International Journal of GEOMATE, May, 2026 Vol.30, Issue 141, pp.153-160
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2026.141.g15374
Geotechnique, Construction Materials and Environment

# STUDY ON THE BEHAVIOR OF RECYCLED AGGREGATE CONCRETE UNDER HIGH TEMPERATURE EXPOSURE AND RECOVERY THROUGH RE-CURING

Husnah[1,2], Herlien Dwiarti Setio[1], *Ivan Sandi Darma[1] and Patria Kusumaningrum[1]

[1]Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Indonesia
[2]Department of Civil Engineering, Universitas Abdurrab, Indonesia

*****Corresponding Author, Received: 27 June 2025, Revised:31 Jan. 2026, Accepted: 05 Feb. 2026

**ABSTRACT:** The effect of high-temperature damage on Recycled Aggregate Concrete (RAC) remains understudied. Strength reduction due to high-temperature exposure is caused by a thermal expansion mismatch between the aggregate and the cement paste. This mismatch generates thermal stresses in the Interfacial Transition Zone (ITZ), which significantly impacts the performance of RAC, particularly during the re-hardening phase after heat exposure. This study investigated the effectiveness of re-hardening as a method to restore the compressive strength of RAC that has been exposed to high temperatures. Recycled Aggregate Concrete (RCA) was sourced from concrete waste with original concrete compressive strengths of 25 MPa and 40 MPa at replacement levels of 0%, 25%, 50%, 75%, and 100%. Mixes with water-cement ratios of 0.3, 0.45, and 0.5 were cured for 28 days before being heated to 550°C and 800°C, respectively. Compressive strength tests showed that as the RCA content increased, the concrete experienced a greater decrease in compressive strength at 800°C, with conventional concrete exhibiting the sharpest decrease. Seven days of water curing restored 44–87% of the compressive strength of concrete with RCA 0–100%, w/c 0.45, and 0.5, but w/c 0.3 required a longer time due to its low permeability. More cracks and pores facilitate hydration recovery in normal concrete, while high-strength concrete (w/c 0.3) limits water penetration. For RCA 25 and 40, water reinfiltration after exposure to high temperatures can restore pre-fire strength and halt further degradation, significantly improving post-fire performance.

*Keywords: RCA, RAC, High Temperature Exposure, Concrete Compressive Strength, Re-Curing*

## 1. INTRODUCTION

Construction and demolition generate concrete waste, while the demand for concrete remains high. One solution to minimize waste and achieve sustainable construction is the recycling of waste into recycled aggregates. Previous research [1] has shown that concrete using Recycled Concrete Aggregate (RCA) can exhibit properties comparable to conventional concrete and meet structural performance requirements, even at high replacement rates. Although substantial progress has been achieved in recent years, several challenges still hinder the widespread adoption of RCA. One such challenge is the limited understanding of how recycled aggregate concrete responds to high-temperature exposure. This is crucial because the presence of residual mortar in recycled aggregates introduces an additional phase into the concrete, potentially resulting in behavior at high temperatures that differs significantly from normal concrete [2]. Aggregates constitute approximately 60–75% of the total volume of concrete, so the thermal behavior of concrete is highly dependent on the type of aggregate used, as different aggregates react differently to high-temperature exposure [3]. The decrease in concrete strength at high temperatures is primarily due to the mismatch between the thermal expansion of the aggregate and the cement paste. This mismatch generates thermal stresses in the Interfacial Transition Zone (ITZ). When stress exceeds the tensile strength of the cement paste, it can cause radial cracks in the paste originating from the ITZ, which can connect with cracks from the nearby ITZ region [4]. Therefore, aggregate selection plays a crucial role in maintaining the stability of concrete under thermal stress. In the case of Recycled Aggregate Concrete (RAC), this is particularly important, as recycled aggregates can exhibit diverse responses to high-temperature exposure [5]. Furthermore, understanding how concrete behaves under high-temperature conditions is crucial, as fire safety plays a crucial role in the structural design of concrete buildings [4]. Although the general behavior of concrete at high temperatures is relatively well understood, heat exposure triggers a series of physicochemical transformations that affect its thermomechanical characteristics. These changes can significantly reduce the material's mechanical performance, especially as the temperature increases. Differences in cracking and dehydration are expected in RAC, potentially affecting the benefits of re-curing. Research results in several literatures [2,6–10] have yielded contradictory results. Gales, [11] reported that concrete containing recycled aggregates exhibited lower relative compressive strength compared to concrete made from natural aggregates, with strength decreasing with increasing proportion of recycled aggregates. This decrease is due to the lower strength and larger Interfacial Transition Zone (ITZ) associated with recycled aggregates. In contrast, Zhao [12] found that concrete with recycled aggregates performed similarly to concrete with natural aggregates. In addition, Sarhat [13] observed an improvement in the mechanical behavior of concrete containing recycled aggregates [14]. This improvement likely arises from a closer match of thermal expansion between the recycled aggregates and the cement paste, which serves to suppress the propagation of cracks within the paste and at the surface. Thus, this study focuses on the investigation of CRCA (Coarse Recycled Aggregate). CRCA is derived from concrete waste, with varying strength grades of waste concrete. The characteristics of CRCA are as follows: 30-60% mortar residue, angular shape, and rough texture, large porosity (due to the presence of mortar residue), and an Interfacial Transition Zone (ITZ). Clean CRCA requires special treatment, but the use of CRCA with mortar residue is more practical, efficient, and utilizes unhydrated cement. used to produce new concrete, called Recycled Aggregate Concrete (RAC), and evaluate the compressive strength and the influence of RAC characteristics before and after exposure to high temperatures and after recuring. This study addresses the gap by (i) varying the original quality of RCA (ii) comparing the settlement coefficient of RAC upon exposure to high temperatures against eurocode 2 (iii) applying recuring to RAC after exposure to high temperatures.

