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Evaluating the Structural Behavior of Recycled Aggregate Concrete Walls Under Fire Exposure: A Finite Element Analysis

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Climate change is raising the demand for change in the construction industry, particularly in the concrete industry. One of the approaches to increase sustainability in the concrete industry is the use of recycled aggregate concrete (RAC). Many studies examined the type and composition of RAC used in construction applications. However, fewer studies examined the structural engineering applications of RAC. Thus, this study investigates the use of RAC in bearing walls. It presents a comprehensive thermal and structural performance assessment of RAC walls exposed to fire using finite element analysis (FEA). The FE model incorporates experimental material models in the literature that consider the degradation of the mechanical properties of RAC at high temperatures. The investigation encompasses a range of critical response measures, including the out-of-plane response of RAC walls under standard fire exposure and the overall stability of the walls during fire scenarios. The walls' out-of-plane and axial deflection and damage patterns were presented. The upper and lower bounds of performance were presented to examine the effect of material models' variability on the response. The findings of this study reveal the complex interaction between fire scenarios, material properties, and their effect on the structural behavior of RAC walls. This study contributes to the growing knowledge on using RAC in structural engineering applications and promoting environmentally friendly materials in the construction industry while ensuring structural safety.

Keywords: Reinforced concrete, RC, RAC, Thermal loads, sustainability, FEM.

1 INTRODUCTION

Adopting recycled aggregate concrete (RAC) in construction practices has gained substantial attention in the last few years. This is due to the increasing need to reduce the environmental footprint of the most widely used material in construction, concrete. The construction and demolition waste comprise about 30% of the total solid waste of materials (Hyder Consulting, 2011). Over the past few decades, incorporating recycled fine and coarse aggregates as a partial or total replacement for natural aggregates in concrete production has demonstrated significant promise in advancing sustainable development (Ahmed Shaikh et al., 2019). Several studies investigated the mechanical properties of RAC under normal and high temperatures (Beatriz da Silva et al., 2020; Hawileh et al., 2023; Tariq & Ahmad, 2023). The compressive strength of RAC at room temperature is relatively lower than normal aggregate concrete (NAC). The extent of reduction in concrete strength depends on many factors, namely, the replacement percentage, the source of the recycled aggregates, and the concrete mix design (Cree et al., 2013).

In general, concrete is considered as a good fire-resistant material. However, concrete properties experience deterioration under elevated temperatures (Assad, Hawileh, & Abdalla, 2022;

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Assad, Hawileh, Abdalla, et al., 2022; Hawileh & Kodur, 2018; Kodur, 2014). The degradation of normal aggregate concrete under high temperatures was extensively studied in the literature. In addition, there are existing developed models for degradation in thermal and mechanical properties of concrete in the standard codes of practice, for instance, Eurocode 2 (EC2) (1992). Many recent experimental studies have also reported on the mechanical properties of RAC under elevated temperatures (Beatriz da Silva et al., 2020; Hawileh et al., 2023; Tariq & Ahmad, 2023). In the majority of the published studies, the degradation models of RAC were reasonably comparable to normal aggregate concrete. Some studies reported a superior performance of RAC compared to normal aggregate concrete when exposed to elevated temperatures (Yang & Hou, 2012). This can be attributed to incorporating cementitious mineral admixtures in RAC, such as silica fume and GGBS, which mitigates the mechanical deterioration by reducing porosity. Gales et al. (2016) found that the mechanical properties degradation of the RA concrete was comparable to the conventional concrete. The authors also stated that the reduction in the mechanical properties did not exceed the conventional Eurocode design guidelines. Sarhat and Sherwood (2013) results also indicated that both partial and total replacement of natural aggregates with RA exhibited good performance under elevated temperatures. Therefore, it can be deduced that the developed models and strength reduction factors vary significantly among the previously published studies. Moreover, the literature did not comprehensively address the behavior of structural elements composed of RAC. Studying the potential of RAC as a construction material for load bearing elements is significant and relevant to reduce the environmental impact of concrete and requires the assessment under fire conditions.

