

Article

Experimental Investigation on Compressive Properties and Carbon Emission Assessment of Concrete Hollow Block Masonry Incorporating Recycled Concrete Aggregates

Chao Liu ^{1,*}, Chao Zhu ², Guoliang Bai ², Zonggang Quan ³ and Jian Wu ⁴¹ College of Science, Xi'an University of Architecture and Technology, Xi'an 710055, China² College of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China; chaozhu@live.xauat.edu.cn (C.Z.); guoliangbai@126.com (G.B.)³ Xi'an Research and Design Institute of Wall and Roof Materials, Xi'an 710061, China; xaqc1965@163.com⁴ Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi'an 710123, China; wujian2085@126.com

* Correspondence: chaoliu@xauat.edu.cn; Tel.: +86-180-9256-1062

Received: 17 October 2019; Accepted: 12 November 2019; Published: 14 November 2019



Featured Application: The compressive properties and carbon emission assessment of recycled aggregate concrete hollow block masonry were analyzed. The formula for calculating the compressive strength of hollow block masonry was presented. The global warming potential between natural and recycled aggregate concrete hollow blocks was compared. This study will contribute to the popularization and application of recycled aggregate concrete hollow block masonry.

Abstract: In this paper, the compressive strength experiment for three groups of recycled aggregate concrete (RAC) specimens with different replacement ratios of recycled aggregate (0%, 50%, 100%) was carried out. The mechanism of the block and mortar properties on the compressive strength of block masonry was investigated by means of a static loading test. The formula for calculating the compressive strength of a recycled concrete block was obtained based on experimental data. Moreover, the global warming potential (GWP) of recycled aggregate concrete (RAC) block masonry was evaluated by life cycle assessment (LCA) methodology. The feasibility for application of RAC block masonry was discussed combined with environmental impact data analysis. The results show that the strength of RAC blocks is the principal element affecting the compressive strength of block masonry, and the strength of mortar also has a certain impact for the compressive of RAC block masonry; the sub-coefficient of material performance should be enhanced appropriately for ensuring the construction quality of RAC block masonry; the total GWP of RAC block is lower than that of natural aggregate concrete (NAC) block. The environmental benefits of the promotion and application of RAC block masonry are inspiring.

Keywords: recycled aggregate concrete; block masonry; compressive strength; carbon emission; stress–strain curves

1. Introduction

In the last decade, the acceleration of urbanization has led to a sharp rise in the production of construction and demolition wastes (C&DW) in China, and the annual production of waste concrete is up to 20 billion tons. These ever-increasing C&DW pose serious challenges to environmental

governance [1–3]. Meanwhile, China's construction raw materials, such as sand and stone, have been overexploited [4,5]. The preparation of recycled aggregate concrete (RAC) by replacing the natural aggregate (NA) with recycled aggregate (RA) from waste concrete can solve the dual problems of environment and resources effectively. The application of RAC is of great significance to the sustainable development of concrete [6–8].

Extensive research on mechanical and durability of RAC has been carried out in recent years [9–11]. Most scholars suggest that RAC is weaker than natural aggregate concrete due to the higher water absorption and crushing index of RA [12,13]. Some articles also reported that the complex and weak interface transition zone (ITZ) in RAC is also an important factor resulting in the performance deterioration of RAC [14]. However, the performance of RAC can be conformed to the specific requirements through reasonable design or adjustment of mixing ratio, and RAC has some applications in the construction industry [15–17].

The masonry structure is composed of blocks that are the oldest building materials, and this form of structure has been widely employed in the world [18]. The combination of RA with the masonry structure is absolutely inspiring. The RAC has certain advantages in block production compared with that in components, which is attributed to the block production technology. Several studies have reported that the process of vibrating and compacting can make up for the disadvantage of RAC slump, making the RAC block have a higher strength [19]. In addition, the reduced water content used in the block production process will significantly reduce the creep and shrinkage of RAC [20].

There have been some reports on recycled concrete bricks in recent years. Poon et al. [21] carried out the study on compressive of RAC bricks, and noticed that the compressive strength of the brick is almost constant with the RA replacement ratio of 50%, but the higher the replacement percentage, the lower the compressive strength of the paving slab. Poon et al. [22] investigated the effect of water–cement ratio and aggregate type on the performance of paving concrete blocks. They reported that the compressive strength of paving slabs decreases as the water–cement ratio increases and is proportional to the crush index of the aggregate. The effect of recycled aggregate on the compressive strength of precast concrete hollow blocks was reported by Matar et al. [19], which determined the content of RA in blocks with appropriate compressive strength. However, a few contrary conclusions have been proposed by Corinaldesi [23]. It can be found that from the above description, most of the current research involves the mechanical properties of RAC paving slabs. However, there are few reports on the use of RCA to manufacture blocks for buildings. This is disappointing for the promotion and application of recycled concrete block masonry structures.

In this paper, three groups of RAC specimens with different replacement ratios of recycled aggregate (0%, 50%, 100%) were prepared. The mechanism of the block and mortar properties on the compressive strength of RAC block masonry were investigated by means of static loading test. Moreover, the global warming potential (GWP) of RAC block masonry was evaluated by life cycle assessment (LCA) methodology. The feasibility of application of RAC block masonry was discussed. It can be inferred that the compressive strength of RAC block masonry increased regularly with the strength of the RAC block being enhanced, and the effect law of mortar performance was similar. The sub-coefficient of material performance should be enhanced appropriately for ensuring the construction quality of RAC block masonry. The environmental benefits of the promotion and application of RAC block masonry were inspiring. These results have a certain positive impact on the development of RAC block masonry.

2. Experimental Program

2.1. Materials and Mixture Proportions

The ordinary Portland cement with a grade of 32.5 MPa was used as cementitious. The RA employed in the study was purchased from a franchiser in Xi'an, China. NCA was crushed limestone with a nominal size of 5–10 mm and the size range was the same as RCA. The river sand was used as FA

with the water absorption and fineness modulus of 1.02% and 2.18, respectively. The size distributions of coarse aggregates are illustrated in Figure 1. The aggregates employed in this research demonstrate a continuous grain curve and conforms to Chinese standard JGJ 52-2006 [24]. The physical properties of the employed NCA and RCA were tested according to Chinese standard GB/T 14685-2011 [25] and are listed in Table 1. The results show that RCAs have a higher crushing value and water absorption compared to NCAs, which may be attributed to the old adhered mortar.

