Mechanical and Thermal Properties Analysis of Recycled Concrete Aggregate on Its Fire Exposure

Haotian Zhuo *

The Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, K1S 5B6, Canada

*Corresponding author Email: bryanzhuo@cmail.carleton.ca

Abstract. Concrete constructions can be badly damaged by fire, and the damage can be estimated using knowledge of material properties. The major focus on using green materials instead of traditional materials are promoted. Recycled concrete aggregates (RCA) are nominated and analyzed its mechanical and thermal properties with its fire exposure. Conclusions are when using RCA to mix natural aggregate in concrete, and it will help obtaining a better performance of concrete at high temperatures (more than 50 percent). Rich mixed RCA outperforms standard mixed RCA and natural concrete aggregate regarding fire resistance and remaining compressive strength. The effects of varying mixing percentages above 50% mixed concrete and different time effects on concrete performance are examined. It suggests the replacement of RCA is suitable for modern building construction and fire safety sector from its performance post fire residual.

Keywords: Recycled concrete aggregate; Fire resistance; Residual compressive strength.

1. Introduction

Nowadays sustainability is a global endeavour that influences the materials used in numerous landmark structures. LEED, BREEAM, and other global certification agencies are assisting in the development of innovative and environmentally friendly building materials. Because of its high embodied energy demand, meeting these certifications might be difficult when concrete is employed. The sustainable and unique concrete mix have been used into multiple construction building project for rewarding green certification for at least the last decade. This concrete mix was created by replacing recycled concrete particles for natural coarse aggregates. Demolition concrete debris can be used to source and grade recycled concrete aggregate (RCA). At least ten different structures have been constructed employing novel construction materials around the world .

When any new material is utilised in construction, public safety is crucial. The studies of behaviour on a novel material in a fire are a part of this protection. The mechanical qualities of a material related to fire can also assist in the development, confidence, and ease of use novel materials in the building sector.

By conducting a deep analysis of the mechanical and thermal properties and behaviour of RCA on its fire exposure. One of these is concerned with the behaviour of RCA concrete in a fire scene. The purpose is to provide a detailed and up to date analysis on the high-temperature behaviour of RCAs in concrete. At high temperatures, mechanical and thermal properties are explored. Inside, there are spalling, medium, and full-scale trials.

2. Mechanical and thermal properties of fire exposed natural concrete

2.1 Mechanical Properties of Fire Exposed Natural Concrete

Natural concrete subjected a fire scene causing change of its mechanical properties served as the foundation for understanding the effects of RCA. With Zawadowska et al.'s Click or tap here to enter text. experiment study, they investigated and compared the obtain results with current widely used model which build a solid background information to compare with from the results of RCA on different mechanisms like strength ratio, strain percentage, compressive strength, and residual strength.

With the widely promote of using green material in different civil engineering project, the concept of using RCA instead of natural concrete aggregate (NA) was suggested. Currently, the usage of RCA is in experiment phase with the focus on building material and fire safety of the building. Building component's capacity to perform desired load-bearing functions while exposed to fire. In certain circumstances, material degradation can manifest as a loss of strength, the development of cracks, and spalling. Click or tap here to enter text..

2.2 Thermal Properties of Fire Exposed Natural Concrete

Several elements determine the effect level, including temperature, heating pace, stress condition, external sealing, and moisture mixing percentage, all of which play a part in explosive spalling . Deficiency of natural aggregate within downtown city settings and widening distance between construction sites and NA prompted constructors to consider using recycled materials such as construction ceramics, concrete, and slag among others in place of the NA. On the other hand, enormous amounts of old concrete always occur within urban settings, whose elimination and disposal presents a significant environmental issue Click or tap here to enter text.. To address the change and impact of RCA replacement, Abed concluded that between 300°C and 600°C, relative residual compressive and flexural strengths were enhanced by 50% NA replacement with RCA. Furthermore, because of strong mortar-to-mortar connections, Replacement of NA with RCA by 50% increased residual strength Click or tap here to enter text.. With these findings, the focus is addressing the RCA as a better material than the natural concrete aggregate and finding RCA’s mechanical and thermal properties of fire exposed NA.

