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RESEARCH

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Utilization of Completely Recycled Fine Aggregate for Preparation of Lightweight Concrete Partition Panels

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Abstract

To reduce the cost of lightweight concrete (LWC) partition panels and to address recycling concrete waste, this work utilized completely recycled fine aggregate (CRFA) to replace the natural fine aggregate and ceramsite in the preparation of LWC and LWC partition panels. To this end, an autoclave-free curing process and an air-entraining agent were used to prepare the CRFA-LWC. The workability, compressive strength, drying shrinkage, and pore structure of the CRFA-LWC and the performance of the CRFA-LWC partition panels were then investigated. The results show that the optimal ratio of the CRFA to the cement is 2.2 for the lightweight concrete, and the optimal panel cross section is a rounded rectangular one. All the pores in the CRFA-LWC have a diameter of smaller than 0.17 mm, and the diameter of 89% of them is less than 0.05 mm. In order to satisfy the drying shrinkage requirements stipulated by Chinese code JC/T 169-2016, the CRFA-LWC should be cured for at least 10 days. The economic analysis concludes that the material cost of CRFA-LWC is 40% lower than that of the autoclaved ceramsite concrete. In addition, utilizing CRFA in lightweight concrete can ease the shortage of natural aggregate.

Highlights

CRFA is used for preparing the lightweight concrete partition panels.
The optimal ratio of the CRFA to the cement is 2.2 for the lightweight concrete.
CRFA lightweight concrete needs to be cured for at least 10 days.
The cost of lightweight concrete is reduced by 40% by using CRFA.

Keywords: completely recycled fine aggregate, lightweight concrete, lightweight partition panels, concrete waste

1 Introduction

With increasing urbanization, a large amount of construction and demolition waste (CDW) is produced every day, while less than 5% of CDW is recycled in China; thus, most of construction waste is buried underground (He et al., 2019), which not only occupies the land, but also causes environmental problems (Abdel-Gawwad et al., 2018; Liu et al., 2020; Zhang et al., 2020). Compared with the recycling methods, the landfill of CDW is not environmentally friendly and has become a severe social and environmental issue all over the world. For recycling construction and demolition waste, its concrete can be crushed into recycled aggregate and reused in new concrete. For example,

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Venkrbec and Klanšek (2020) crushed the precast panel from the CDW into the recycled aggregate and validated its suitability. Colangelo et al. (2020) conducted the life cycle assessment on the recycled concrete and concluded that using the recycled concrete is a good solution to deal with CDW from an environmental viewpoint. The material properties of different recycled products were studied by many researchers (Chen et al., 2021; Ju et al., 2019; Seo & Lee, 2015) in recent years as well. As one of the main recycled products, the recycled fine aggregate (RFA) produced using the conventional recycling technology is of undesirable quality. Compared with river sand, RFA has low density and high water absorption (Etxeberria et al., 2007), so the concrete made of RFA has lower compressive strength and a higher drying shrinkage (Kou & Poon, 2009). With RFA replacing over 50% of natural fine aggregate, the workability of the concrete made of RFA can significantly be influenced (Zega & Di Maio, 2006). In order to improve the performance of recycled fine aggregate, Yang et al. (2020) proposed the completely recycled fine aggregate (CRFA) technology which crushes all concrete waste into recycled fine aggregate without producing recycled coarse aggregate. Compared with the conventional recycled fine aggregate, CRFA has a lower mortar ratio, lower water absorption, and higher apparent density (Yang et al., 2016).

Although CRFA shows better performance than the conventional RFA, the workability of CRFA concrete is not as good as the river sand concrete, which limits the utilization of the CRFA in practice. In recent years, the feasibility of using recycled aggregates for preparing nonstructural member has drawn the attention of many researchers. Some researchers (Kou et al., 2012; Poon et al., 2002; Yan et al., 2018) demonstrated that producing nonstructural precast concrete members with recycled aggregate can make better use of them with less consideration on the workability of the fresh state. Poon et al., (2002, 2009) used recycled coarse and fine aggregate to prepare concrete bricks and blocks. Chan and Poon (2006) compared the paving block made of recycled fine aggregate with those made of river sand and indicate the inclusion of lightweight material should be limited. Xiao et al. (2011) use the recycled aggregate made from earthquake waste to prepare the partition wall blocks. The fire resistance of partition walls blocks prepared by recycled aggregate was also studied by Yan et al. (2018) and Xiao et al. (2013). Although plenty of studies are conducted on the reuse of recycled fine aggregate in partition blocks, there are few studies on the lightweight partition panels and the utilization of CRFA.