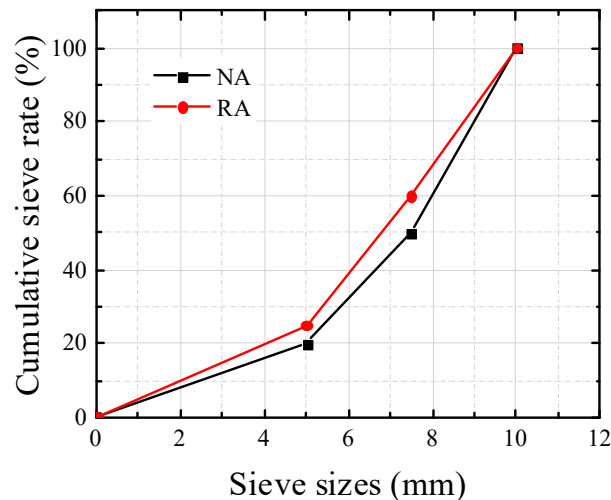


Figure 1. The size distribution of NA and RA used in this study.

Table 1. Physical properties of coarse aggregates.

Aggregate Type	Apparent Density (kg/m ³)	Crushing Value (%)	Water Adsorption (%)	Particle Size Range (mm)
NA	2802	6.0	0.4	5~10
RA	2522	24.7	3.5	5~10

The three types of mixture proportions were used in the study with the RA replacement ratios of 0%, 50%, and 100%, respectively (by weight). The workability of mixture was guaranteed by means of additional water. The mixture proportions for concrete hollow block are summarized in Table 2.

Table 2. Mixing proportions of concrete.

Replacement Ratio of RA (%)	Water Absorption of Mixed Aggregate (%)	Unit Weight (kg/m ³)				
		Water	Cement	FA	NA	RA
0	1.5	190	380	633	1232	-
50	3.5	239	380	633	616	616
100	5.0	276	380	633	-	1232

2.2. Specimens Preparation

Three types of RAC hollow blocks were fabricated with the RA replacement ratio of 0%, 50%, and 100%, respectively, and the strength grades of corresponding block were MU10, MU7.5, and MU5. The commonly employed block with dimensions of 390 mm × 240 mm × 190 mm and a half block with dimensions of 190 mm × 240 mm × 190 mm were used as the bond characteristic test piece, as presented in Figure 2. The volume percentages of the vertical holes for whole and half concrete hollow blocks were 33.8% and 33.9%. The RAC block masonry was prepared in accordance with standard test methods for basic mechanical properties of masonry GB/T 5129-2011 [26]. The thickness of mortar joint was 10 mm. Compressive prisms were manufactured by two full blocks and two half

blocks with the dimensions of 390 mm × 240 mm × 590 mm, as presented in Figure 3. The design parameters of specimens are listed in Table 3. Three test pieces were produced for each code, and a total of 27 specimens were tested.

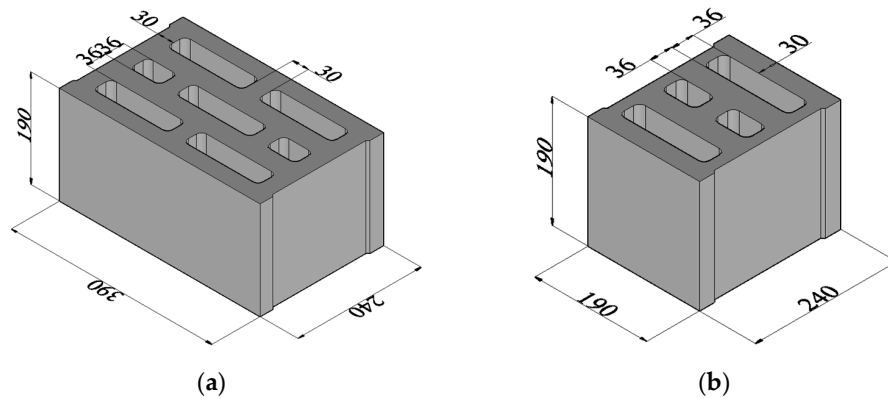


Figure 2. Diagrams of blocks with dimensions of (a) 390 mm × 240 mm × 190 mm; (b) 190 mm × 240 mm × 190 mm.

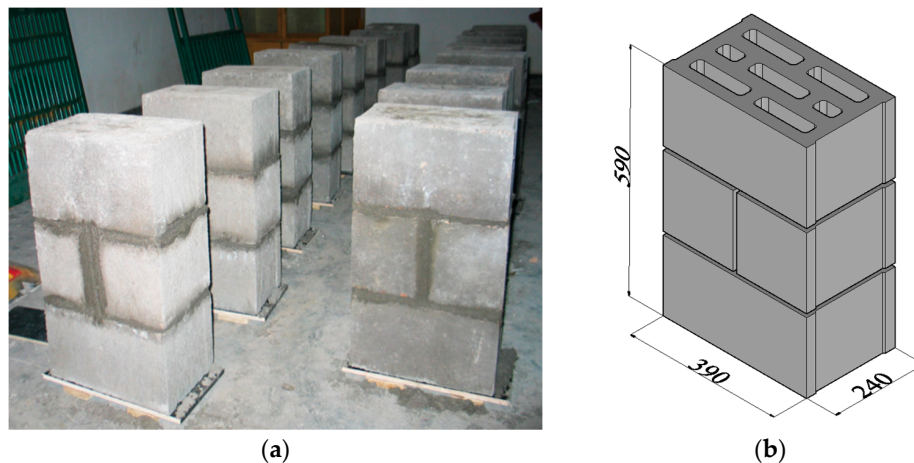


Figure 3. Specimens employed to test the compressive strength: (a) left for curing; (b) dimensions (mm).

Table 3. Design parameters of specimens.

Code	r (%)	f_1 (MPa)	f_2 (MPa)
B-0-1	0	10.5	14.8
B-0-2		10.5	12.0
B-0-3		10.5	8.0
B-50-1	50	7.53	12.0
B-50-2		7.53	8.0
B-50-3		7.53	6.2
B-100-1	100	5.31	8.0
B-100-2		5.31	6.2
B-100-3		5.31	3.1

Note: r: replacement ratio of RA, f_1 : compressive strength of concrete blocks, f_2 : compressive strength of mortar.