3. Mechanical behaviors post fire residual and fire exposure of rca

3.1 Residual Strength

The relative residual strength is displayed in this section as a function of temperature. With capability of the identical combination at room temperature was used as the basis for dividing the residual strength at each temperature level. Separate calculations were made for the strengths in compression and flexion to get its relative data respectively. Due to the numerous curves and challenges of comparing data from different days, the impact of increased temperature on the ageing of the concrete was depending on calculating the entire region under the relative residual strength curve between 20 and 800 Celsius Click or tap here to enter text..

Cree et al. stated that for temperatures ranging from 500 to 700 degrees Celsius with comparison to regular concrete, RCA has a higher residual strength. With adhering mortar bonded with original aggregate, RCA has a larger porosity, causing multiple ITZ to develop. Obviously, residual strength would be impacted. Click or tap here to enter text. This is something worth to discover.

3.2 Compressive Strength After Fire Exposure

In a different study, it can be noted that even though the fire duration (24 hours at 1000°C) employed in the study is rare, the authors maintained that the findings provide tutorial for embracing the right choices to strengthen or retrofitting the burned-out building before putting it back in service. However, the long subjection of the concrete to fire coupled with the long process of cooling led to several cracks of hair line appearing on the beams’ surface, which in turn presented difficulties when it comes to monitoring the first or initial crack during testing. Nonetheless, the conclusions are made by the authors are still logical as they are founded on the experimental observations associated with the reinforced beams of concrete subjected to 24-hour fire at temperature of 1000°C .

Vieira et al. Click or tap here to enter text. employed an experimental design of study to achieve the research objective. Among the four various compositions of concrete that were composed, concrete prepared with NA and different mixes of concrete with 20 percent, 50 percent, and 100 percent replacement ratio of NA by RCA. Following heating in keeping with time-temperature curve supplied by ISO 834, these specimens were heated to 400 °C, 600 °C, and 800 °C for an hour. After

the specimens were cooled down to ambient temperatures, elasticity modulus, tensile splitting strength, and compressive strength were three fundamental mechanical properties that were assessed and then compared with reference values recorded before thermal exposure. His findings showed that significance differences do not exist in the concrete's post-fire mechanical and thermal response behavior that compared to NA, RCA-made construction.

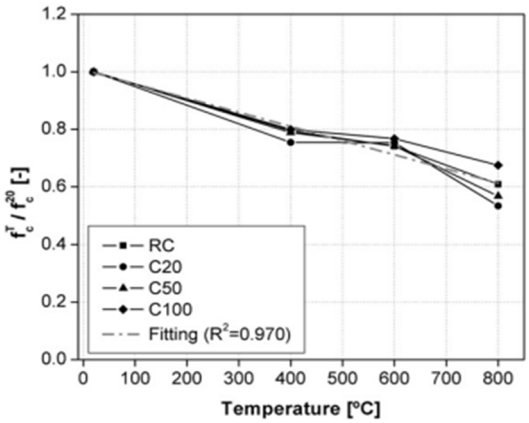

Figure 1. Graph of residual compressive strength with various RCA replacements

The relationship between residual strength at each exposure temperature and in relation to room temperature is depicted in Figure 1. The curves introduce the decrease of strength with respect to the increase of temperature Between 20 and 400 degrees Celsius, the temperature drops the most, with a significantly smaller drop between 400 and 600 degrees Celsius. The samples were subjected to a temperature gradient because of the ISO 834 curve's abrupt starting temperature increase is largely to blame for this fluctuation pattern. The concrete sample' internal temperatures rose to their highest levels at various depths., as previously mentioned, were often below the traditional critical range, where concrete suffers severe permanent structural damage (between 300 and 400 °C) Click or tap here to enter text..

On the other hand, the findings of Chen et al. Click or tap here to enter text. showed that the concrete's compressive strength and stiffness are considerably decreased after subjection to elevated temperatures. Moreover, the results revealed that the steel filaments are added to help for prevention of spalling, and significantly enhances the cracking behavior and ductility associated with the RCA following the subjection to high temperatures. As such, the authors conclude that RCA is appropriate for use in building construction.

