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Fire Resistance Evaluation of Recycled Aggregate Concrete: Experimental Study and Analysis

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Abstract

To assess the fire resistance performance of recycled aggregate concrete (RAC) components with varying compressive strengths, four full-scale concrete columns were designed and tested under high-temperature conditions. Two of the specimens were constructed using normal concrete with compressive strengths of C20 and C30, while the other two were made from recycled coarse aggregate (RCA) concrete with compressive strengths of C30 and C40. These specimens were subjected to identical constant axial forces and exposed to simulated building fire conditions in a laboratory furnace. Various parameters from the experimental results were analyzed and compared, including temperature change, vertical displacement, lateral deflection, fire endurance, and failure characteristics. The temperature distribution within the specimens was simulated using ABAQUS Software (ABAQUS Inc., Providence, RI, USA), and the simulated results closely matched the experimental findings. The results indicate that the rate of heat transfer from the surface to the interior of the columns increases with higher concrete compressive strengths for both RAC and normal concrete columns. Under identical initial axial force ratios and column cross-sections, columns with lower concrete compressive strengths exhibited better fire resistance performance. Additionally, the RAC columns demonstrated superior fire resistance performance compared to the normal concrete columns with equivalent compressive strengths.

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Keywords: *Recycled aggregate concrete (RAC) column; fire resistance; high-temperature test; temperature field; finite element method (FEM) analysis; concrete compressive strength*

INTRODUCTION

The loss of human life and property is a significant feature of in-building fire disasters. Statistics show that the most common and serious losses in connection with fires occur during building structure fires. Reinforced concrete (RC) construction accounts for a large proportion of buildings; during a building fire its structural performance is degraded, structural deformation increases, and the load-carrying capacity declines. Lots of studies focusing on the fire performance of concrete components were conducted. In the 1990s, Canadian scholars carried out fire resistance tests mainly on normal RC columns and concrete-filled steel tubular columns with different cross sections, and published their fire endurance formulae, which are now widely used in the international construction industry Some scientists investigated the fire resistance of RC beams and columns made of normal concrete.

Recycled aggregate concrete (RAC), a new type of environmentally friendly material using waste concrete as recycled aggregates to substitute for natural aggregates, is made partly or totally by processes of washing, crushing, grading, and proportional mixing. Although RAC is no longer considered a new technology and many studies have focused on its use, currently most of the experimental studies on RAC fire resistance performance have been confined to RAC material rather than structural components. Some analyzed the factors affecting thermal conductivity of RAC and provided the calculation method and formula for RAC thermal performance parameters with different amounts of recycled coarse aggregate (RCA) replacement. They conducted an experimental study on the residual mechanical performance of concrete produced with RCA after being subjected to high temperatures. Results obtained show that there are no significant differences in the thermal response and post-fire mechanical behavior of concrete made with RCA, when compared to normal concrete. They studied the residual mechanical response of RAC after exposure to elevated temperatures.

However, few experimental studies on the fire resistance performance of RAC structures and components have been conducted except when, investigated the fire resistance performance

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of the recycled concrete-filled steel tube. Vertical columns are the primary load-carrying structural components in most buildings, and the loss of their load-carrying capacity in a fire may lead to partial or total destruction of the entire structure. Therefore, research into the fire resistance performance of RAC columns is crucial to the preservation of life and property in fire emergencies. In China, they designed and tested four concrete tubular structure specimens, with one made from normal concrete C20, one made from RCA concrete C20, and the other two made from recycled coarse and fine aggregate concrete, C20 and C40, respectively. Results show that the temperature of specimens with recycled concrete is lower than that of normal concrete in the same position, force conditions, and fire conditions. The load-carrying capacity of specimens with recycled concrete is lower than that of the normal concrete specimens. Fire endurance decreases with the increase of recycled aggregate replacement rate in the specimens.

Considering most columns used in low-rise buildings are concrete columns without an outer steel tube, it is essential to study their fire resistance performance. For this paper, in order to ascertain the fire resistance performance of RAC-constructed components with different concrete compressive strengths, the fire resistance performance of two RAC columns and two normal RC columns with different concrete compressive strengths was analyzed based on experimental data, with the aim of providing an experimental basis for fire resistance design using RAC columns.

OBJECTIVES

1. To compare the temperature distribution and heat transfer characteristics within recycled aggregate concrete (RAC) columns under fire conditions, relative to conventional concrete.
2. To analyse the vertical displacement and lateral deflection behavior of RAC columns subjected to simulated fire, compared with traditional concrete columns.
3. To determine the fire endurance and failure modes of RAC columns with varying compressive strengths and under different axial forces.
4. To compare the fire resistance performance between RAC and traditional concrete columns with equivalent compressive strengths.