Lightweight concrete partition panels are one of the main nonstructural components which have become increasingly popular recently with the progress of prefabricated buildings (You et al., 2020). Compared with the conventional concrete, lightweight concrete (LWC) has lower self-weight and higher efficiency (Shafigh et al., 2012). LWC is often produced by using lightweight aggregate (Polat et al., 2010), such as shale, ceramsite, perlite, and expanded clay (Aslam et al., 2016). Autoclaved ceramsite lightweight concrete, composed of ceramsite as the coarse aggregate and river sand as the fine aggregate, is popular in China for preparing partition panels. For broadening the variety of CRFA applications and reducing the cost of LWC, this paper utilizes CRFA to replace both natural fine aggregate and ceramsite in the preparation of LWC and LWC partition panels. LWC partition panels made of CRFA can not only recycle concrete waste effectively, but also reduce the cost of LWC partition panels. Besides, different from conventional autoclaved ceramsite lightweight concrete, the LWC made of CRFA is produced through an autoclave-free process, so it has a significantly lower cost of production and energy consumption.

In the following, the design of the partition panel and the preparation of the CRFA-LWC are introduced in Sect. 2. The properties of the CRFA-LWC and the partition panel are then discussed in Sect. 3. Finally, Sect. 4 summarizes the obtained results.

2 Materials and Methods

2.1 Raw Materials

The ordinary Portland cement P.II 42.5R used herein was purchased from Guangzhou Zhujiang Cement Co. Ltd., China. The physical and mechanical properties of the cement are listed in Table 1. These properties of cement were tested based on Chinese codes GB 175-2007 (2007). A polycarboxylate water reducer with a solid content of 20% and an air-entraining agent were employed as the admixture. The CRFA was prepared in the laboratory by using waste concrete (strength grade: C30) according to the procedure reported in Yang et al., (2020). The physical properties of the CRFA are presented in Table 2.

Table 1 The physical and mechanical properties of the cement.

Density (g/cm^3)	Specific area (m^2/kg)	Flexural strength (MPa)		Compressive strength (MPa)		Setting time (min)	
		3-day	28-day	3-day	28-day	Initial	Final
3.14	362	6.5	8.7	36.5	60.4	113	162

Table 2 The physical properties of the CRFA.

Fineness modulus	2.46
Apparent density (kg/m^3)	2470
Bulk density (loose condition) (kg/m^3)	1360
Bulk density (dense condition) (kg/m^3)	1580
Saturated-surface-dry water absorption (%)	5.0

2.2 Design of Partition Panel

The strength of the lightweight concrete correlates positively with the concrete density (Iffat, 2015; Just & Middendorf, 2009). However, the area density of the wall panel needs to be controlled at a certain level, so there is an upper limit for both the strength and the density of the concrete. In order to simultaneously satisfy the strength and the area density requirements instructed by Chinese standard JG/T169-2016 (2016a), a hollow-core panel was considered in the current work. With the help of the openings in the panel, the upper limit for the strength and density of the concrete can be increased.

To this end, two types of openings, namely circular and rounded rectangular openings, and two wall panel thicknesses of 90 and 120 mm were taken into account. The cross sections of these four types of partition panels are presented in Fig. 1. According to Chinese standard JG/T169-2016 (2016a), the specification and the density requirements of the wall panels are listed in Table 3.

2.3 Preparation of CRFA-LWC

The water-to-cement ratio (W/C) of the CRFA-LWC was set to 0.28, and three different CRFA-to-cement ratios (C/C), namely 1.8, 2.2, and 2.4, were examined. As presented in Table 3, the maximum allowable density of the concrete is between 1610 and 1745 kg/m^3. As the density of the fresh concrete is higher than that of the hardened concrete, the density of the fresh LWC needs to be smaller than 1750 kg/m^3. To investigate the influence of the concrete density, samples with a density of 1550, 1650, and 1750 kg/m^3 were prepared. Since the water absorption of the CRFA was higher than that of natural aggregate, additional water was used to improve the workability of the concrete made of the CRFA. The additional water is not included in calculating the W/C. The amount of the additional water is calculated by $m_f \times \beta \times SF$, where m_f is the mass of the CRFA, β represents the saturated-surface-dry water absorption of the CRFA, that is 5.0% in the current work, and SF indicates the saturation factor of the CRFA (Yang et al., 2020).

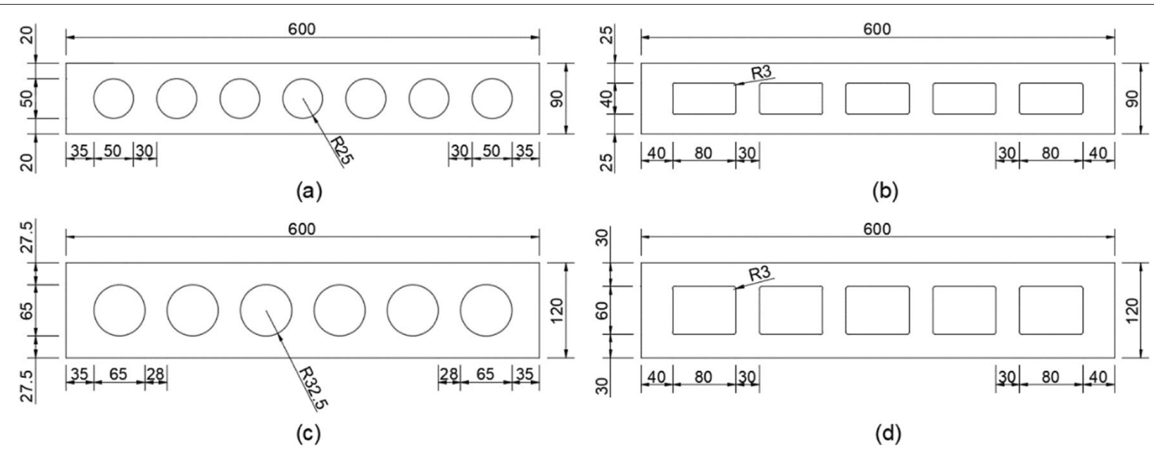


Fig. 1 The cross sections of the partition panels **a** 90C; **b** 90R; **c** 120C; **d** 120R.