## 2. RESEARCH SIGNIFICANCE

Recycled Aggregate Concrete (RAC) is recognized as an environmentally friendly material in civil engineering due to its sustainability advantages [14,15]. However, its compressive strength tends to decline markedly when subjected to elevated temperatures, such as those experienced during fire events. This study examines the performance of RAC after exposure to high temperatures and explores the effectiveness of re-curing as a method for strength recovery. Concrete samples were heated to 550°C and 800°C, then underwent a controlled re-curing process for a defined period. This study provides insights for structural rehabilitation using recycled materials under thermal stress conditions.

## 3. METHODS

This study investigates the presence of Unhydrated Cement Granules (UCG) in Recycled Concrete Aggregate (RCA) using SEM and XRD analysis. SEM was conducted at 15 kV, 10 mm working distance, 2000x magnification, and 10 μm layer thickness. XRD was performed using Rigaku SmartLab (θ–2θ mode, Cu $K\alpha_1$, 40 kV, 30 mA, 10°–70° range). Recycled concrete aggregates (RCA) obtained from original concrete with compressive strengths of 25 MPa and 40 MPa were incorporated into new concrete mixtures at replacement levels of 50% and 100%, using water-to-cement ratios of 0.30 and 0.45. After a 28-day curing period, the RAC specimens were subjected to temperatures of 550°C and 800°C to assess the decomposition of the C-S-H phase. The impact of this thermal exposure was analyzed by measuring the compressive strength of the concrete both immediately after heating and following a re-curing treatment

## 4. RESULT AND DISCUSSION

RCA morphology testing using SEM to identify the possible presence of UCG minerals in RCA, which affect the mechanical behavior of RAC before and after exposure to high temperatures. This test was carried out at a magnification level of 2000x. The results of the RCA morphology test can be seen in Fig.1, while the identification of mineral chemical compounds can be seen in Fig. 2.

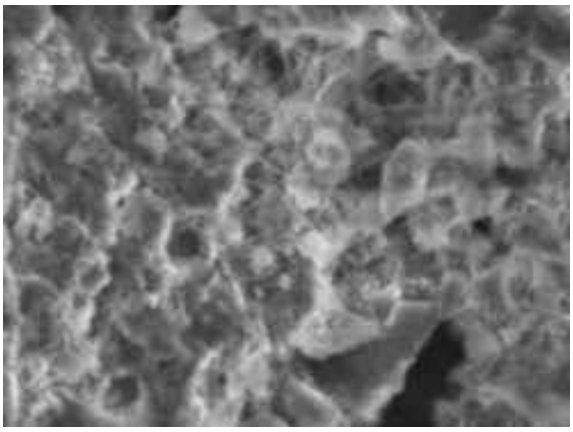


Fig.1 2000x magnification level

Fig.1 shows the presence of C3S, C2S, CSH, CH, ettringite and pores in RCA which affect the mechanical behavior of RAC.