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EXPERIMENTAL DETAILS

Model Design

Four full-scale concrete columns were constructed: NCC-1, a normal RC column constructed from C20-specified concrete; NCC-2, a normal RC column from C30-specified concrete; RCC-1, a 100% RCA replacement RAC column with C30-specified concrete; and RCC-2, a 100% RCA replacement RAC column using C40-specified concrete. All specimens were constructed outside in winter. The geometry and reinforcement details of the four columns were identical, each with a cross section of 450 mm × 450 mm, a height of 3640 mm, longitudinal bars of 8D20, a ratio of reinforcement of 1.24%, D10-150 stirrups, and a volume stirrup ratio of 0.6%, as shown in Figure 1a. The thickness of the concrete cover was 30 mm for all four columns. The picture of columns in construction and under curing is shown in Figure 1b, c, respectively.

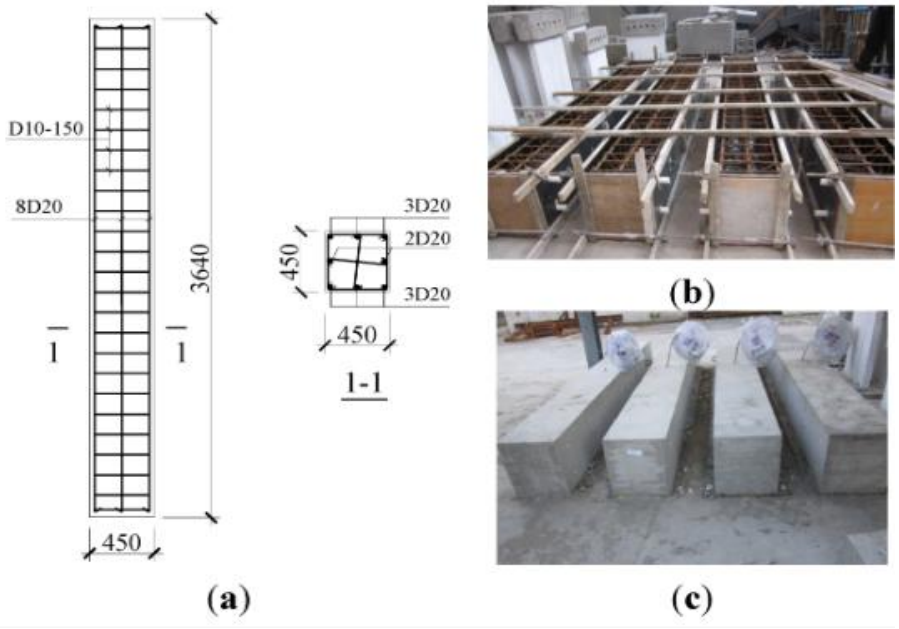


Figure1. (a) Reinforcement details and cross section dimension of columns (mm); (b) columns in construction; and (c) columns under curing.

Aggregates, Concrete Mix Design, and Concrete Mechanical Properties

These fine natural aggregates (FA) and coarse natural aggregates (NA) are typical in ready-mix concrete construction in India. The RCA used in the research came from a local construction and demolition recycling plant. It was made from concrete columns and beams of an old building demolished at Hyderabad, Telangana; the test cubic compressive strength

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was 32.43 MPa. Since the RCA came from demolition, components such as bricks were inevitable (about 1.62 wt%). The RCA used in the research had an aggregate content of 40.1%, mortar aggregate content of 34.9%, residual mortar content of 23.42%, and deleterious material content of 1.62%. The density of the RCA was 2290 kg/m3. Its water absorption was 3.23%.

The direct mass replacement method was used to replace NA with RCA. Table 1 shows the dry-weight proportions of the four concrete mix designs in this paper. The RAC was mixed at the site and ready-mixed concrete was used for the normal concrete. A high range water reducer (HRWR) was also used in each normal concrete mix.

Table1. Dry-weight proportions of normal and recycled coarse aggregate (RCA) concrete mixes. FA: fine natural aggregates; NA: coarse natural aggregates; and HRWR: high range water reducer.