In light of the above, the present research investigates a critical structural element bearing walls. This study aims to investigate the structural performance of RAC bearing walls when subjected to fire conditions, utilizing finite element analysis (FEA). The developed model incorporates non-linear material properties of concrete and steel reinforcement. Furthermore, the degradation in thermal and mechanical properties of RAC and NAC were incorporated into the FE model, using existing degradation models in the literature. The RC walls were subjected to standard fire exposure (ASTM E119-19, 2019) from one side. The results of the verified model were analyzed in terms of load versus out-of-plane displacement, load versus axial displacement curves, and cracking patterns.

2 DESCRIPTION OF THE FE MODEL

A three-dimensional (3-D) finite element (FE) model was created in Abaqus (2019) for a reinforced concrete (RC) wall. The analysis of the wall under fire exposure was performed in two phases: the first one is thermal analysis to extract temperature distribution and nodal temperatures of each node and element of the wall after subjecting one side of the wall to standard fire. The second one involves structural analysis of the wall to obtain stresses and displacement data. The geometry of the wall, elements definition, and material properties used in the model are illustrated in this section.

2.1 Geometry

For verification purposes, the geometry of the wall corresponds to a previously tested wall by Ngo et al. (2013) in a previous experimental investigation. The wall has a height of 2400 mm, a depth of 150 mm, and a width of 1000 mm. The wall was reinforced with Ø16 mm steel bars in one direction and Ø14 bars in the other direction, both at a 300 mm spacing. Figure 1-a shows the geometrical and mesh configuration of the wall. The wall was simply supported on top and bottom, and concentrically load with a load of 485 kN. Half of the wall was modelled to reduce

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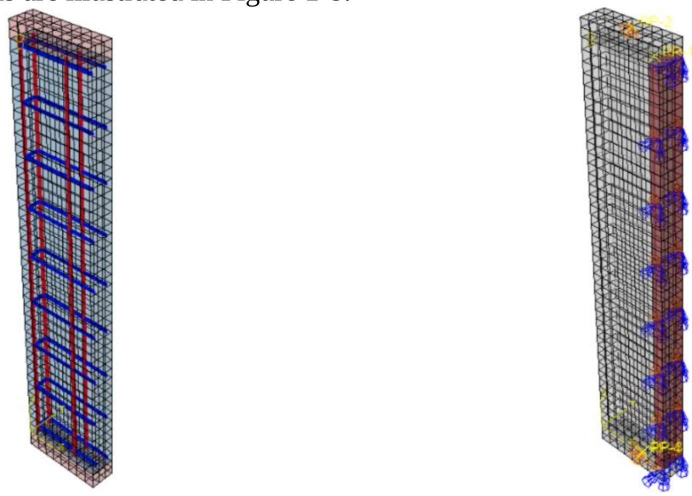
computational time. Therefore, movement was restricted in the direction of symmetry. The boundary conditions are illustrated in Figure 1-b.



a) b)

Figure 1. FE model geometry: a) Reinforcement and mesh configuration; b) Boundary conditions

2.2 Elements Definition

In the thermal analysis, concrete was represented using the DC3D8 element, a diffusive heat-transfer three-dimensional solid element with 8 degrees of freedom. This element is linear, and its nodal temperatures are computed at the 8 corner nodes. Steel reinforcement was modeled using the DC1D2 element, a 2-node linear truss element. Both elements featured linear interpolation functions for temperature. Additionally, they facilitated heat transfer via conduction, convection, and radiation, as elaborated in the analysis section. In the structural analysis, concrete was represented using a C3D8 element, a continuum three-dimensional solid element similar in layout and node count to the DC3D8 element. Steel rebars were assigned a C1D2 element, identical to the DC1D2 thermal element, but suited for stress/displacement analysis.

2.3 Material Properties

The variation of the constituent materials' properties with elevated temperatures highly affects the performance of RC walls under fire conditions. In this study, two material models for the degradation in the compressive strength of RAC at elevated temperatures were adopted from the literature (Hawileh et al., 2023; Tariq & Ahmad, 2023). It should be noted that the adopted material models are taken for a RA replacement percentage of 100%. For comparison purposes, strength degradation models for NAC were taken from the same reference and assigned in the FE model. In order to verify the FE model, EC2 material models for NAC were used and numerical model output were compared with the experimental results. The variation of the thermal properties (Thermal conductivity, and specific heat) for RAC is taken from Zhao et al. (2018), whereas the variation of the thermal properties for NAC is taken from EC2.