2.3. Experimental Procedures

The Chinese standard test methods for the concrete block and brick GB/T 4111-2013 [27] were employed to guide the compressive strength test. The rough surfaces of specimen were coated with

high-strength gypsum in order to ensure the uniform load distribution during compression test. The servo-hydraulic actuator (YE-200A) with force-controlled 2000 kN capacity was used in the study. The transverse and vertical deformations of specimen were measured by the dial indicator. The load and test scenario are shown in Figure 4.

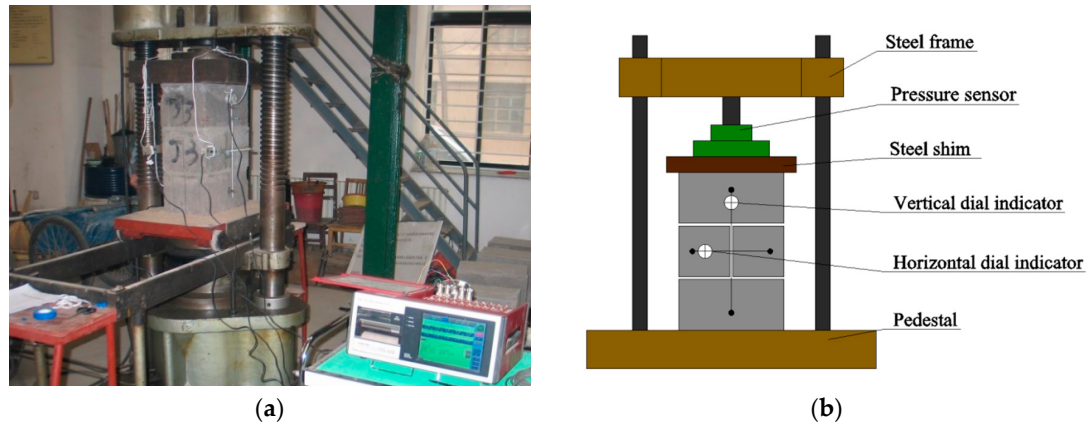


Figure 4. Test setup for the compressive strength: (a) experimental picture; (b) schematic diagram.

Firstly, 5% of the estimated failure load of specimen was applied to check the performance of test apparatus. Three to five repeated loads were carried out within the range of 5% to 20% of the estimated failure load. The relative error of axial deformation value of the two opposite surfaces should not exceed 10%, otherwise the position of the test piece should be adjusted. The 10% of estimated failure load of specimen was served as the increment of each stage with a loading rate of 1 kN/s. The deformation value of each load grade should be recorded.

3. Experimental Results and Discussions

3.1. Description of Experimental Phenomena

The failure characteristics of RAC hollow block masonry are presented in Figure 5. It can be noticed that the specimens with a different replacement ratio of RAs have the similar failure characteristics. The failure process can be summarized as the following phases:

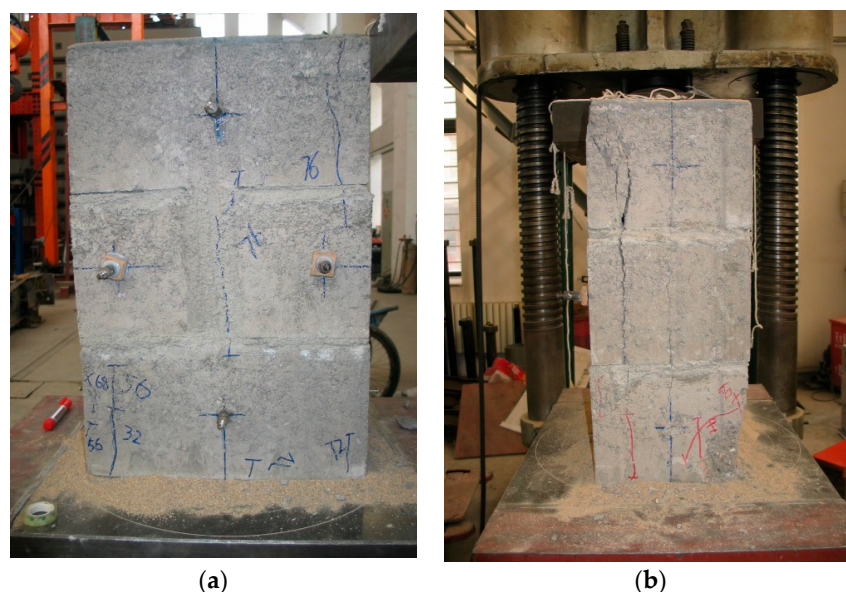


Figure 5. Failure modes of compressive strength: (a) front view; (b) side view.

Phase I: Before the test piece cracks, the value of the compression machine and dial indicator increased steadily with the increase of the load, and there were no abnormal phenomena on the surface of the specimen. The end of the first stage was accompanied by the appearance of the first micro-crack. Meanwhile, the micro-crack will not extend when the load stops increasing, and the specimen remains stable at this stage.

Phase II: The specimen from the initial crack to the limit state was regarded as the second stage. With the emergence of slight vertical cracks on the narrow side of the recycled concrete hollow masonry, the bearing capacity of the specimens began to increase tardily. The vertical or oblique crack was generated on the wide side of the specimen, accompanied by the persistent augment in load. The dial indicator increased rapidly. With the further enhancement of the load, the penetrating cracks were generated on the narrow side of the specimen, which divided the test piece into several small columns. The RAC hollow block masonry reached ultimate bearing capacity when the load did not grow persistently. The reading of the hydraulic press and dial indicator fluctuates obviously. Then the second stage terminated.

Phase III: When the limit load was exceeded, the number of the hydraulic press was decreased fiercely, and the deformation of the specimen increased sharply. The specimen was crushed and destroyed eventually.

It can be seen from the failure status of RAC hollow block masonry that the top face and the connection of the two ribs were weak links, where the penetration cracks will appear firstly, and the whole specimen was destroyed finally. This was mainly attributed to by the fact that there were more holes and ribs in the recycled concrete block with three rows of holes, and there were still process grooves in the end of the holes at the junction of the two ribs on the top surface, which was effortless in forming a failure surface. The compression test values of the RAC hollow block masonry are listed in Table 4.

Table 4. Compression strength test results of RAC block masonry.