Grade level	RCA replacement ratio (%)	Water-to-cement ratio	Water ($kg \cdot m^{-3}$)	Cement ($kg \cdot m^{-3}$)	FA ($kg \cdot m^{-3}$)	NA ($kg \cdot m^{-3}$)	RCA ($kg \cdot m^{-3}$)	HRWR ($kg \cdot m^{-3}$)
C20	0	0.56	107	152	906	1037	-	6.08
C30	0	0.45	111	208	894	990	-	7.56
C30	100	0.56	186	335	576	-	1116	-
C40	100	0.37	178	482	464	-	1124	-

Each grade of concrete after 28 d was tested to ascertain its mechanical properties prior to heating—these results are shown in Table 2. The yielding strength, ultimate strength, and elastic modulus of bar D20 used are 375 MPa, 559 MPa, and 2.02 × 105 MPa, respectively, and those of bar D10 are 433 MPa, 497 MPa, and 1.99 × 105 MPa, respectively.

Table2. Concrete mechanical properties as tested.

Specimen	RCA replacement ratio (%)	Designed concrete level	Test cubic compressive strength (MPa)	Elastic modulus (MPa)
NCC-1	0	C20	17.84	2.34×10^4
NCC-2	0	C30	30.85	3.03×10^4
RCC-1	100	C30	28.57	2.65×10^4
RCC-2	100	C40	40.70	3.15×10^4

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Loading Equipment and the Heating Curves

The test was carried out in the test column furnace at the Testing Center of the National Fixed Fire Extinguishing System and Fire-Resistant Component Quality Supervision, Essar Analytical, Old Bowenpally, Hyderabad, Telangana, Hyderabad. The test furnace is shown in Figure 2a. There are 13 orifices on the body of the furnace for attaching thermo couplings so as to obtain the temperature inside in real time. To ensure uniformity of temperature within the furnace during heating, the diesel nozzles in the combustion furnace were arranged spirally in order to generate a spiral-shaped heat source. Both ends of the column were hinged to the flanges inside the furnace. The distance between the unaffected parts, which were protected by asbestos insulation, and the fire at each end was 320 mm. Thus, the actual height of the middle part that was in the fire of 3000 mm. The test set-up is shown in Figure 2b.

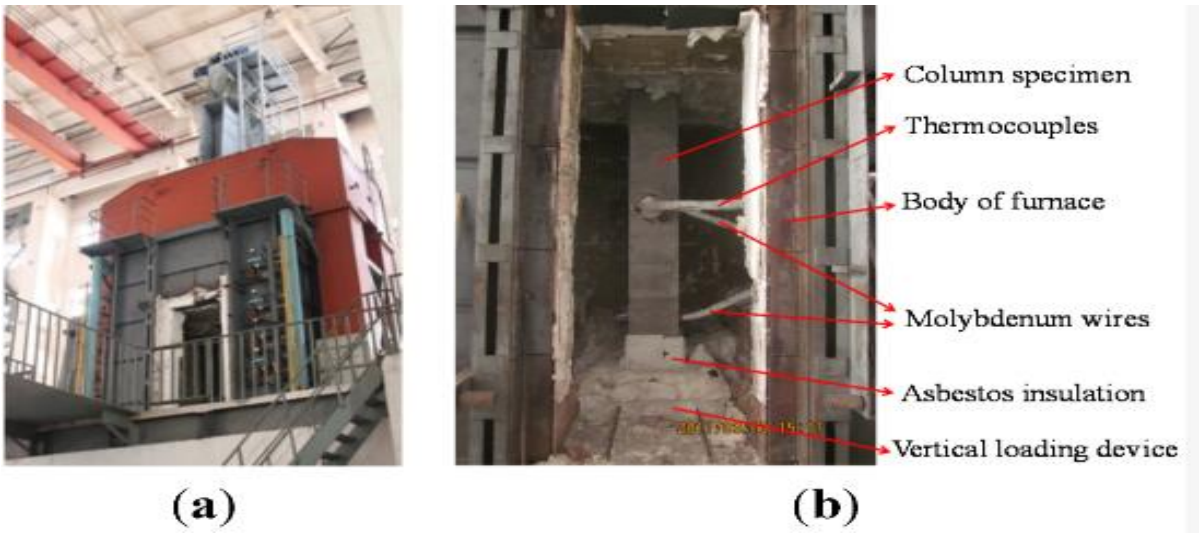


Figure2. (a) Test furnace; and (b) test set-up.

According to International Standard ISO834 [21, the heating curve formula T = T0 + 345lg (8t + 1) was used to control the heating. Here, T is the heating temperature in Celsius, T0 is the initial temperature in Celsius of the furnace, and t stands for the heating time in minutes. The actual heating curve, as shown in Figure 3, agrees very well with the one in ISO834.