Abedalqader and his colleagues Click or tap here to enter text. highlighted in their experimental report that small replacement quantities of reclaimed asphalt pavement (RAP) are utilised, the deterioration in mechanical characteristics is more pronounced. However, when significant amounts of RCA replacement are used, the features are reduced more noticeably. Even though these mixtures were formed completely of recycled aggregates, the loss in mechanical characteristics under exceedingly hot situation for RAP-RCA mixtures are comparable to NA, RAP, and RCA alone mixtures. The compressive, splitting tensile, flexural, and modulus of elasticity are lowing when the substitution ratio of RAP and RCA rise for constant temperature. The ideal recycled mixture for use at high temperatures is 90% NA, 10% RAP for RAP mixes, 80% NA, and 90% RCA, 10% RAP mixtures. The mechanical qualities of RCA can still be employed in concrete mixtures even when they degrade at high temperatures since efforts to RCA and RAP's detrimental effects on the environment and public health are lessened, outweighing any decline.

4. Thermal properites of rca

4.1 Fire Resistance of RCA

According to Gales et al .'s research, The standard weight Eurocode guidelines for mechanical property reduction are satisfied by RCA that incorporates up to 100 percent recycled aggregate. They examined the microstructure of RCA and found that the mechanical properties of the material are significantly influenced by the source of the recycled aggregate. Mechanical characteristics, for example, indicated for every single percentage increasement in recycled aggregate, retained value decreases by 0.2 percent with 500°C. In relation to assemblies, Abed showed that supplementary cementitious materials when used with RCA improve resistance to fire. The finds also showed that the inclusion of RCA assemblies such as pulverized slag and ash in blended cement or Portland cement can largely maintain the RCA concrete's mechanical properties at a higher-level following heating to an elevated temperature.

Some controversial opinion was overview by Bruno Click or tap here to enter text., the inferior mechanical behaviour of RCA concrete is due to the RCA's unique porous microstructure and weaker interfacial transition zones. The superior behaviour found in the studies, on the other hand, was attributable to an improved thermal compatibility. Thermal conductivity diminishes as temperature rises, and specific heat produces a variety of consequences. Thermal characteristics are typically unaffected using RCA. Additionally, full-scale testing on concrete columns built with RCA were conducted. The results showed that concrete built with NA had higher fire resistance ratings. When RCA beams were tested, the experimental bending seconds prior to collapse exceeded the code limitations.

As a result of Chen's discovery of the residual thermal properties of fire resistance, recycled pebble concrete aggregate has a low ductility and peak stresses and strains are considerable around 20–22 °C. As the temperature rises, RAC's peak strain and compressive strength both declines, while ductility drops by 10%. The compressive strength and peak strain grow as the aggregate substitution percentage rises, but RCA's capacity to deform without breaking swings within 8%. An RCA with a 50% aggregate replacement rate demonstrates good endurance to severe temperature variation, and water spraying from a fire hydrant under conditions of extreme temperature exposure. This entire replacement rate is advised to be applied.

4.2 Impact of RCA Mix

4.2.1 Impact of Different Mix Percentage

With the substitution on different percentage RCA, the proportional remaining compressive strength demonstrates an increase with the respective of more percentage of RCA. Concrete built with varying recycled aggregate replacement ratios and its residual compressive strength was investigated by Xiao and Zhang Click or tap here to enter text.. Recycled siliceous aggregate was employed as the recycled aggregate. They discovered that when up to 30% recycled aggregate was added to conventional aggregate concrete, the residual strength deteriorated. However, remaining compressive strength was greatly increased when the replacement rate was increased to 50%. Abed organized and analysis the concept of over 50% of combining recycled aggregate would significantly affect the residual compressive strength, as shown in Figure 2.

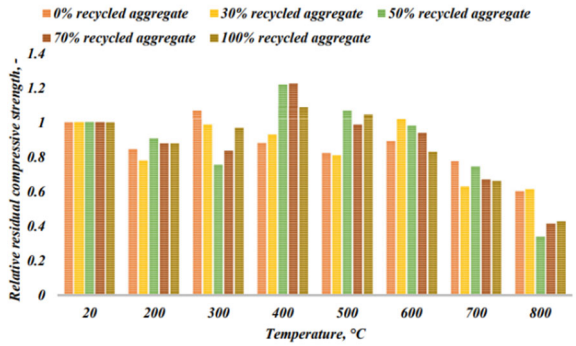

Figure 2. Various recycled aggregate replacement ratios and different relative compressive strengths were compacted at a certain temperature .