Table 3 The specification and density requirements of the partition panels.

Panel ID	Opening type	Panel thickness (mm)	The number of openings	Opening size (mm)	Percentage of opening (%)	Panel area density (kg/m^2)	Concrete density (kg/m^3)
90C	Circular	90	7	$d = 50$	25.4	≤ 110	≤ 1635
90R	Rounded rectangular	90	5	$80 \times 40, R = 3$	29.6	≤ 110	≤ 1735
120C	Circular	120	6	$d = 65$	27.6	≤ 140	≤ 1610
120R	Rounded rectangular	120	5	$80 \times 60, R = 3$	33.3	≤ 140	≤ 1745

With the known W/C and C/C, the mass ratio between the water, the cement and the CRFA can be derived. By setting the total mass of the water, the cement and the CRFA for 1 m^3 concrete to the target density, the mass of three components for 1 m^3 concrete can be calculated based on their mass ratio. The amount of the water reducer and the saturation factor of the CRFA is adjusted by making the slump flow of the concrete reach 100 mm. In the meantime, the density of the concrete is adjusted to the target density by adding the air-entraining agent content of the concrete. The final water content in mixture proportion = the water in W/C + additional water for CRFA − the water in the water reducer (80% of the water reducer). The final mixture proportions of the CRFA-LWC with different target densities and various CRFA-to-cement ratios are presented in Table 4. Since the concrete sample with a C/C of 2.4 and a target density of 1750 kg/m^3 showed undesirable workability in the preliminary experiment, its mixture proportion is not listed in Table 4.

The preparation process of the CRFA-LWC is illustrated in Fig. 2. Since there are many bubbles in the CRFA-LWC, vibration is not allowed in the molding. The fresh CRFA-LWC should be poured into the mold layer-by-layer, and the mold can be shaken to homogenize the concrete.

2.4 Characterization of CRFA-LWC

The slump flow of the fresh CRFA-LWC was tested by the methods recommended by Chinese standard GB/T 8077-2012 (Standardization-Administration-of-China, 2012), and the density of the fresh CRFA-LWC was determined using the methods recommended by Chinese standard GB/T 50080-2016 (Ministry-of-Housing-and-Urban–Rural-Development-of-PRC, 2016b).

The density of the CRFA-LWC was measured under absolute dry conditions. Indeed, before measuring the density of a concrete sample, it should be dried in an oven at a temperature of 105 °C until it reaches a constant weight. The 3-day density refers to the density of the concrete measured 3 days after demolding it. The compressive strength of the CRFA-LWC was measured using samples with the dimensions 70.7 mm × 70.7 mm × 70.7 mm at a loading rate of 0.5 kN/s. The 3-day compressive strength refers to the compressive strength of the concrete measured 3 days after demolding it. The drying shrinkage of the CRFA-LWC was determined using samples with the dimensions 40 mm × 40 mm × 160 mm by the method recommended by Chinese standard GB/T 30100-2013 (2013), and the dry shrinkage of the concrete samples was measured at four different curing periods, namely 3, 7, 10, and 14 days. The shrinkage of the samples was measured after 3, 7, 14, 21, 28, and 35 days after putting them in the drying room. The pores in the CRFA-LWC were analyzed by using Image-Pro Plus 6.0 software (Media Cybernetics, Inc., the USA).

According to Chinese code JG/T169-2016 (2016a), the compressive strength of the partition panels was measured using the sample cut from the whole panel; each sample had a height of 100 mm. The cross section of each type of the panels shown in Fig. 1 is depicted in Fig. 3. The area density of the panels was also determined using the sample cut from the whole panel.

3 Results and Discussion

3.1 Workability of CRFA-LWC

The density and the slump flow of the fresh CRFA-LWC are presented in Table 5. By adjusting the air-entraining agent content of the concrete, the target density can be achieved. At a C/C of 1.8 and 2.2, by adding a proper amount of additional water and the water reducer to the concrete, it can fulfill the workability requirements; however, it is difficult for the concrete with a

Table 4 The mixture proportions of the CRFA-LWC.