Code	P_c (kN)	P_u (kN)	P_c/P_u
B-0-1	623.1	802.3	0.78
B-0-2	513.2	771.3	0.66
B-0-3	480.3	712.3	0.67
B-50-1	401.1	581.2	0.69
B-50-2	373.8	479.2	0.78
B-50-3	299.7	422.1	0.71
B-100-1	255.6	387.1	0.66
B-100-2	250.7	347.9	0.72
B-100-3	231.5	330.1	0.70

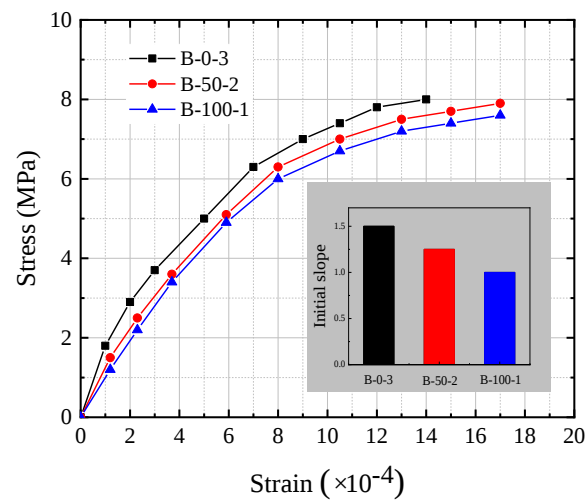
Note: P_c : cracking load of concrete masonry, P_u : ultimate load of concrete masonry.

3.2. Analysis of Test Results

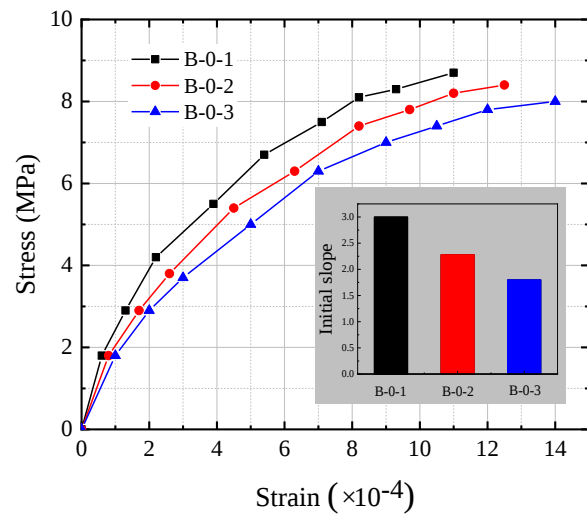
3.2.1. The Stress–Strain Curve of RAC Masonry

The stress–strain diagrams of the RAC hollow block masonry with different replacement ratios of RA are shown in Figure 6a. The effects of mortar strength for stress–strain curves are also presented in Figure 6b–d. The ascending section of the stress–strain curve was only discussed in this research due to the difficult measurement on the descent section by the servo-hydraulic actuator.

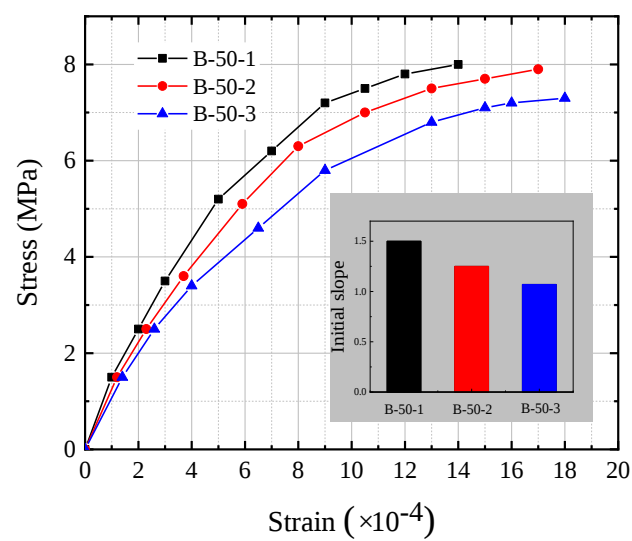
It can be noticed from Figure 6a that the variation trend of stress–strain diagram for different specimen was similar. The strength and deformation of specimen with NAs were higher than that of the specimen with RAs, and these values decreased with the replacement ratio of RA enhanced. This result may be attributed to there being more ITZs in the RAC block. As can be seen from Figure 6b–d, the deformation of specimens enhanced with the increase of mortar strength no matter what the replacement ratio of RA was.



(a)



(b)



(c)

Figure 6. Cont.

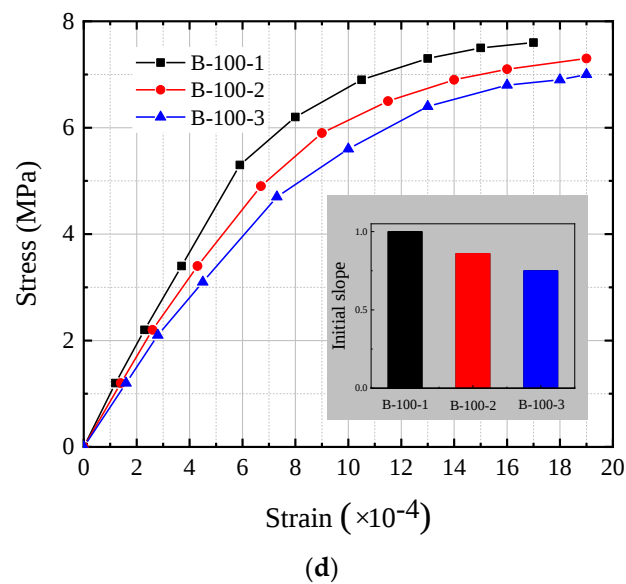


Figure 6. Stress–strain curves of RAC block masonry under compression: (a) effect of RA replacement ratio; (b–d) effect of mortar strength.

The elastic modulus of the specimen can be described by the slope of the stress–strain curve. The bar diagram shows that the increase in the replacement ratio of RA played an inhibitory influence for the elastic modulus of the test piece, while the effect of the mortar strength was reversed.

3.2.2. Analysis of Influencing Factors

The effects of the block and mortar strength on the compressive strength of RAC block masonry structure are shown in Figures 7 and 8, respectively.