3 RESULTS AND DISCUSSION

3.1 Validation of the FE Model Results

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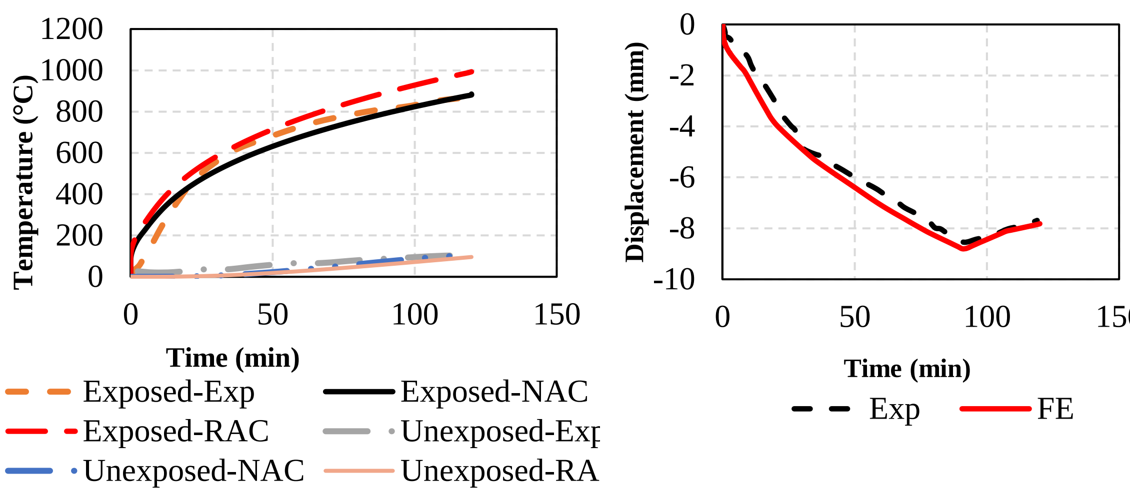
The accuracy of the FE models was ensured by verifying the thermal and structural analysis results through a comparison of the FE numerical results with the experimental data provided by Ngo et al. (2013) for natural aggregates and normal strength concrete. Figure 2-a presents the temperature versus time curves from the experimental data and numerical analysis at the exposed and unexposed face. It can be seen that the results of the NAC wall exhibited better correlation with the experimental results since the walls in the experiments are composed of natural aggregates. The wall composed of RAC showed higher temperatures at the exposed face than the NAC wall. Temperatures at the unexposed face for RAC wall were very close to the temperatures exhibited by the NAC wall. Figure 2-b shows the out-of-plane displacement versus time for NAC wall. A good correlation can be noticed between experimental and numerical results, indicating the accuracy of the developed FE model. It is noteworthy that only natural aggregate concrete results were validated. This is due to the lack of experimental data on the behavior of RAC walls, which emphasizes the importance of the paper's investigation.



a) b)

Figure 2. Validation of the FE model results: a) Temperature versus time curves; b) Out-of-plane displacement versus time

3.2 Load-Displacement Behavior and Damage Patterns

The structural analysis results of RAC and NAC walls, corresponding to Hawileh et al. (2023) and Tariq & Ahmad (2023) are presented in this section, respectively. The results of the walls composed of RAC and NAC, where material properties are taken from Hawileh et al. (2023) are denoted by RAC-1 and NAC-1 in Figure 3, respectively. The results of the walls with material properties taken from Tariq & Ahmad (2023) are denoted by RAC-2 and NAC2, respectively. Figure 3-a shows the out-of-plane displacement versus time for the four investigated materials (RAC-1, NAC-1, RAC-2, NAC-2), in addition to the material models taken from EC2 for NAC. It can be detected that all tested walls exhibited a similar behavior, which is characterized by a reversal in curvature direction at a certain point during the fire exposure. However, the reversal in the wall's bowing direction for RAC walls is noticed to occur earlier during the fire for both out-of-plane displacement and axial displacement. The reason for this is due to the higher rate of degradation in concrete strength, experienced by RAC. This degradation prevails more on the exposed side, compared to