No.	C/C	Target concrete density (kg/m^3)	SF (%)	The content of the concrete materials (kg/m^3)				
				Cement	Water	Water reducer	Air-entraining agent	CRFA
AR18-1	1.8	1550	65	503	161	12.1	3.82	906
AR18-2	1.8	1650	65	536	171	12.9	2.95	964
AR18-3	1.8	1750	65	568	181	13.6	2.04	1023
AR22-1	2.2	1550	85	445	157	11.6	3.56	980
AR22-2	2.2	1650	85	474	167	12.3	2.75	1043
AR22-3	2.2	1750	85	503	177	13.1	2.11	1106
AR24-1	2.4	1550	100	421	159	11.8	3.58	1011
AR24-2	2.4	1650	100	448	169	12.5	2.33	1076

C/C CRFA-to-cement ratio, *SF* saturation factor of the CRFA, *CRFA* completely recycled fine aggregate.

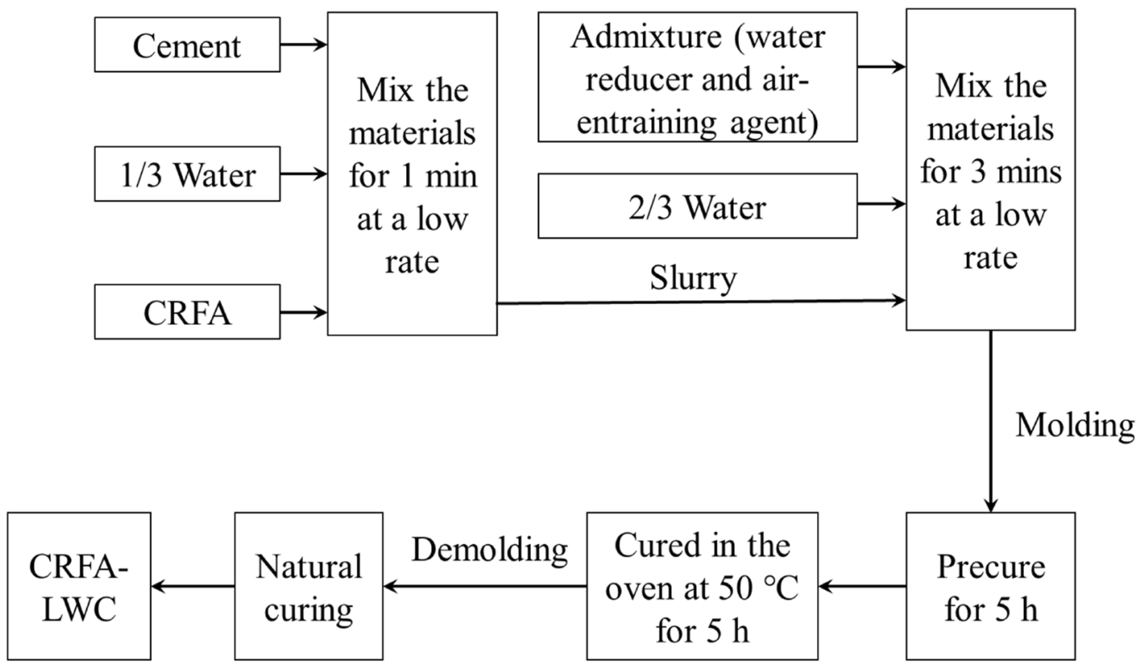


Fig. 2 The preparation process of the CRFA-LWC.

CRFA-to-cement ratio of 2.4 to reach both the target density and the required workability. Therefore, the C/C of 2.4 is not suitable for the CRFA-LWC. Although the CRFA-to-cement ratios of 1.8 and 2.2 can both satisfy the workability requirements, the concrete consumes less cement at a C/C of 2.2 than at a C/C of 1.8. To reduce the cement content of the concrete and thus the cost of the concrete, a CRFA-to-cement ratio of 2.2 was used for preparing the wall panels.

3.2 Strength of CRFA-LWC

The correlation between the 3-day compressive strength and the 3-day density of the hardened CRFA-LWC is delineated in Fig. 4. At a constant C/C, the compressive strength of the CRFA-LWC increases with a rise in the concrete density, which is consistent with the results given in refs (Iffat, 2015; Just & Middendorf, 2009). Moreover, at a constant concrete density, the compressive strength of the concrete declines as the CRFA-to-cement ratio enlarges, which can be attributed to two possible reasons. First, an increment in the C/C leads to a lower cement content of the concrete, which may reduce the compressive strength of the concrete. Second, the CRFA content of the concrete increases as the CRFA-to-cement ratio rises, and a higher amount of the CRFA requires more additional water; thus, the actual water-to-cement ratio of the concrete may be affected.

3.3 Strength of CRFA-LWC Partition Panels

The CRFA-LWC partition panels were prepared using mixture proportions AR22-1, AR22-2, and AR22-3. The correlation between the 3-day compressive strength and 3-day density of the CRFA-LWC partition panels with various types of cross sections is presented in Fig. 5. The compressive strength of the panels correlates positively with the concrete density. At a similar thickness and concrete density, the panel with a circular opening, owing to a smaller percentage of the opening, has higher compressive strength than that with a rounded rectangular opening. Chinese code JG/T 169-2016 stipulates that the compressive strength of the partition panels must be larger than 5 MPa. Therefore, to satisfy the strength requirements of the different panel cross sections, the concrete used to produce the partition panels must have a 3-day density of larger than 1600 kg/m^3.