It can be observed from Figure 7 that the compressive strength of RAC block masonry was enhanced with the increase of block strength. The difference between NAC and RAC blocks masonry may be attributed to more ITZs present in RAC blocks. The weak ITZs in concrete were more likely to generate micro-cracks under the pressure, which led to the destruction of the concrete masonry.

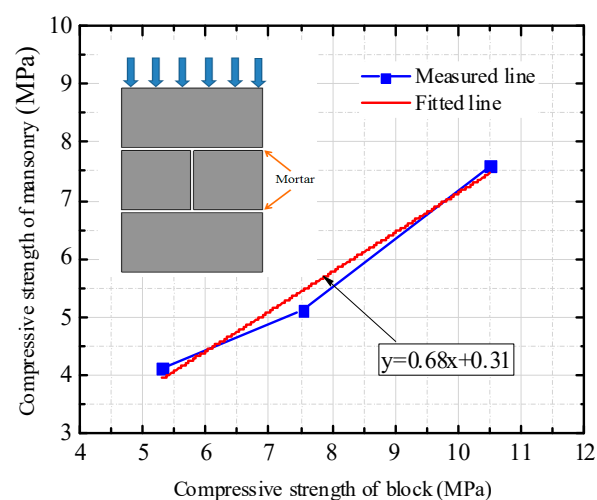


Figure 7. Effect of RAC block strength on the compressive strength of RAC blocks masonry.

According to Figure 8, it can be found that the mortar strength also had a significant effect on the strength of concrete block masonry. The increase of mortar strength was encouraging to improve the strength of concrete masonry. Moreover, the lower the concrete block strength was, the more sensitive

the concrete block masonry strength was to mortar strength. The results may be due to the characteristic of recycled concrete block being unstable, which weakened the contribution of block strength to the compressive strength of concrete masonry and reinforced the effect of mortar strength relatively.

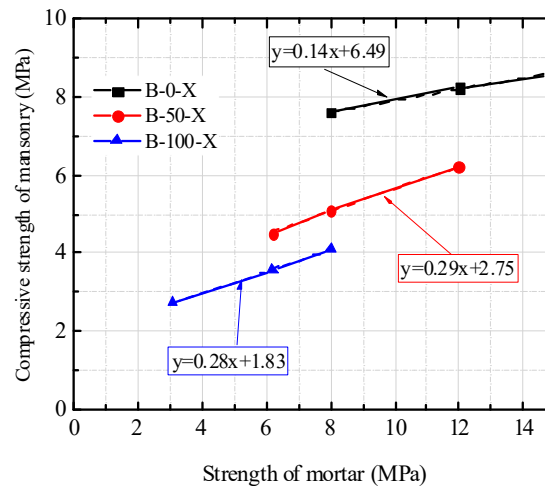


Figure 8. Effect of mortar strength on the compressive strength of RAC blocks masonry.

This paper compared the effects of mortar strength and block strength on masonry structure performance. A 40% increase in block strength will result in a 39% increase in compressive strength of concrete block masonry, but a 40% increase in mortar strength will only increase the compressive strength of concrete block masonry by 8%. It can be found that the strength of block is more sensitive to the compressive strength value of concrete block masonry than that of mortar.

3.3. The Calculation Formula of Recycled Concrete Hollow Block Masonry Strength

It was significant to research the formula for calculating the compressive strength of RAC hollow block masonry for its application. It can be found from the above results that the evolution law and internal mechanism of compressive strength were similar between NAC and RAC hollow block masonry.

The calculation formula of NAC block masonry applies to this study [28], as follows:

$$f_m = k_1 f_1^\alpha (1 + 0.07 f_2) k_2 \quad (1)$$

where f_m was the calculated value of masonry compressive strength; f_1 and f_2 were the average compressive strength of block and masonry respectively; α and k_1 were the effect coefficients of block shape, size, masonry method, and other factors of different types of masonry; α and k_1 were equal to 0.9 and 0.46 for concrete block; k_2 was the influence coefficient of mortar strength on the compressive strength of masonry, and k_2 was 1.0 in this study. α was still 0.9 in the study due to there being the same size between NAC and RAC blocks. Regression analysis was carried out on the strength test value of RAC block masonry, and $k_1 = 0.538$ was obtained, which was higher than 0.46 in the specification. Guo et al. [29] reported similar results. For safety reasons, the parameter values in the specification should be adopted because the strength of RAC blocks was discrete relatively. The results were calculated according to formula 1 and are listed in Table 5.

It can be found that the measured value of RAC block masonry compressive strength was higher than the calculated value by formula in specification. The ratio of the measured value to the calculated value was concentrated between 1.1 and 1.2, which can be indicated by the formula for the compressive strength of NAC block masonry being suitable for RAC block masonry.

The standard value and design value of material strength were significant in the design of masonry structure. The probability distribution of material strength should conform to the normal distribution,

and the standard value of material strength could be determined by the 0.05 quantile of probability distribution. According to the literature [28,30], the standard value f_k of its compressive strength can be calculated as follows:

$$f_k = f_m - 1.645\alpha = f_m(1 - 1.645\delta) \quad (2)$$

where α was the standard deviation of compressive strength, δ was the variation coefficient of compressive strength, and the value of δ was 0.21 (the average variation coefficient of specimen with 50% recycled aggregate substitution rate) in this paper.

The ratio of the standard value to the component coefficient was defined as the design value of material performance.

The strength design value f of RAC block masonry structure was the strength representative value adopted by masonry structural members when they were designed according to the ultimate state of bearing capacity. Considering the influence of geometric parameter variation, calculation mode uncertainty, and other factors on reliability, the calculation formula of f is as follows:

$$f = \frac{f_k}{\gamma_f} \quad (3)$$

where γ_f was the partial factor for material performance of RAC block masonry structure, and γ_f was taken as 1.612 when the construction quality was considered to be B.

Table 5. The measured and calculated values of compressive strength for RAC block masonry.

Code	f'_m (MPa)	f_m (MPa)	f'_m/f_m
B-0-1	8.57	7.78	1.10
B-0-2	8.24	7.03	1.17
B-0-3	7.61	5.96	1.28
B-50-1	6.21	5.76	1.08
B-50-2	5.12	4.42	1.16
B-50-3	4.51	4.06	1.11
B-100-1	4.12	4.94	1.20
B-100-2	3.55	4.08	1.15
B-100-3	2.72	3.05	1.12

Note: f'_m : experiment values of compressive strength, f_m : calculated values of compressive strength.