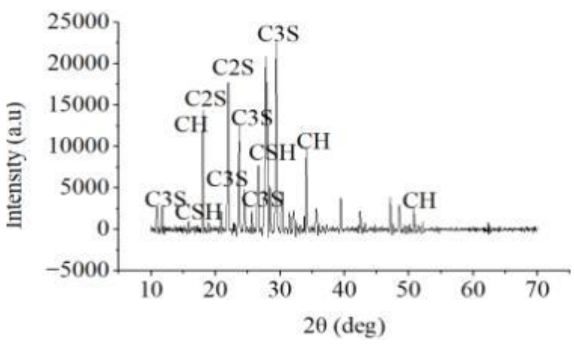



Fig.2 Mineral chemical compounds in RCA

Figure 1 shows the presence of hydration products such as C-S-H gel and calcium hydroxide ($Ca(OH)_2$) crystals in the aged cement paste. Furthermore, voids and microcracks are also present, which are factors that influence the physical and mechanical properties of recycled aggregate.

### 4.1 Effect of temperature on concrete fc' based on the original quality of RCA

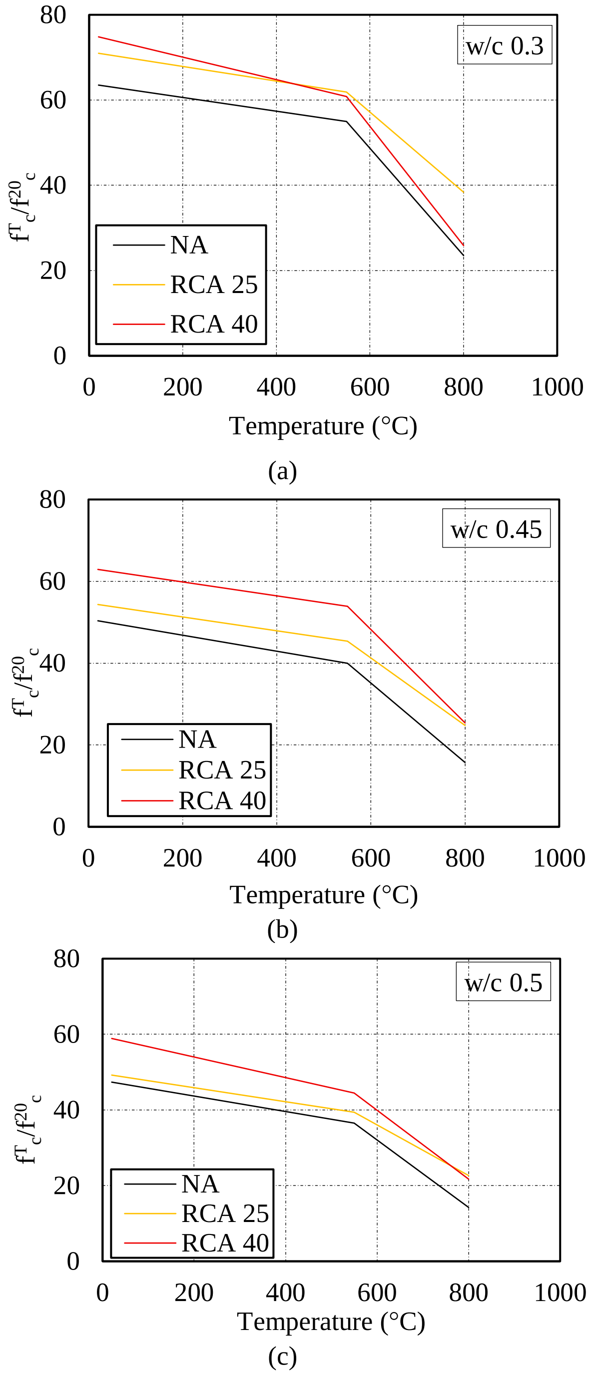



Fig.3 Effect of temperature on concrete fc' based on the original quality of RCA (a) w/c 0.3 (b) w/c 0.45 (c) w/c 0.5