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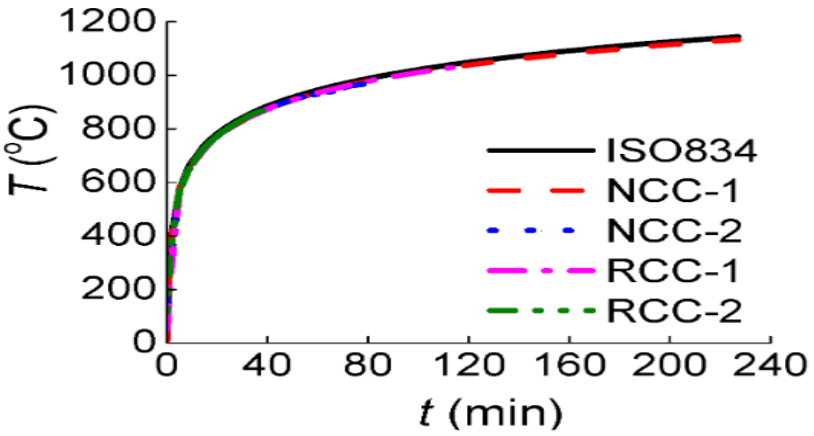


Figure3. Comparison curves between the actual temperature and ISO834 heating curve.

The specimens were allowed to cool down naturally after the heating test. The thermocouples used were of nickel-chromium or nickel-silicon, and chromel construction; three of these were arranged in the middle cross section along the height of the column, with a distance from the outer side of 15 mm, 112 mm, and 225 mm, respectively, as shown in Figure 4. The main test method and content are: (1) the end of the fire resistance duration was indicated by a sudden drop in vertical load; (2) the temperature inside the cross section was measured by the thermocouples; (3) the axial deformation of the column was obtained using a vertical displacement meter, which was set under the bottom of the column; (4) the lateral deflection at the height of 320 mm and 1820 mm from the bottom of the column was obtained using two molybdenum wires, which were connected to the column through orifices in the furnace; and (5) the failure process was also observed through the observation port on the furnace. There was only one fixed port and only the lower part of the column in furnace could be seen.

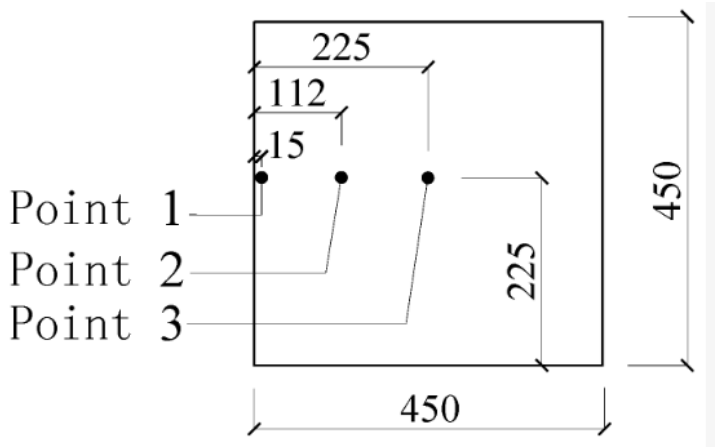


Figure4. Thermocouple layout diagram (mm)

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RESULTS AND DISCUSSION

Test Results and Analysis

Fire Resistance Duration

The initial vertical load was determined by a fixed axial force ratio and remained unchanged during the heating test. The heating curve from ISO834 was adopted inside the furnace. According to Chinese Standard GB/T 9978-2008 [22], the fire resistance duration of the specimen, meaning the time from the start of the test until the specimen fails, is determined when the axial deformation becomes greater than or equal to H/100 (mm), or when the rate of the axial deformation reaches 3H/1000 (mm/min). H is the valid height of a column on fire, which is 3000 mm here. In this instance, the fire resistance duration of a column was determined to be when the axial deformation is greater than or equal to 30 mm, or when the rate of the axial deformation reaches 9 mm/min. The experimental fire resistance duration of specimens NCC-1, NCC-2, RCC-1, and RCC-2 is 227 min, 78 min, 118 min, and 39 min, respectively. All of the specimens failed because of the large axial deformation. The concrete cubic specimens were put into the furnace with the columns at the same time and subjected to International Organization for Standardization (ISO) fire exposure. The cubic compressive strength after fire was also tested; Figure 5 shows the cubic compressive strength test before and after fire.