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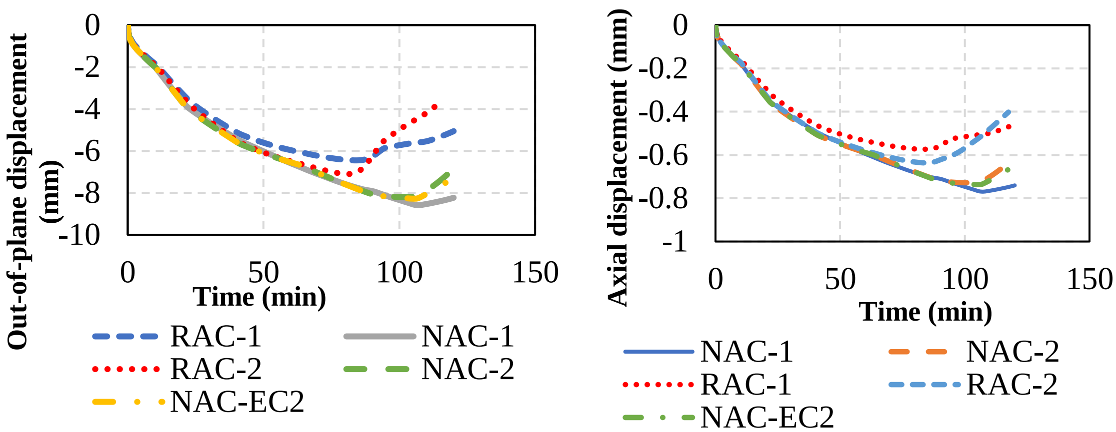
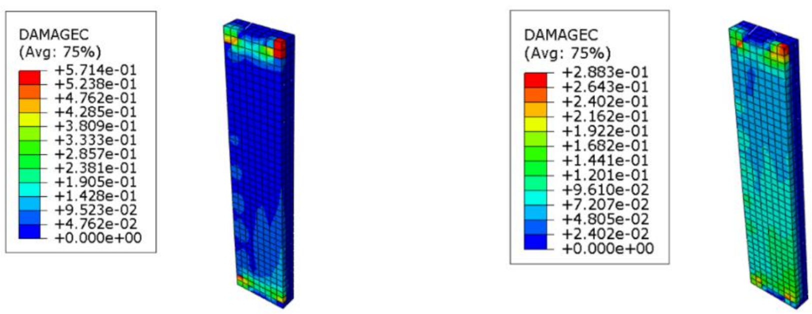
the unexposed side, which results in the reversal bowing of the wall. Figure 4 illustrates the compression damage/crushing of concrete elements after fire exposure in RAC and NAC walls, respectively. A higher damage is observed in RAC walls compared to NAC walls, which is attributed to the faster rate of material deterioration.



a) b)

Figure 3. Structural analysis results: a) Out-of-plane displacement results; b) Axial displacement results



a) b)

Figure 4. Damage patterns of NAC and RAC walls: a) NAC; b) RAC

4 CONCLUSIONS

In this study, the use of recycled aggregate concrete (RAC) in reinforced concrete (RC) walls was investigated. A comprehensive thermal and structural analysis was performed on RAC walls exposed to fire through finite element analysis.. The numerical model's results were validated with data from a previously published experimental paper. The following conclusions can be drawn from this study:

- The FE model predicts to a good extent the temperature profiles and displacement of RC walls under fire exposure.
- Walls composed of RAC displayed higher degradation under elevated temperatures compared to walls having NAC composition. Therefore, it is important to quantify the fire resistance of RAC walls that corresponds to the wall thickness, concrete cover, and fire scenario, which could be a subject of future investigation.

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- Further research is required on the structural response of RC walls composed of different replacement percentages and mix designs of RAC, under various fire scenarios.

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