The original quality of the concrete used as the source of RCA (25 MPa and 40 MPa) affects the performance of recycled concrete at high temperatures. This is evident from the compressive strength that can still be maintained at medium temperatures. However, at extreme temperatures (>600 °C), both NAC and RCA of 25 MPa and 40 MPa qualities experience degradation due to exposure to high temperatures. Therefore, it can be concluded that the higher the original quality of RCA, the better the resistance of RAC concrete to the effects of high temperatures, although under extreme conditions all original qualities of RCA show a significant decrease in strength. The test results show that concrete with original RCA of 25 MPa and 40 MPa qualities has a higher residual strength than concrete with natural aggregate (NA) after exposure to high temperatures. This indicates that the presence of old mortar in RCA can act as an additional layer of protection against thermal damage, so that RAC is able to maintain its compressive strength better than NAC at extreme temperatures. This finding is in line with the results of research [16-18], who emphasized that the original quality of RCA is the main determining factor in the mechanical performance of recycled concrete at high temperature exposure.

### 4.2 Effect of RCA 25 Mpa's Percentage on concrete fc' after exposure to high temperatures

Figure 4 (a), (b), (c) shows the relationship between exposure temperature and relative compressive strength of concrete ($f'c^{T}$ / $f'c^{20°}C$) with variations in recycled aggregate (RCA) content at fixed water-cement ratios of 0.3, 0.45 and 0.5. In general, all specimens experienced a decrease in compressive strength as the heating temperature increased. This decrease was caused by the degradation of the concrete microstructure due to high temperatures, the formation of thermal cracks, and the release of water vapor from the pores of the concrete. The performance of RAC was relatively stable; temperatures of 550°C and 800°C Optimum 50% RCA NAC Temperature 800°C decreased drastically by 81%. This phenomenon indicates that the use of RCA is able to improve the thermal resistance of concrete. RCA allows for better thermal expansion compatibility between aggregate and cement paste, thereby reducing stress concentration and microcracking at high temperatures. Thus, the use of recycled aggregate is not only environmentally friendly but can also improve the performance of concrete under extreme conditions such as exposure to high temperatures. The same RCA, under any conditions, the greater the use of RCA results in a greater reduction in strength, especially at a temperature of 800°C, Conventional concrete has the greatest reduction in strength. Because RCA and cement paste have a suitable thermal expansion coefficient, internal stress is smaller, micro/macro cracks are reduced, resulting in a small reduction in strength and an increase in residual mechanical properties after exposure to high temperatures.

