x10^-1 mg/mm^3), and \( \text{erfc}^{-1}() \) is the inverse complementary error function, \( C_{\text{mean}} \) is the mean value of \( C_T \) at the position of \( x \) and the mean value of chloride amount along the boundary \( X = 5 \text{ mm} \) is calculated by \( C_{\text{mean}} = C_T \div 10 \text{ mm} \).

Theoretical equation, finite element method (FEM) and simulation on modeled RAC (MRAC) [26] showed that \( D_{\text{eff}} \) decreases with the rise in RCA volume fraction, but increases with the adhesive rate of the old mortar adhering and the thickness of the ITZ.

3 New types of RAC

3.1 Modification of conventional RAC

Compared to traditional concrete, it is hard to predict the properties of RAC on a direct basis. Investigators have found that a two-stage mixing approach (TSMA) have improved the mechanical properties and durability of RAC [27]. Nano-indentation was used to evaluate the microstructural and nanomechanical properties of ITZs in RAC prepared with different mixing approaches. The contour variation of indentation modulus histogram is seen in old ITZ and new ITZ with TSMA (Figure 5). The result proves that TSMA can effectively reduce the size and effect of water layers, reducing the amount of porosity enhancing hydration. TSMA also produce a stronger and denser ITZ due to the calcium carbonate crystals covering the RCA surface [28]. Moreover, it should be noted that modulus distribution with age of old and new ITZ is different. The properties of old ITZ in RAC do not change with the hydration age, while the indentation modulus of new ITZ and new paste matrix increases with the curing age.

Nano-SiO\(_2\) and nano-TiO\(_2\) particles were also used to enhance the properties of RAC. Due to the large specific surface area and high activity [29], nano-particles helped in refining the pore structure of RAC. The pore structure increases and then decreases up to an extent with increasing content. Results proved that 2% addition of nano-TiO\(_2\) is slightly better than nano-SiO\(_2\) [30]. Moreover, hydrated cement in old ITZ between gravel and cement paste (OITZ), the calcium silicate hydrate (CSH) having a short rapid growth and decline rapidly, whereas in new ITZ between new and old cement paste (NITZ) the rapid growth is close to zero and begin with a relatively high generation of CSH gel.
Based on the previous studies and sustainability issues, the combination of seawater, sea-sand, and RCA was investigated. The focus is on the demolition of the structures from coastal and the marine regions, which suffer the corrosion from chemicals like chloride, and hard to separate the harmful chemicals from the waste. So, this kind of concrete can be used to deal with resource exhaustion and the disposal of waste concrete [31]. Two additional types of sea-sand with seawater is used for mixing of concrete. Various concrete mixes were cast and tested for the mechanical properties. The concrete produced with sea-sand, seawater, and RCA showed good cohesion, required workability, increased behavior of early strength is noted but delayed in the underlying strength. Moreover, an increase in 8%-16% of elastic modulus is observed in the concrete made with sea-sand, seawater, and RCA, following the models for strain and strain by previous researchers and specifications [10,32]. Figure 6 and Figure 7 represent the compressive strength, split tensile and variation between split tensile and axial compressive strength of concrete made with sea-sand, seawater, and RCA.

Figure 5: Modulus distribution across (a) old ITZ (b) new ITZ with TSMA, Contour map of indentation modulus across (c) old ITZ and (d) new ITZ with TSMA, Modulus distribution across (a) old ITZ (b) new ITZ with TSMA at different hydration ages
4 RAC structures

4.1 Flexural and shear properties

Properties may differ due to different mix proportions and different replacement percentage of RA. Based on these, semi-precast elements are better in quality as compared to precast hybrid-components. Flexural and shear specimens were cast with U-shape and C-shape precast beams, regular and eccentric columns and slabs for shear. Based on the assumptions of “plan cross-section” and the results, plane section assumptions remain valid in applications for semi-precast beams made of RAC and follows the Chinese code DG/TJ08-2018-2007 [33]. Based on the reliability analysis, beams showed that the reliability was lowest and highest when 100% permanent and 100% live load was applied respectively [34]. In bending behavior of RAC beam, diagonal cross-sectional area cracking load is smaller than NAC. Also, the cracking pattern, deflections, and bearing capacity of U-, C-shaped beams are similar to that of NAC beams with no adverse effects on flexural performance. Along with RAC columns under axial and eccentric compressions, the RAC column showed failure by axial compression, small eccentricity compression failure, limit failure, and large eccentric compression failure, and the increase in the RCA replacement percentage did not cause any change.