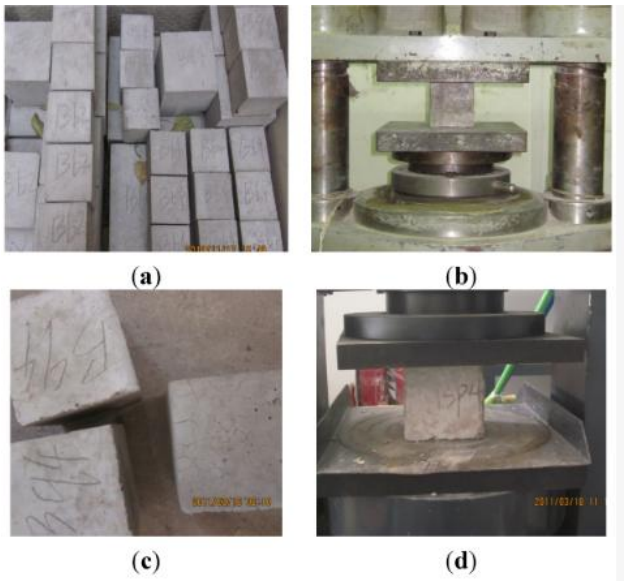


Figure 5. The cubic compressive strength test before and after fire: (a) the cubic concrete specimens before fire; (b) testing before fire; (c) the cubic concrete specimens after fire; and (d) testing after fire.

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Figure 6 shows the moire pattern of the cross section temperature for the four specimens.

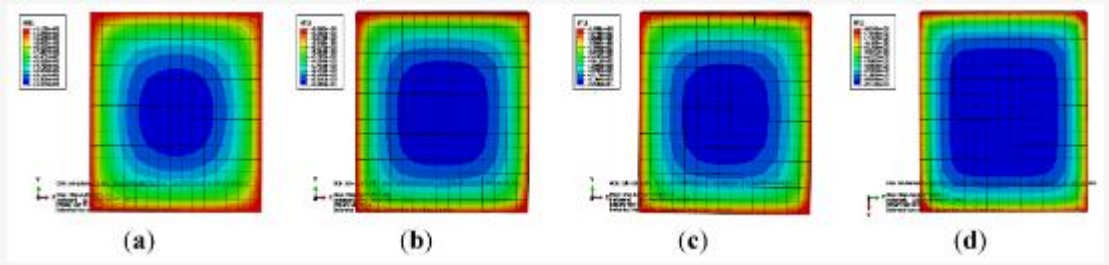


Figure 6. Moire pattern of temperature of specimens: (a) NCC-1; (b) NCC-2; (c) RCC-1; and (d) RCC-2.

CONCLUSIONS

- The rate of heat transfer from the surface to the inside of the column increases with compressive strength for both RAC columns and normal RC columns during fire conditions.
- Under the same initial axial force ratio, for both RAC columns and normal RC columns with the same cross section, those with lower concrete compressive strengths demonstrate better fire resistance performance. The fire resistance performance decreases as the concrete compressive strength increases, due to its higher density and lower porosity, which cause cracks to appear earlier and the material to degrade more rapidly.
- The fire resistance performance of RAC columns is better than that of the normal concrete columns with the same concrete compressive strength. This is because the rate of temperature penetration for RAC columns is lower than that of normal RC columns under nominal fire condition heating.
- Finite element method (FEM) analysis on the temperature fields of both the normal concrete columns and RAC columns, which showed almost the same results as the experiments, is able to be used to avoid the expensive test cost.
- The RAC columns may be applied in practical projects.

SCOPE OF THE STUDY

The study titled "Fire Resistance Evaluation of Recycled Aggregate Concrete: Experimental Study and Analysis" aims to comprehensively assess the fire resistance performance of recycled aggregate concrete (RAC) compared to conventional concrete. The scope includes designing and testing full-scale concrete columns under simulated building fire conditions in

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a controlled laboratory environment. Specimens are prepared with varying compressive strengths to investigate their thermal behavior, structural response, and endurance under fire exposure, while maintaining constant axial forces to simulate realistic loading scenarios.

Key objectives encompass the measurement and analysis of temperature distribution, vertical displacement, lateral deflection, fire endurance, and failure characteristics of both RAC and traditional concrete columns. These parameters are crucial for understanding how RAC performs in fire conditions relative to conventional concrete. Numerical simulations using ABAQUS software will be employed to validate experimental findings, ensuring accuracy and providing deeper insights into the mechanisms governing fire resistance.

By conducting a comparative analysis between RAC and traditional concrete columns with similar compressive strengths, the study aims to identify potential advantages or limitations of using recycled materials in structural applications exposed to fire. The outcomes are expected to contribute valuable data-driven insights and recommendations for enhancing the fire resistance of recycled aggregate concrete in practical construction settings.

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