The construction quality was difficult to guarantee due to the RAC block masonry being prepared by RAs with high water absorption and porosity. It was necessary to increase the γ_f to 1.7 in order to ensure a reliable strength design value. The standard and design values of compressive strength for RAC block masonry are listed in Table 6.

Table 6. Standard values and design values of compressive strength for RAC block masonry.

Code	f_1 (MPa)	f_2 (MPa)	f_m (MPa)	
			Standard Values	Design Values
B-0-1	10.50	14.8	5.61	3.30
B-0-2	10.50	12.0	5.39	3.17
B-0-3	10.50	8.0	4.98	2.93
B-50-1	7.53	12.0	4.06	2.39
B-50-2	7.53	8.0	3.35	1.97
B-50-3	7.53	6.2	2.95	1.73
B-100-1	5.31	8.0	2.56	1.75
B-100-2	5.31	6.2	1.96	1.36
B-100-3	5.31	3.1	1.35	0.95

4. The Carbon Emissions Assessment on the Life Cycle of Recycled Concrete Block

4.1. Description of Life-Cycle Assessment (LCA) Methodology

The methodology employed in this study was in accordance with the ISO 14040 and 14044 standards [31,32], which defined the environmental impact assessment principles for concrete and its mixtures from “cradle to gate”. The functional unit of this research was per cubic meter of concrete with different replacement ratio of RAs (0%, 50%, 100%). The cradle-to-gate system boundaries of the NAC and RAC production are illustrated in Figure 9. Carbon emission calculation can be divided into the following three stages: the raw material production process (C1); transporting raw materials to batching plant (C2); the preparation of concrete blocks (C3).

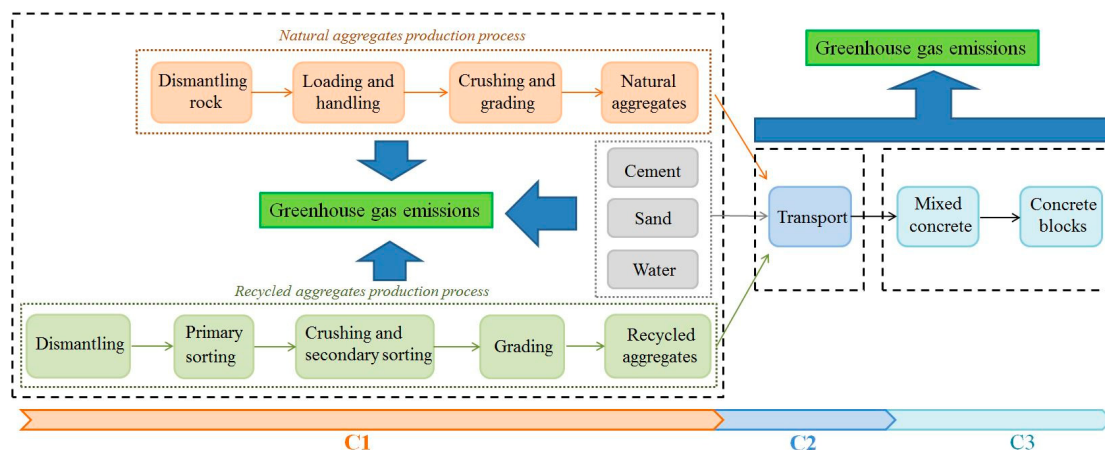


Figure 9. The cradle-to-gate concrete blocks production processes.

4.2. Assumptions and Description of Life-Cycle Inventory (LCI)

Five different concrete mixtures were specified to determine the life-cycle inventory. The assumptions and restrictions associated with the life-cycle inventory for each concrete component will be presented in detail in the following paragraphs.

The carbon emission generated per ton of cement produced was 0.80 kg, and the transportation distance of cement was 150 km. The electricity and fuel consumption required to produce per ton of natural crushed stone were 1.17 kW/t and 0.723 L/t, respectively, and converted into carbon emissions of 3.12 kg. The carbon emission per ton of sand produced was 3.66 kg. The transportation distance of natural gravel and sand was 200 km [33].

The typical preparation process of RA was as follows: The waste concrete was crushed by a forklift into the crusher, and then the broken concrete was screened by the sieving machine to obtain the recycled coarse aggregate with different particle sizes, and this process was assisted by some iron and impurity removal equipment. Statistical data on mass production of recycled aggregate were relatively lacking, as it was still in the stage of popularization in China. The data in reference [16] was referred to in this paper. The carbon emission generated per ton of RA produced was 1.61 kg, and the transportation distance of recycled aggregate was 30 km. The direct carbon emission coefficient of diesel truck transportation was 89.84 g/(km·t). These data apply only to Shaanxi province in China.

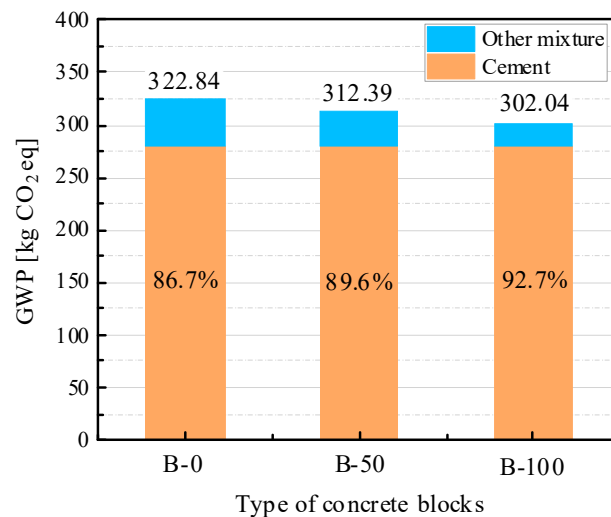
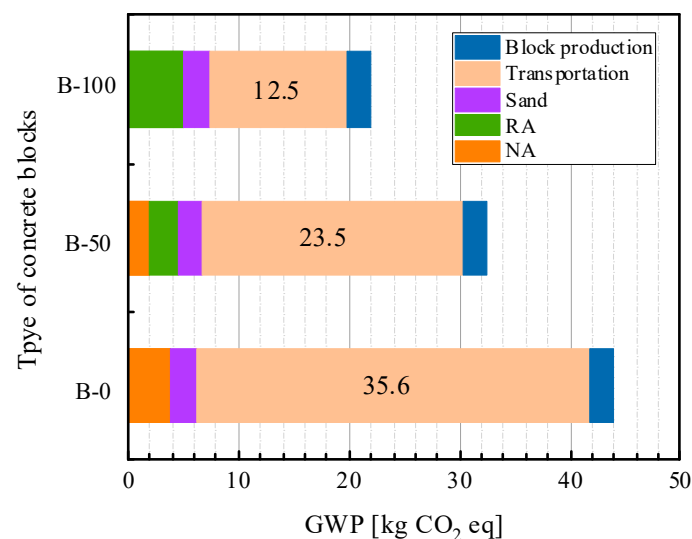
4.3. Discussion and Interpretation of Global Warming Potential (GWP)