The remaining mechanical qualities of concrete after being exposed to high temperatures and having a low water to cement ratio are improved by up to 50% recycled aggregate, the scientists found after examining the performance of RCA over time. Click or tap here to enter text. The significant contact region with mortar and RCA, as well as their thermal expansion similarities, were factors in this behaviour. The long-age data, on the other hand, revealed that the age of concrete affects its reactivity under situation affected by high temperatures. Due to variations in the moisture content and the binder's hydration process, concrete aging had an impact on its responsiveness to high temperatures, especially if supplemental cementitious material was utilised.

4.2.2 Impact of RCA With Multiple Periods of Time

With different study on the impact of RCA cause during different periods of time, the conclusions were made that the addition of RCA in the beam would results in the reduction of load carrying capacity and residual strength. Buller et al investigated that rich mixed RCA beam have a better performance than normal mixed RCA beam especially on the properties like residual strength and flexural strength.

According to Abed et al research, concrete performs differently depending on how long it has been exposed to high temperatures (between 90 and 270 days). To measure the entire area within the range of the comparison residual strength from 20 to 800 Celsius, the scientists developed a new metric called heat resistance. The binder's hydration process and variations in its water content changes were the primary causes of the residual strength change over time. Therefore, Continual evaluation of the characteristics of concrete closely mimics how concrete structures behave. It displays the heat resistance of the compressive strength for different mixes made with 0%, 25%, or 50% RCA. It is advised to continue the study of concrete's fire resistance at ages beyond a short term to accurately depict the mechanical behaviour of RCA (See Figure 3) .

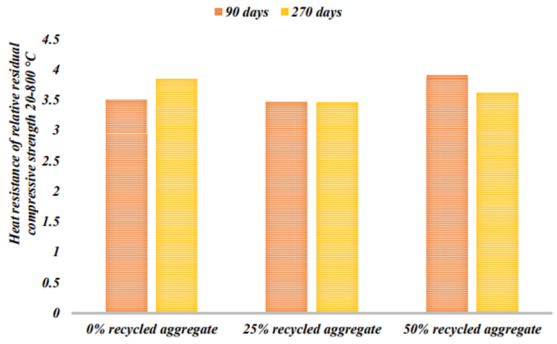

Figure 3. Heat resistance of different percentages mixed recycled aggregate with age of 90 days and 270 days .

5. Conclusion

The impact of RCA, its mechanical behavior post fire residual and the thermal properties of RCA were reviewed and discussed. The importance of studying RCA were addressed.

RCA with 50 percentage and more mixed in the concrete are giving a better performance than the natural aggregate and normal mixed RCA.

RCA has better mechanical and thermal behavior than the NA in general.

There are limited time researches which impact on RCA, the focus in experiment RCA in longer term need to be addressed in the future.

Focus on experiment last longer than one year or two is necessary due to the use of RCA in building constructions.

From current finding on amount of percentage mixed RCA, the exact amount which has the best performance would be a focus in future experiment.

References

[1] J. Gales, T. Parker, D. Cree, and M. Green, Fire Performance of Sustainable Recycled Concrete Aggregates: Mechanical Properties at Elevated Temperatures and Current Research Needs, Fire Technology, vol. 52, no. 3, pp. 817–845, May 2016, DOI: 10.1007/s10694-015-0504-z.

[2] A. Zawadowska, L. Giuliani, and K. D. Hertz, Experimental study on the mechanical properties of fire exposed concrete, Safety Science, vol. 142, Oct. 2021, DOI: 10.1016/j.ssci.2021.105357.

[3] J. Novak and A. Kohoutkova, Mechanical properties of concrete composites subject to elevated temperature, Fire Safety Journal, vol. 95, pp. 66–76, Jan. 2018, DOI: 10.1016/j.firesaf.2017.10.010.