The relation between the 3-day compressive strength and the area density of the CRFA-LWC partition panels with various types of cross sections is plotted in Fig. 6. There is a direct relationship between the compressive strength and the area density of the wall panels. At an identical area density and thickness of the panel, the partition panel with a rounded rectangular cross section has higher compressive strength than that with a circular cross section, which indicates that the rounded rectangular cross section is more suitable for CRFA-LWC partition panels. Chinese code JG/T 169-2016 (2016a)

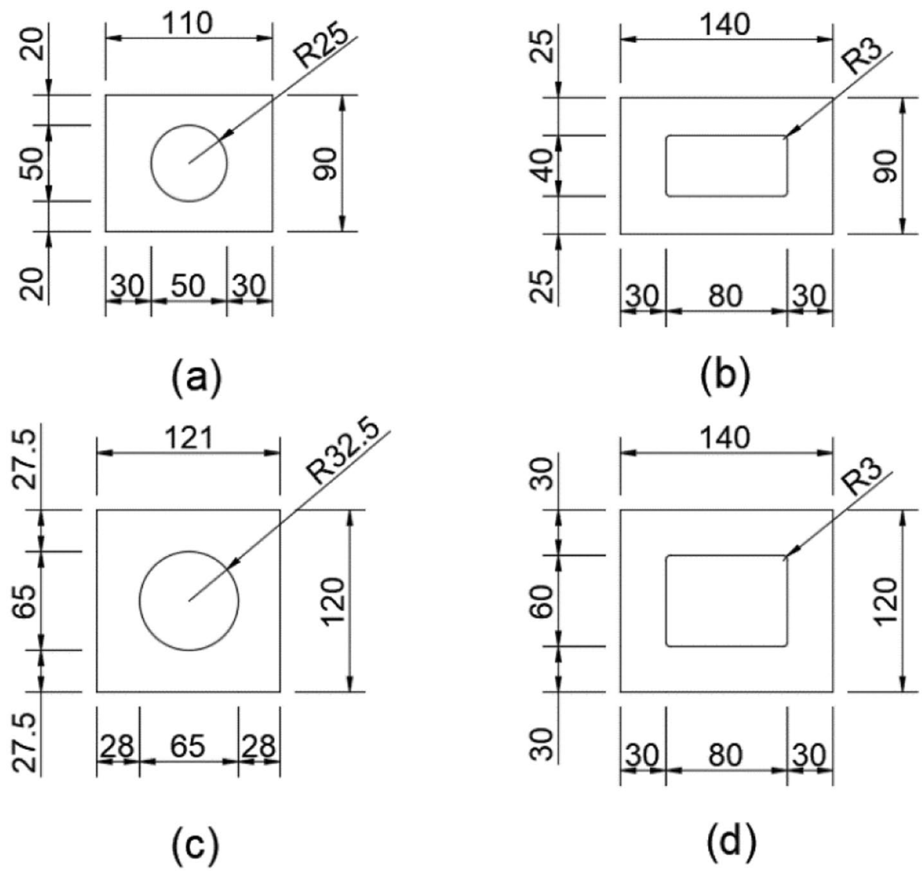


Fig. 3 The cross section of the panel samples cut from whole panel **a** 90C; **b** 90R; **c** 120C; **d** 120R.

Table 5 The density and the slump flow of the fresh CRFA-LWC.

Sample ID	AR18-1	AR18-2	AR18-3	AR22-1	AR22-2	AR22-3	AR24-1	AR24-1
Density (kg/m^3)	1565	1622	1706	1579	1661	1718	1586	1674
Slump flow (mm)	109	106	105	105	102	101	93	83

stipulates that for a panel thickness of 90 and 120 mm, the area density of the panel must be smaller than 110 and 140 kg/m^2, respectively. Thus, at a panel thickness of 120 mm, the partition panels produced using mixture proportions AR22-2 and AR22-3 and a rounded rectangular cross section can simultaneously satisfy the requirements of both panel strength and panel area density, while only mixture proportion AR22-3 can be used for the preparation of the panel with a thickness of 90 mm.

3.4 Pore Structure of CRFA-LWC

The analysis of the pore structure of the CRFA-LWC was conducted on the typical concrete sample produced using mixture proportion AR22-2. To this end, the sample was cut, and then a photograph of the cut surface was uploaded to Image-Pro Plus 6.0 software. The grayscale image and the pore structure image of the concrete sample are presented in Fig. 7; the pore size distribution of the concrete sample is also depicted in Fig. 8. All the pores in the CRFA-LWC have a diameter of smaller than 0.17 mm, and the diameter of 89% of them is less than 0.05 mm. According to Kumar Mehta (2014), the diameter of the pores formed by air-entraining agents normally ranges from 0.05 to 0.2 mm. The small pore size of the CRFA-LWC may be caused by the special air-entraining agent used in this work. Hence, the pores formed by our air-entraining agent are smaller than those created by other air-entraining agents.