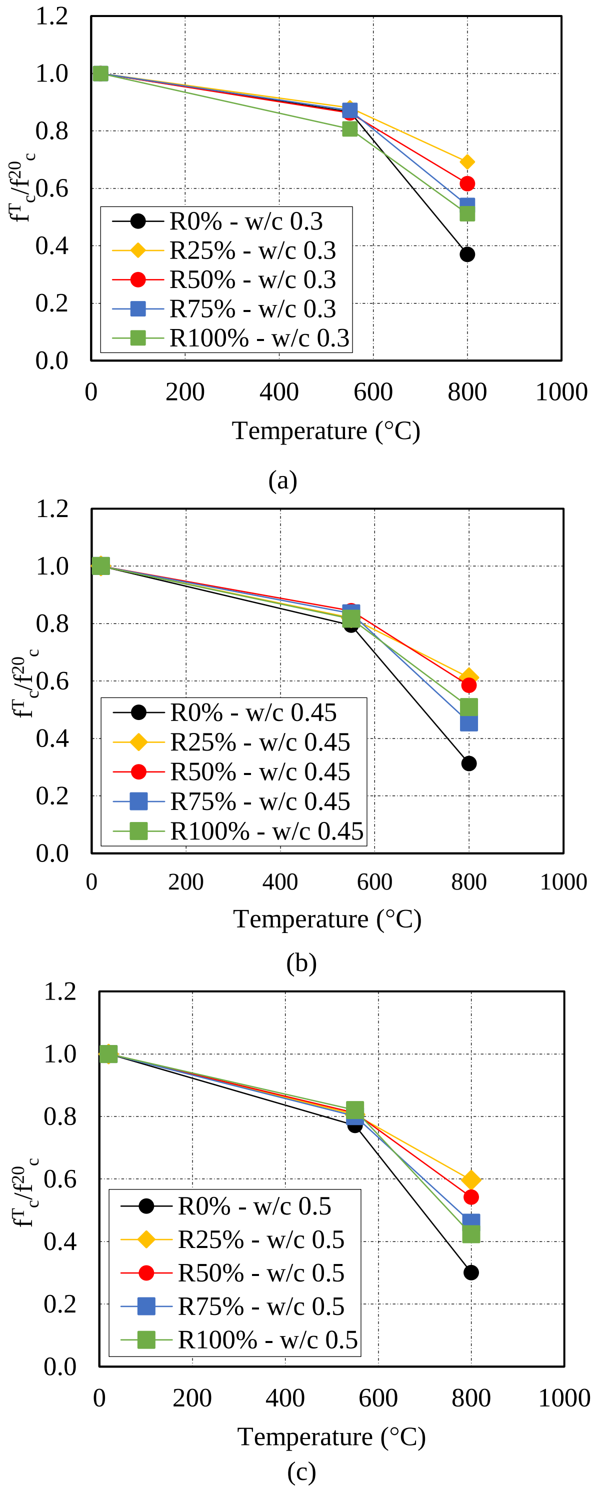
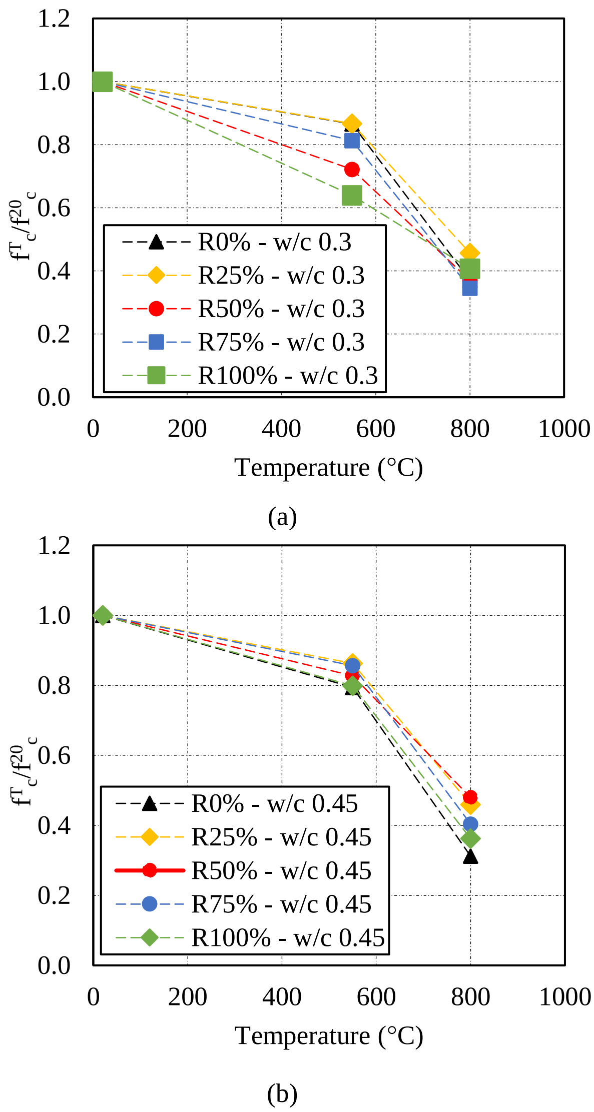
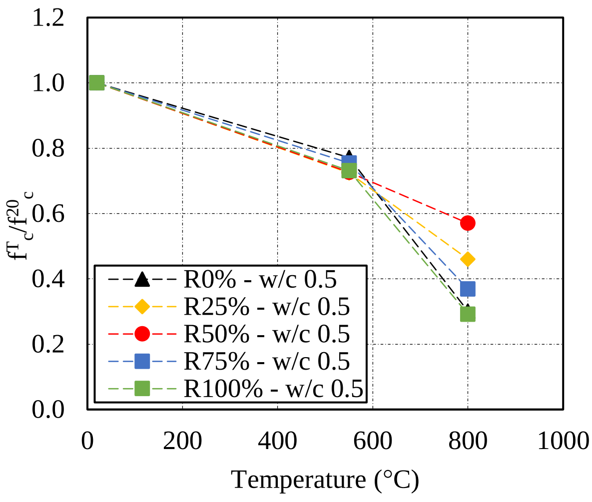