The calculated GWP (kg CO₂-eq) related to the production of per unit volume of concrete blocks are listed in Table 7. The total index consists of the carbon emissions of each mixed material during quarrying, transportation, and production processes that take place within the system boundaries.

Table 7. The GWP (kg CO₂-eq) for each 1 m³ of concrete blocks.

Periods	Details	B-0	B-50	B-100
C1	Cement	280	280	280
	NA	3.8	1.9	-
	RA	-	2.55	5.1
	Sand	2.31	2.31	2.31
C2	Transportation	35.6	23.5	12.5
C3	Block production	2.13	2.13	2.13
Total		323.84	312.39	302.04

It can be understood from Table 7 that the production process of aggregates and the transportation of materials were main factors leading to differences in carbon emissions between NAC and RAC blocks. The total GWP for RAC block (with recycled aggregate replacement ratio was 100%) was 7.2% lower than that of NAC block. This opinion was inspiring for the promotion and application of RAC blocks. In addition, the calculated total GWP and the allocation of GWP by the major concrete ingredients and production processes are illustrated in detail in Figures 10 and 11.

**Figure 10.** Comparison of total GWP for concrete blocks with different RA content.**Figure 11.** The GWP results for 1 m³ of concrete blocks (excluding cement).

It is well known that cement production makes the greatest contribution to GWP, and it accounts for about 89.7% of total carbon emissions. Moreover, the transportation of raw materials to the concrete block plant was the second highest source of emission, which was about 7.5% of the total carbon emissions. The percentage of other concrete mixtures in total GWP was as follows: 1.2% for NA, 1.7% for RA, and 0.73% for sand.

According to the data of each stage, the transport of raw materials was the decisive reason that the carbon emission of concrete decreased with the increase of the replacement ratio of RA. The shorter transport distance was mainly due to the raw material of the RA being waste concrete, the source was less restricted by the region, and the processing plant can be located close to the mixing plant. However, from the life-cycle inventory, the carbon emission of RAC block will exceed that of the NAC block when the transported distance of RA exceeds a certain range. In addition, the carbonization of RA to absorb CO₂ was also of great significance for the total GWP. However, the measured mechanical performance of the concrete block decreased with the incorporation of RAs. It is necessary to limit the proportion of RAs to 50%. Therefore, it can be concluded that the RAC blocks prepared by RAs (replacement ratio was 50%) do have great significance towards improving the environmental quality.

5. Conclusions

In this study, the compressive properties and carbon emission assessment of RAC hollow block masonry were investigated by several methods, and the following conclusions can be obtained.

1. The compressive strength of RAC block decreased with the increases of RA replacement ratio. The compressive strength of RAC block masonry increased regularly with the strength of RAC block being enhanced, and the effect law of mortar performance was similar.
2. The calculation formula of compressive strength for the NAC block masonry was still applicable to the RAC block masonry. However, the partial coefficient for material performance should be enhanced appropriately for ensuring the construction quality of RAC block masonry.
3. The design values and standard values of the RAC block masonry strength with different replacement ratio of RA were calculated based on the experimental data in this study.
4. In the case of rational allocation of resources, such as controlling the distance between the RA production plant and the ready-mix plant, the environmental benefits of the promotion and application for RAC block masonry were very inspiring, attributed to the total GWP of the RAC block being lower than that of the NAC block.

Author Contributions: C.L. and C.Z. were responsible for the writing of this article. G.B. and Z.Q. were responsible for the evaluation and comments of the paper content, and J.W. was responsible for the organization of the article data.

Funding: This research was funded by the Natural Science Foundation of China [grant number 51878546], the Natural Science Basic Research Program of Shaanxi Province [grant number 2019JM-597], the Innovative Talent Promotion Plan of Shaanxi Province [grant number 2018KJXX-056], the Key Research and Development Program of Shaanxi Provincial [grant number 2018ZDCXL-SF-03-03-02], the Open Fund Project of Shaanxi Province [grant number XJKFJJ201904] and the Science and Technology Innovation Base of Shaanxi Province [grant number 2017KTPT-19].

Acknowledgments: The authors would like to acknowledge the National Natural Science Foundation of China (Grant NO. 51878546), the Natural Science Basic Research Program of Shaanxi Province (Grant NO. 2019JM-597), the Innovative Talent Promotion Plan of Shaanxi Province (Grant NO. 2018KJXX-056), the Key Research and Development Projects of Shaanxi Province (Grant NO. 2018ZDCXL-SF-03-03-02), the Open Fund Project of Shaanxi Province (Grant NO. XJKFJJ201904) and the Science and Technology Innovation Base of Shaanxi Province (Grant NO. 2017KTPT-19) for financial support.

Conflicts of Interest: All authors declare that this article has no conflict of interest, and the data (including figures, tables) and other relevant information used in the article are approved by all authors. The correspondent authors exercise power over the article on behalf of all authors.