[4] J. P. B. Vieira, J. R. Correia, and J. de Brito, Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates, Cement and Concrete Research, vol. 41, no. 5, pp. 533–541, May 2011, DOI: 10.1016/j.cemconres.2011.02.002.

[5] W. Safwat Fahmy, E. Abdel-Latif Heneidy, E. Emam Ali, and I. Saad Mohammed Agwa, "MECHANICAL PROPERTIES OF CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATES SUBJECTED TO DIFFERENT FIRE DURATIONS," 2011.

[6] M. Abed, R. Nemes, and É. Lublóy, The impact of time on the heat resistance of self-compacting high-performance concrete incorporated with recycled martials, Journal of Thermal Analysis and Calorimetry, vol. 138, no. 1, pp. 35–45, Oct. 2019, DOI: 10.1007/s10973-019-08263-z.

[7] D. Cree, M. Green, and A. Noumowé, Residual strength of concrete containing recycled materials after exposure to fire: A review, Construction and Building Materials, vol. 45. pp. 208–223, 2013. DOI: 10.1016/j.conbuildmat.2013.04.005.

[8] M. A. Abed, Indirect Evaluation of the Compressive Strength of Recycled Aggregate Concrete at Long Ages and after Exposure to Freezing or Elevated Temperatures, Russian Journal of Nondestructive Testing, vol. 57, no. 3, pp. 195–202, Mar. 2021, DOI: 10.1134/S1061830921030025.

[9] B. A. Memon, A. Salam Buller, I. H. Sodhar, A. Hafeez Buller, A. Memon, and I. N. Sodhar, Modeling Fire Effect of Reinforced Recycled Aggregate Concrete Beams by Regression Analysis, International Journal on Emerging Technologies, vol. 12, no. 1, pp. 97–102, 2021, DOI: 10.13140/RG.2.2.29740.39048.

[10] G. M. Chen, Y. H. He, H. Yang, J. F. Chen, and Y. C. Guo, Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures, Construction and Building Materials, vol. 71, pp. 1–15, Nov. 2014, DOI: 10.1016/j.conbuildmat.2014.08.012.

[11] A. Abedalqader, N. Shatarat, A. Ashteyat, and H. Katkhuda, Influence of temperature on mechanical properties of recycled asphalt pavement aggregate and recycled coarse aggregate concrete, Construction and Building Materials, vol. 269, Feb. 2021, DOI: 10.1016/j.conbuildmat.2020.121285.

[12] B. Fernandes, H. Carré, J. C. Mindeguia, C. Perlot, and C. la Borderie, Effect of elevated temperatures on concrete made with recycled concrete aggregates - An overview, Journal of Building Engineering, vol. 44. Elsevier Ltd, Dec. 01, 2021. DOI: 10.1016/j.jobe.2021.103235.

[13] Z. Chen, R. Xu, and H. Liang, Residual mechanical properties and numerical analysis of recycled pebble aggregate concrete after high temperature exposure and cooled by fire hydrant, Construction and Building Materials, vol. 319, Feb. 2022, DOI: 10.1016/j.conbuildmat.2021.126137.

[14] J. Z. Xiao and C. Z. Zhang, Fire Damage and Residual Strengths of Recycled Aggregate Concrete, Key Engineering Materials, vol. 348–349, 2007, DOI: 10.4028/www.scientific.net/kem.348-349.937.

[15] M. A. Abed and E. Lubloy, Understanding the effect of recycled concrete aggregate and cementitious materials on concrete's fire resistance, Journal of Structural Fire Engineering, 2021, DOI: 10.1108/JSFE-09-2021-0056.

[16] Abed, M., Nemes, R. and Lublóy, É., 2020. Performance of Self-Compacting High-Performance Concrete Produced with Waste Materials after Exposure to Elevated Temperature. Journal of Materials in Civil Engineering, 32(1).

[17] B. A. Memon, M. Oad, S. Sohu, and A. H. Buller, 24-hour Fire Produced Effect on Reinforced Recycled Aggregates Concrete Beams, Technology & Applied Science Research, vol. 9, no. 3, pp. 4213–4217, 2019, DOI: 10.13140/RG.2.2.26736.10245.