Fig.4 Coefficient of Decrease in Compressive Strength of RCA 25 MPa Concrete (a) w/c 0.3 (b) w/c 0.45 and (c) 0.5

### 4.3 Effect of RCA 40 Mpa's Percentage on concrete fc' after exposure to high temperatures

Microstructural degradation of concrete due to high temperatures. Thermal cracks form and water vapor escapes from the pores of the concrete. The greater the amount of RCA used, the greater the strength loss, especially at temperatures above 800°C. Conventional concrete experiences the greatest strength loss. RCA and cement paste have compatible coefficients of thermal expansion, resulting in lower internal stresses, reducing micro/macrocracking, resulting in less strength loss and improved residual mechanical properties after high temperatures. Interestingly, despite the strength reduction of RCA, some mixture variations (such as R25% or R50%) still show superior resistance compared to R100%. This suggests that the use of RCA in moderate proportions is still feasible for non-structural applications or at moderate temperatures.

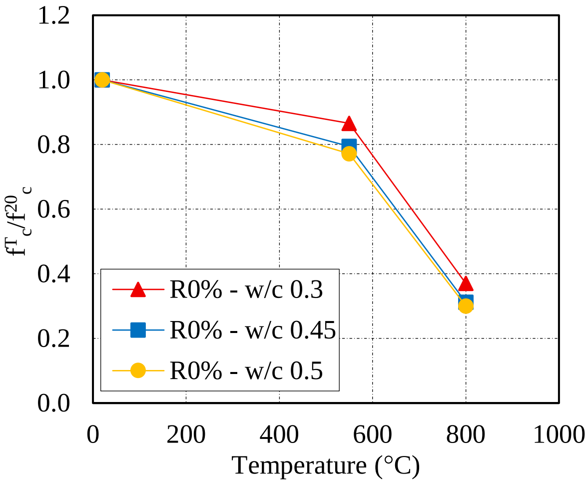




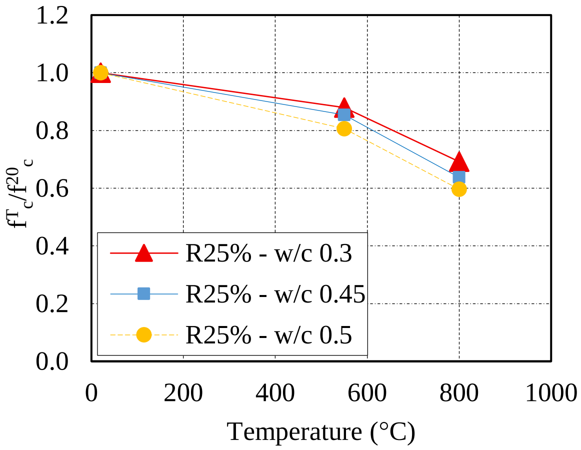

(c)

Fig.5. Coefficient of Decrease in Compressive Strength of RCA 40 MPa Concrete (a) w/c 0.3 (b) w/c 0.45 and (c) 0.5