References

1. Xiao, J.Z.; Li, W.; Fan, Y.H.; Huang, X. An overview of study on recycled aggregate concrete in China (1996–2011). *Constr. Build. Mater.* **2012**, *31*, 364–383. [\[CrossRef\]](#)
2. Liu, C.; Liu, H.W.; Zhu, C.; Bai, G.L. On the mechanism of internal temperature and humidity response of recycled aggregate concrete based on the recycled aggregate porous interface. *Cem. Concr. Compos.* **2019**, *103*, 22–35. [\[CrossRef\]](#)
3. García-Sanz-Calcedo, J.; Al-Kassir, A.; Yusaf, T. Economic and environmental impact of energy saving in healthcare buildings. *Appl. Sci.* **2018**, *8*, 440. [\[CrossRef\]](#)
4. He, S.Y.; Lai, J.X.; Wang, L.X.; Wang, K. A literature review on properties and applications of grouts for shield tunnel. *Constr. Build. Mater.* **2020**, *231*, 468–482.
5. Li, P.L.; Lu, Y.Q.; Lai, J.X.; Liu, H.Q. A comparative study of protective schemes for shield tunneling adjacent to pile groups. *Adv. Civ. Eng.* **2020**, *12*, 1874137.
6. GB/T 25177-2010. *Recycled Coarse Aggregate for Concrete*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2010.
7. Nie, X.X.; Feng, S.S.; Zhang, S.D.; Gan, Q. Simulation study on the dynamic ventilation control of single head roadway in high-altitude mine based on thermal comfort. *Adv. Civ. Eng.* **2019**, *12*, 2973504. [\[CrossRef\]](#)
8. Liu, C.; Fan, Z.Y.; Chen, X.N.; Zhu, C.; Wang, H.Y.; Bai, G.L. Experimental study on bond behavior between section steel and RAC under full replacement ratio. *KSCE J. Civ. Eng.* **2018**, *23*, 1159–1170. [\[CrossRef\]](#)
9. Suryawanshi, S.R.; Singh, B.; Bhargava, P. Characterization of recycled aggregate concrete. In *Advances in Structural Engineering*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 1813–1822. [\[CrossRef\]](#)
10. Debieb, F.; Courard, L.; Kenai, S.; Degeimbre, R. Mechanical and durability properties of concrete using contaminated RAs. *Cem. Concr. Compos.* **2010**, *32*, 421–426. [\[CrossRef\]](#)
11. Leite, F.C.; Motta, R.S.; Vasconcelos, K.L.; Bernucci, L. Laboratory evaluation of recycled construction and demolition waste for pavements. *Constr. Build. Mater.* **2011**, *25*, 2972–2979. [\[CrossRef\]](#)
12. Rao, M.C.; Bhattacharyya, S.K.; Barai, S.V. Influence of field recycled coarse aggregate on properties of concrete. *Mater. Struct.* **2011**, *44*, 205–220. [\[CrossRef\]](#)
13. Wang, Y.; Zhang, S.H.; Niu, D.T.; Su, L.; Luo, D.M. Strength and chloride ion distribution brought by aggregate of basalt fiber reinforced coral aggregate concrete. *Constr. Build. Mater.* **2020**, *234*, 117390. [\[CrossRef\]](#)
14. Bai, G.L.; Zhu, C.; Liu, C.; Liu, H.W. Chloride ion invasive behavior of recycled aggregate concrete under coupling flexural loading and wetting-drying cycles. *KSCE J. Civ. Eng.* **2019**, *23*, 4454–4462. [\[CrossRef\]](#)
15. JGJ/T 240-2011. *Technical Specification for Application of Recycled Aggregate*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2011.
16. Marinković, S.; Radonjanin, V.; Malešev, M.; Ignjatović, I. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag.* **2010**, *30*, 2255–2264. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Liu, C.; Lv, Z.Y.; Zhu, C.; Bai, G.L.; Zhang, Y. Study on calculation method of long term deformation of RAC beam based on creep adjustment coefficient. *KSCE J. Civ. Eng.* **2019**, *23*, 260–267. [\[CrossRef\]](#)
18. Marrocchino, E.; Fried, A.N.; Koulouris, A.; Vaccaro, C. Micro-chemical/structural characterization of thin layer masonry: A correlation with engineering performance. *Constr. Build. Mater.* **2009**, *23*, 582–594. [\[CrossRef\]](#)
19. Matar, P.; Dalati, R.E. Using recycled concrete aggregates in precast concrete hollow blocks. *Mater. Werkst.* **2012**, *43*, 388–391. [\[CrossRef\]](#)
20. Poon, C.S.; Chan, D. Paving blocks made with recycled concrete aggregate and crushed clay brick. *Constr. Build. Mater.* **2006**, *20*, 569–577. [\[CrossRef\]](#)
21. Poon, C.S.; Kou, S.C.; Lam, L. Use of recycled aggregates in molded concrete bricks and blocks. *Constr. Build. Mater.* **2002**, *16*, 281–289. [\[CrossRef\]](#)
22. Poon, C.S.; Lam, C.S. The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks. *Cem. Concr. Compos.* **2008**, *30*, 283–289. [\[CrossRef\]](#)
23. Corinaldesi, V. Mechanical behavior of masonry assemblages manufactured with recycled-aggregate mortars. *Cem. Concr. Compos.* **2009**, *31*, 505–510. [\[CrossRef\]](#)
24. JGJ 52-2006. *Standard for Technical Requirements and Test Method of Sand and Crushed Stone (or Gravel) for Ordinary Concrete*; Chinese Building Press: Beijing, China, 2006.

25. GB/T 14685-2011. *National Pebble and Crushed Stone Code for Buildings*; Chinese Building Press: Beijing, China, 2011.
26. GB/T 5129-2011. *Standards for Test Method of Basic Mechanical Properties of Masonry*; Chinese Building Press: Beijing, China, 2011.
27. GB/T 4111-2013. *Test Methods for the Concrete Block and Brick*; Chinese Building Press: Beijing, China, 2013.
28. GB 50003-2011. *Code for Design of Masonry Structures*; China Building Industry Press: Beijing, China, 2011.
29. Guo, Z.G.; Sun, W.M.; Peng, Y.; Liu, J.L. Experimental study on the compression behavior of recycled aggregates concrete small hollow block masonry. *Build. Struct.* **2011**, *41*, 127–128. [[CrossRef](#)]
30. Xu, S.F.; Xiong, Z.M.; Wei, J. *Masonry Structure*; China Science Press: Beijing, China, 2004.
31. ISO 14040. *Environmental Management Life Cycle Assessment Principles and Framework*; International Organization for Standardization: Geneva, Switzerland, 2006.
32. ISO 14044. *Environmental Management Life Cycle Assessment Requirements and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006.
33. Gao, Y.X.; Wang, J.; Xu, F.L.; Lin, X.H.; Chen, J. Carbon emissions assessment of green production for ready-mix concrete. *Concrete* **2011**, *1*, 110–112. [[CrossRef](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).