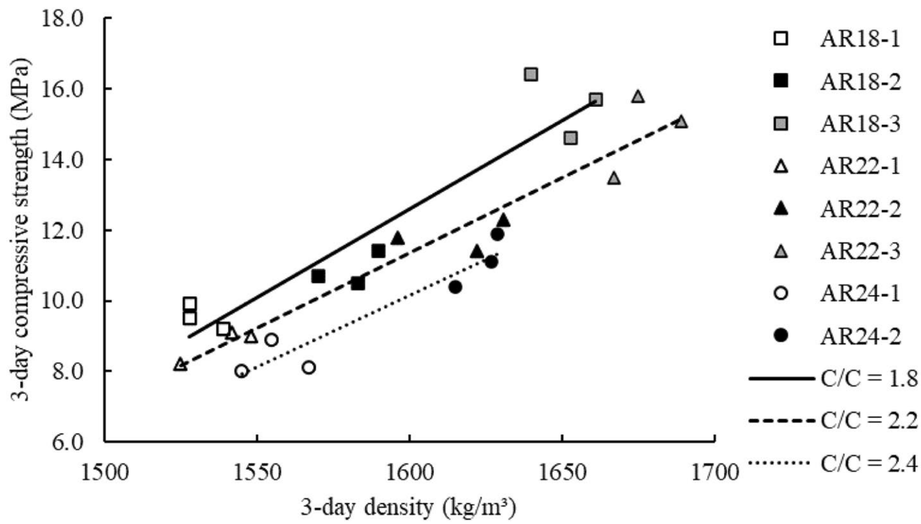


Fig. 4 Relationship between the 3-day compressive strength and 3-day density of the hardened CRFA-LWC.

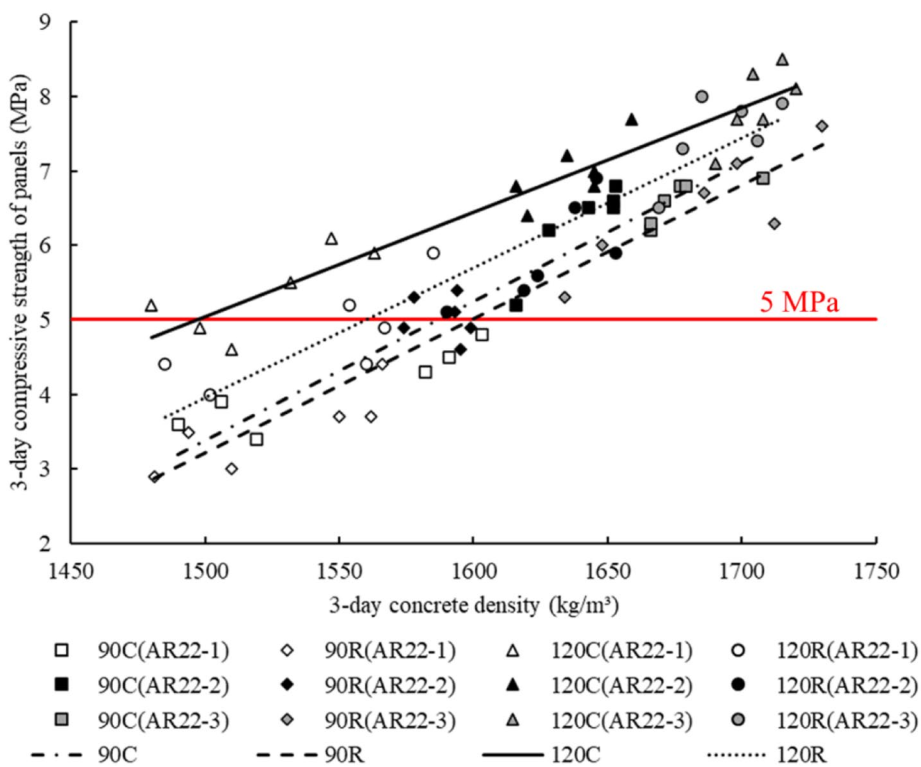


Fig. 5 The relationship between the 3-day compressive strength and 3-day concrete density of the CRFA-LWC partition panels with different types of cross sections.

3.5 Dry Shrinkage of CRFA-LWC

The dry shrinkage of the four concrete samples prepared using proportion AR22-2 was measured as a function of time as delineated in Fig. 9. The curing period of the four concrete samples was 3, 7, 10, and 14 days. The drying shrinkage of the concrete samples with different curing periods follows a similar trend. The drying shrinkage of all the samples increases up to 7 days and then plateaus. Further, the concrete samples cured for a longer period have