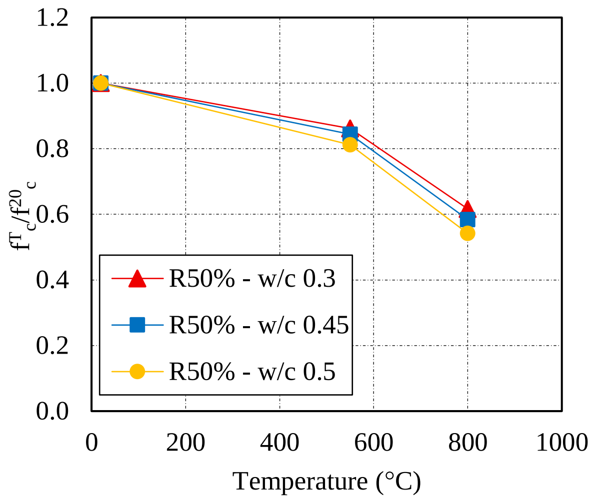
**4.4 Effect of w/c ratio on concrete fc' after exposure to high temperatures**



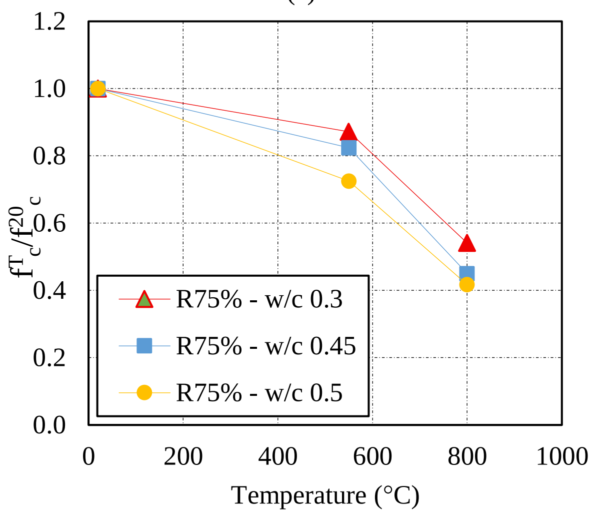

(a)



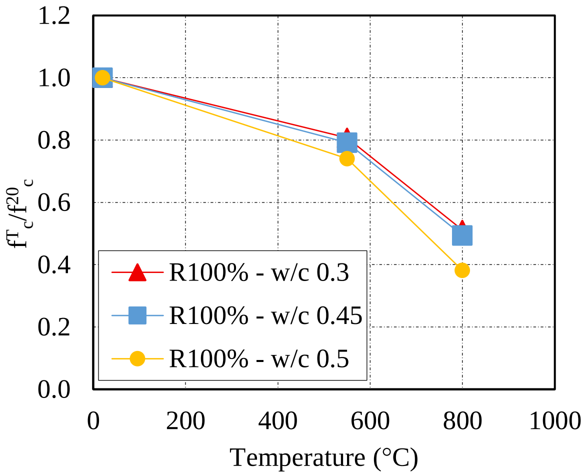

(b)




(c)




(d)




(e)

Fig.6 Concrete Compressive Strength Decrease Coefficient against Water Cement Ratio Variation (a) R 0% (b) R 50% and (c) R 100%

The higher the w/c ratio, the higher the reduction in concrete strength after exposure to high temperatures, the more significant the reduction in post-burning compressive strength. Concrete with a lower w/c (0.3) has a greater residual strength ratio. This occurs because a low w/c produces denser concrete, fewer pores, and stronger bonds between particles, making it more resistant to damage due to high temperatures. Based on the graph, it can be concluded that the water-cement ratio (w/c) has a significant effect on the thermal resistance of concrete with 25% RCA, 50% RCA, 75% RCA and 100% RCA. Concrete with a w/c of 0.3 shows the best performance against high temperatures, maintaining more than 86% of its strength at 550°C and about 45% at 800°C. Conversely, a w/c of 0.5 shows the most drastic reduction in strength. This confirms that a low w/c is important to increase the resistance of concrete to thermal damage.