4.2 Seismic performance

Based on the test on the precast elements, under cyclic loading, the characteristics of the RAC elements are the same as that of NAC. The ductility coefficient of fully cast-in-situ is more than that of semi-cast columns, along with better ductility of external elements than internal. These results conclude on the full-scale test on the elements with a generation of hysteresis loops. In this study, understanding of structural behaviour of frames under low-frequency cyclic lateral load with constant vertical actions. Based on these the failure pattern, the hysteresis curves, the skeleton curves, the energy dissipation capacity, and the stiffness degradation laws of frame structures with RAC were examined. The failure of the frames is characterized in a manner of “strongest joints, stronger columns and weaker beams” because the ductility coefficient was about 4.0 implying the fine ductility of the structural frames [35]. Whereas, RCA has no remarkable effect on the energy dissipation capacity of frames and is good enough to resist earthquake according to Chinese standard GB 50011-2001 [36].

5 Life cycle assessment

Apart from the specifications, and technical objectives, the drive toward sustainable development leads to the methodological framework and the life cycle assessment (LCA). From the time of introduction from 1994, International Standard Organization (ISO) played an essential role in the area of multi-criteria optimization for NAC and RAC, based on their local life cycle inventory (LCI) [37–41]. The research was focused on the feasibility of aggregate delivery and production and is based on ISO 1404
SUSTAINABLE BUILT ENVIRONMENT CONFERENCE 2019 (SBE19 Graz)  
IOP Conf. Series: Earth and Environmental Science 323 (2019) 012134  
doi:10.1088/1755-1315/323/1/012134

(2016) and ISO 14044 (2006) [37,39]. In this study, the data for regional LCI for NAC and RAC collected and comparative study was made between both with 50% and 100% replacement ratio to have a rational understanding of LCA [42]. To be more precise the cradle-to-grave theory was adopted to change it to cradle-to-crade (Figure 8) shows the methodologies. Another method for the LCA based on the CO₂ absorption model is evaluated. Effect of NAC replacement with RAC on the carbon footprint of a tall structure having 12 floors and area of 15000 m² were investigated. The system boundary used in this study, as shown in Figure 9. In this whole study, the pre-wetting RCA were used to provide the required additional water.

It should be noted that utilizing non-local LCI data for estimation of carbon emissions. The assumption was made on the choice of NAC or RAC as the new building material, which has been the determining factor which affects the choice of waste processing strategy, recycling vs. landfilling, for the container terminal. Based on these, the end-of-life phase of the demolished project was considered. The RAC and NAC structures emitted on average $2.152 \times 10^6$ (i.e., 143.47 kgC/m² or 366.64 kgC/m³ of concrete) and $2.302 \times 10^6$ kgC (i.e., 153.47 kgC/m² or 392.20 kgC/m³ of concrete), respectively. Furthermore, these two towers led, on average, to $8.345 \times 10^6$ MJ (i.e., 556.32 MJ/m² or 1421.71 MJ/m³) and $8.907 \times 10^6$ MJ (i.e., 593.78MJ/m² or 1517.45MJ/m³ of concrete) embodied energy, respectively. Based on the RAC’s environmental benefits and reduced embodied carbon, energy consumption, need of natural resource and C&D wastes processing and its competitive structural performance, the result highlights RAC as a sustainable alternative to NAC. The carbon emission implications of RAC were found to be highly dependent on landfill and transportation phases.