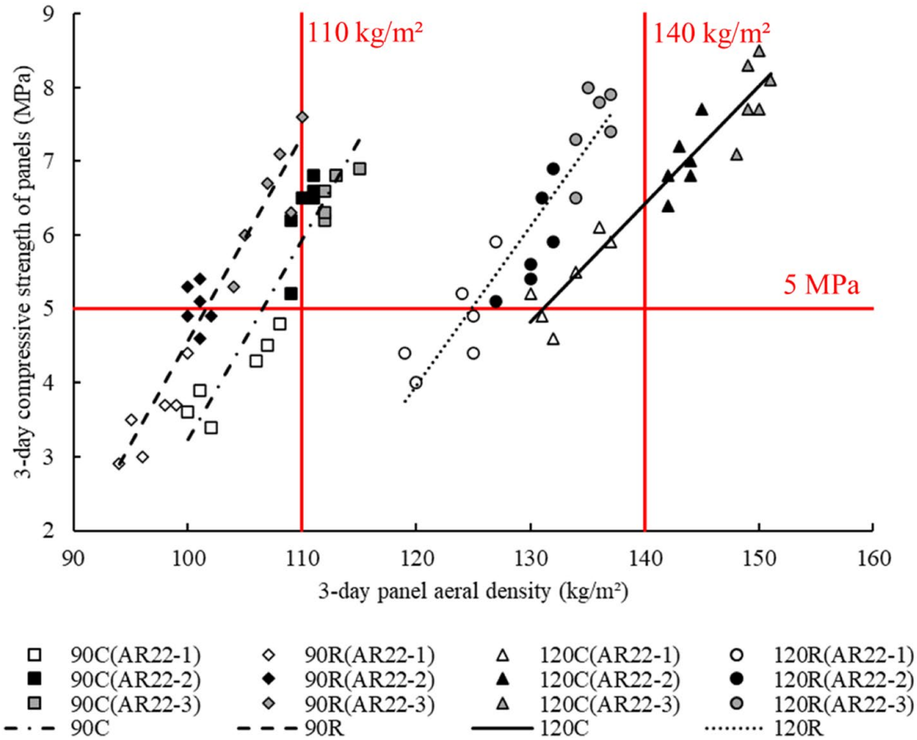
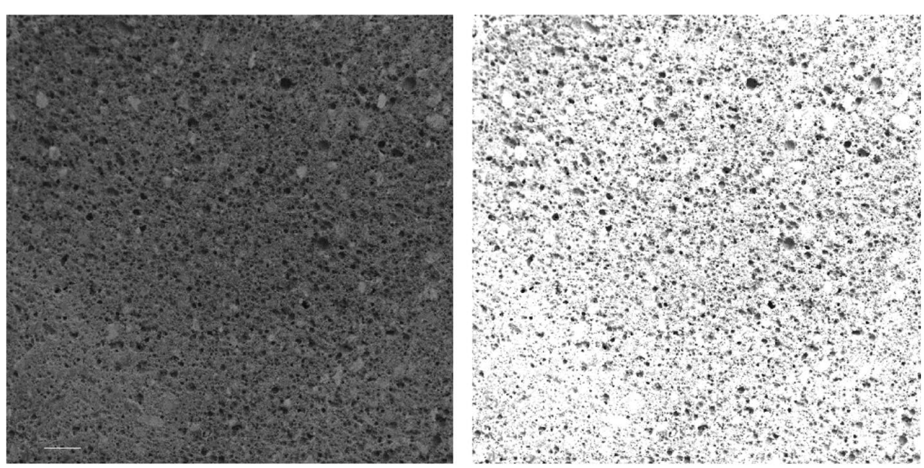


Fig. 6 The relationship between the 3-day compressive strength and 3-day area density of the CRFA-LWC partition panels with different types of cross sections.



(a) (b)

Fig. 7 **a** Grayscale image and **b** pore structure image of concrete sample AR22-2.

a smaller final drying shrinkage. In fact, the drying shrinkage of the CRFA-LWC is chiefly caused by the loss of water. As the curing period of the CRFA-LWC extends, the cement is hydrated sufficiently, and the moisture content of the concrete is reduced, which may lead to the reduction in the drying shrinkage of the CRFA-LWC. In addition, the sufficient hydration of cement can improve the strength and impermeability of concrete, which consequently prevents concrete from shrinking. Chinese code JG/T169-2016

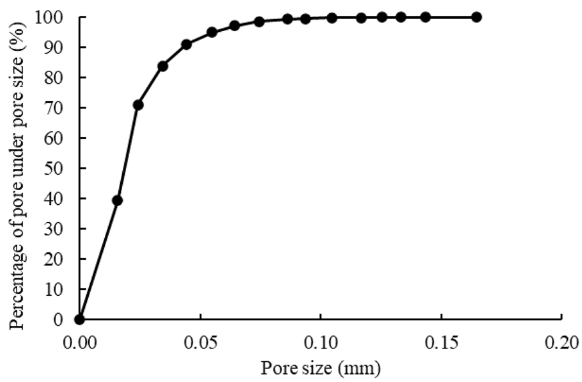


Fig. 8 Pore size distribution of concrete sample AR22-2.