---

Figure 8: Methodologies from cradle-to-grave and cradle-to-crade

---

Figure 9: System’s boundary
Conclusions

Based on the experimental results and analysis, the main findings can be summarized as follows:

The structural behaviour of RAC elements/members has inferior properties as compared to members or structures made with NAC. Tensile and shear strengths of RAC are generally lower than those of conventional concrete, modulus of elasticity for RAC generally reduces as the RCA content increases; however, the strain at peak stress is larger than that of conventional concrete. Additional modification parameters such addition of nano-SiO$_2$ and nano-TiO$_2$ helps in enhancing the durability, chloride diffusion resistivity. Whereas, the modification with carbonation proves to be beneficial for enhancing the interfacial properties of RAC. Sea-sand and seawater minimum affect the workability and accelerate the strength development at an early age due to higher chloride content. Addition of three components (sea-sand, seawater, and RCA) is expected to enhance the sustainability of concrete structures at a greater level.

Further investigation on LCI and LCA showed that carbon emission implications of RAC were found to be highly dependent on the transportation phase. Also, with the continuing expansion of cities and the resulting increase in distance to remote quarries and landfills, the carbon reduction benefits of RAC, compared to NAC, is expected to increase.

However, taking in the account of the situation where we can use the recycled aggregates instead of natural aggregates to supplement the need the environment protection, would definitely leads to the solution to the sustainability of concrete structures. This concept can lead to a ‘zero’ waste encouraging researchers and construction industry to provide green solution for a sustainable future.
References

[1] Xiao J 2017 Recycled Aggregate Concrete Structures (Springer)
[2] Xiao J, Ma Z, Sui T, Akbarnezhad A and Duan Z 2018 Mechanical properties of concrete mixed with recycled powder produced from construction and demolition waste J. Clean. Prod. 188 720–31
[3] Nixon P J 1978 Recycled concrete as an aggregate for concrete-a review Matériaux Constr. 11 371–8
[4] ACI 2001 ACI 555R-01: Removal and Reuse of Hardened Concrete. American Concrete Institute.
[5] Hansen T C 1986 Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945-1988 Mater. Struct. 19 201–46
[6] Jia-Bin L I, Xiao J Z and Sun Z P 2004 Properties of Recycled Coarse Aggregate and Its Influence on Recycled Concrete J. Build. Mater. 7 390–5
[7] Xiao J, Li W and Poon C 2012 Recent studies on mechanical properties of recycled aggregate concrete in China-A review Sci. China Technol. Sci. 55 1463–80
[8] Sagoe-Crentsil K K, Brown T and Taylor A H 2001 Performance of concrete made with commercially produced coarse recycled concrete aggregate Cem. Concr. Res. 31 707–12
[9] Lin Y H, Tyan Y Y, Chang T P and Chang C Y 2004 An assessment of optimal mixture for concrete made with recycled aggregate Cem. Concr. Res. 34 1373–80
[10] Xiao J, Li J and Zhang C 2005 Mechanical properties of recycled aggregate concrete under uniaxial loading Cem. Concr. Res. 35 1187–94
[11] Xiao J-Z, Li J-B and Zhang C 2007 On relationships between the mechanical properties of recycled aggregate concrete: An overview Materials and Structures vol 39 pp 655–64
[12] Xiao J, Huang Y, Yang J and Zhang C 2012 Mechanical properties of confined recycled aggregate concrete under axial compression Constr. Build. Mater. 26 591–603
[13] Liu Q, Xiao J and Sun Z 2011 Experimental study on the failure mechanism of recycled concrete Cem. Concr. Res. 41 1050–7
[14] Xiao J, Xie H and Yang Z 2012 Shear transfer across a crack in recycled aggregate concrete Cem. Concr. Res. 42 700–9
[15] Xiao J, Li L, Shen L and Poon C S 2015 Compressive behaviour of recycled aggregate concrete under impact loading Cem. Concr. Res. 71 46–55
[16] Guo Z 2004 Strength and constitutive relation of concrete: principles and applications. Beijing China Archit. Build. Press
[17] Anon 2006 GB 50090–2006 Design specifications for railway line, China Ministry of Transportation (Beijing, China)
[18] Fan Y, Xiao J and Tam V W Y 2014 Effect of old attached mortar on the creep of recycled aggregate concrete Struct. Concr. 15 169–78
[19] GB/T50082-2009 Standard for test methods of long-term performance and durability of ordinary concrete. China Architecture & Building Press, 2009
[20] 34 F B 2006 Model code for service life design Int. Fed. Struct. Concr.
[21] CECS 2007 Standard for Durability Assessment of Concrete Structures (CECS220-2007)
[22] Qian Z and Lixue J 1998 A practical mathematical model of concrete carbonation depth based on the mechanism Ind. Constr. 28 16–9
[23] Xiao J Z and Lei B 2008 Carbonation Model and Structural Durability Design for Recycled Concrete J. Archit. Civ. Eng.
[24] Xiao J, Ying J and Shen L 2012 FEM simulation of chloride diffusion in modeled recycled aggregate concrete Constr. Build. Mater. 29 12–23
[25] Ying J, Xiao J, Shen L and Bradford M A 2013 Five-phase composite sphere model for chloride diffusivity prediction of recycled aggregate concrete Mag. Concr. Res. 65 573–88
[26] Xiao J and Ying J 2012 Meso-level numerical simulation on two-dimensional chloride diffusion in modeled recycled aggregate concrete J. Tongji Univ. Nat. Sci. 40 1051–7
[27] Tam V W Y and Tam C M 2008 Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAsand TSMAsc Constr. Build. Mater. 22 2068–77
[28] Li W, Xiao J, Sun Z, Kawashima S and Shah S P 2012 Interfacial transition zones in recycled aggregate concrete with different mixing approaches Constr. Build. Mater. 35 1045–55
[29] Zhang M and Li H 2011 Pore structure and chloride permeability of concrete containing nanoparticles for pavement Constr. Build. Mater. 25 608–16
[30] Ying J, Zhou B and Xiao J 2017 Pore structure and chloride diffusivity of recycled aggregate concrete with nano-SiO2and nano-TiO2 Constr. Build. Mater. 150 49–55
[31] Xiao Jianzhuang, Zhang Qingtian, Yu Jiangyu, Ding Tao, Li Yan S J 2018 A novel development of concrete structures: composite concrete structures J. Tongji Univ. (Natural Sci. 46 147–55
[32] Xiao J, Zhang Q, Zhang P, Luming S and Qiang C 2018 Mechanical behavior of concrete using seawater and sea-sand with recycled coarse aggregates
[33] DG/TJ08-2018-2007 2007 Technical code on the application of recycled concrete. Shanghai Construction & Transportation Commission (Shanghai, P. R China)
[34] Xiao J Z, Pham T L, Wang P J and Gao G 2014 Behaviors of semi-precast beam made of recycled aggregate concrete Struct. Des. Tall Spec. Build. 23 692–712
[35] Xiao J, Sun Y and Falkner H 2006 Seismic performance of frame structures with recycled aggregate concrete Eng. Struct. 28 1–8
[36] Code C S D 2001 Code for Seismic Design of Buildings (GB50011-2001) China Archit. Build. Press. Beijing (in Chinese)
[37] ISO 14040 2006 Environmental management–Life cycle assessment-principles and framework. International Standard Organisation, Geneva, Switzerland, pp. 28.
[38] Da Fonseca L M C M 2015 ISO 14001: 2015: An improved tool for sustainability J. Ind. Eng. Manag. 8 37–50
[39] ISO 14044 2006 International Standard. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.
[40] ISO 14006 2011 International Standard. Environmental Management Systems – Guidelines for Incorporating Eco-design. International Organization for Standardization, Geneva, Switzerland.
[41] ISO 14004 2016 International Standard. Environmental Management Systems – General Guidelines on Implementation. International Organization for Standardization, Geneva, Switzerland.
[42] Ding T, Xiao J and Tam V W Y 2016 A closed-loop life cycle assessment of recycled aggregate concrete utilization in China Waste Manag. 56 367–75