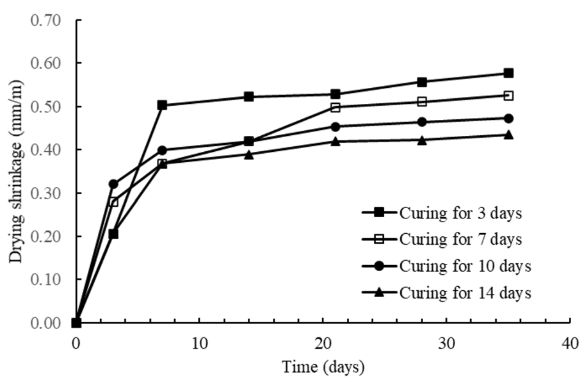


Fig. 9 The variation of the drying shrinkage of the CRFA-LWC samples prepared using mixture proportion AR22-2 and cured for different periods with time.

(Ministry-of-Housing-and-Urban–Rural-Development-of-PRC, 2016a) stipulates that the drying shrinkage of concrete should not exceed 0.50 mm/m, so the curing period of the CRFA-LWC should not be shorter than 10 days according to Fig. 9. Since the period between the preparation of CRFA-LWC partition panels and the on-site construction is usually longer than 10 days, the required curing period of 10 days does not affect the application of the CRFA-LWC partition panels.

3.6 Economic Analysis of CRFA-LWC

The production cost of the CRFA-LWC was calculated based on the price of the raw materials listed in Table 6 and compared with that of the autoclaved ceramsite concrete (ACC). The price of the CRFA was considered to be equal to that of recycled aggregate in Shanghai, China, and the price of the other raw materials was provided by the market. Also, the mixture proportions of the autoclaved ceramsite concrete were provided by the local partition panel plant as tabulated in Table 7. Since the price of water is low, and the admixture content of the concrete

Table 6 The price of the raw materials.

Material	Cement	River sand	CRFA	Ceramsite
Price (RMB/ton)	450	190	60	609

is small, the cost of the water and the admixture is not taken into account. The price of the CRFA-LWC prepared using mixture proportions AR22-2 and AR22-3 is 275.9 and 292.7 RMB/m^3, respectively, while that of the autoclaved ceramsite concrete is 469.4 RMB/m^3. The material cost of the CRFA-LWC produced using mixture proportions AR22-2 and AR22-3 is, respectively, 41% and 38% lower than that of the autoclaved ceramsite concrete. Considering that the production of the CRFA-LWC does not need an autoclave curing process, the economic benefit of the CRFA-LWC is remarkable.

4 Conclusions

This study presents a series of experiments to investigate the application of completely recycled fine aggregate in preparing lightweight concrete and lightweight concrete partition panels and to evaluate the performance of the LWC and LWC partition panels. The main conclusions drawn from the results can be summarized as follows:

- The LWC with a CRFA-to-cement ratio of smaller than 2.2 can satisfy the target density and the workability requirements. The strength of the concrete correlates negatively with the ratio of the CRFA to the cement. Given that the price of cement is higher than that of CRFA, the optimal CRFA-to-cement ratio for preparing the LWC partition panel is 2.2.
- The pores of the CRFA-LWC have a diameter of smaller than 0.17 mm, and the diameter of 89% of the pores is less than 0.05 mm.
- The drying shrinkage of the CRFA-LWC decreases as the curing period of the samples extends. To fulfill the drying shrinkage requirements stipulated by Chinese standard JC/T 169-2016, the CRFA-LWC should be cured for at least 10 days. As the period between the preparation and the on-site construction of the wall panels is usually longer than 10 days, the necessary curing period of 10 days does not affect the application of the CRFA-LWC.
- At a similar thickness and panel area density, the CRFA-LWC partition panel with the rounded rectangular cross section presents higher compressive strength than that with the circular cross section. Thus, the optimal cross section of the CRFA-LWC partition panels is a rounded rectangular one.

Table 7 The mixture proportions of the autoclaved ceramsite concrete and the CRFA-LWC.

Concrete	Curing condition	Content (kg/m^3)				Price (RMB/m^3)
		Cement	River sand	CRFA	Ceramiste	
ACC	Autoclave	350	600	–	325	469.5
AR22-2	Autoclave-free	474	–	1043	–	275.9
AR22-3	Autoclave-free	503	–	1106	–	292.7

- Mixture proportion AR22-3 with a CRFA-to-cement ratio of 2.2 and a target density of 1750 kg/m^3 is suitable for the panel with a thickness of 90 mm, and mixture proportions AR22-2 and AR22-3 with a similar CRFA-to-cement ratio of 2.2 and a target density of 1650 and 1750 kg/m^3, respectively, suit the panel with a thickness of 120 mm.
- The material cost of the CRFA-LWC is around 40% lower than that of the autoclaved ceramsite concrete. Moreover, enjoying an autoclave-free curing process, the production of the CRFA-LWC will be of remarkable economic benefit.

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Authors' contributions
Conceptualization: YY. Data curation: BC and WZ. Investigation: BC, YL, QC, and WZ. Methodology: BC and YY. Resources: YC and HW. Software: QC. Supervision: YY, WG, and HW. Validation: QC. Writing: original draft, BC; writing: review and editing, BC. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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