### 4.5 Compressive strength comparison of concrete with recycled, silica, and calcareous aggregates.

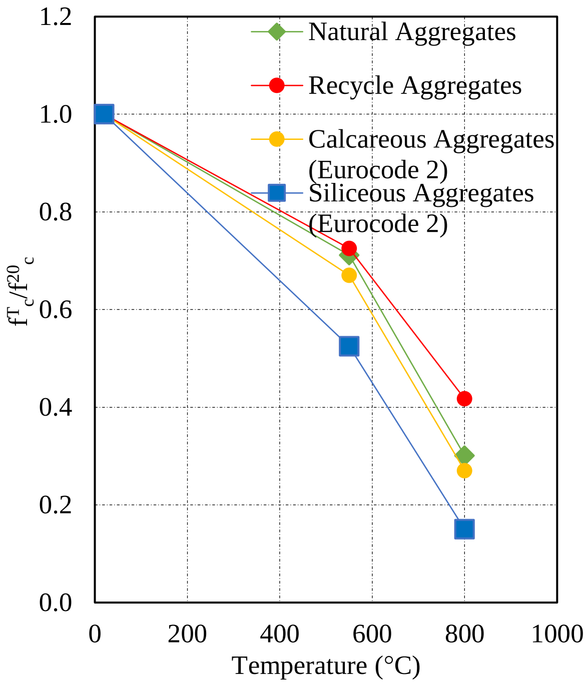



Fig.7 Comparative Analysis of Compressive Strength Reduction Coefficients in Recycled, Silica, and Calcareous Aggregate Concrete

The coefficient of settlement of recycled aggregate concrete under high temperature exposure was compared with the coefficients of settlement of silica aggregate and lime aggregate concrete. The coefficients of settlement of silica aggregate and Calcareous aggregate concrete are specified in Eurocode 2: Design of Concrete Structures - Structural Fire Design 19]. The natural aggregate used in this study was calcareous aggregate, as seen in Figure 7. The coefficient of settlement of recycled aggregate concrete was close to that of natural aggregate. Natural aggregate and calcareous aggregate showed fairly similar thermal performance, but still lower than that of recycled aggregate concrete. Siliceous aggregate concrete experienced the most drastic strength decline, with a relative strength of only about 0.1 at 800°C. These results demonstrate that aggregate selection is crucial in designing structures subject to high temperatures, such as industrial structures, tunnels, or fire-resistant buildings.

### 4.6 The effect of re-curing concrete after exposure to high temperatures on compressive strength

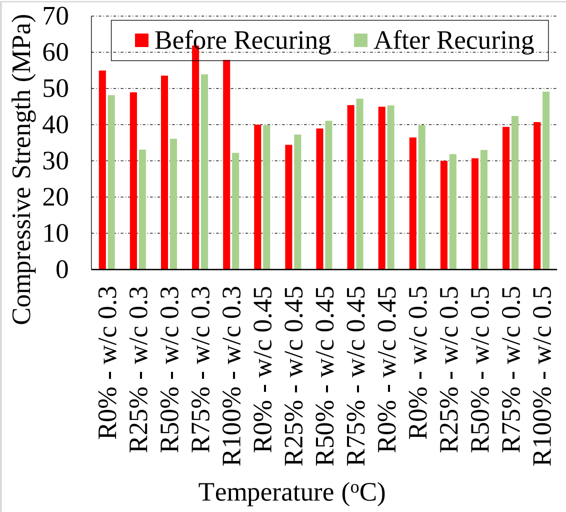



Fig.8 Residual Compressive Strength at 550°C After Recurring RCA 25 MPa

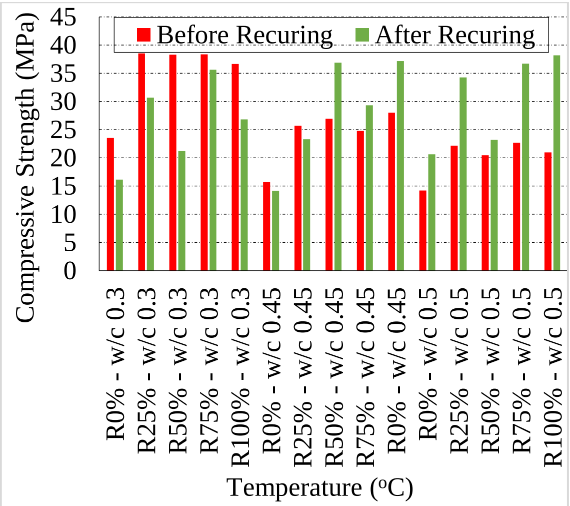



Fig.9 Residual Compressive Strength at 800°C Temperature After Recuring RCA 25 Mpa

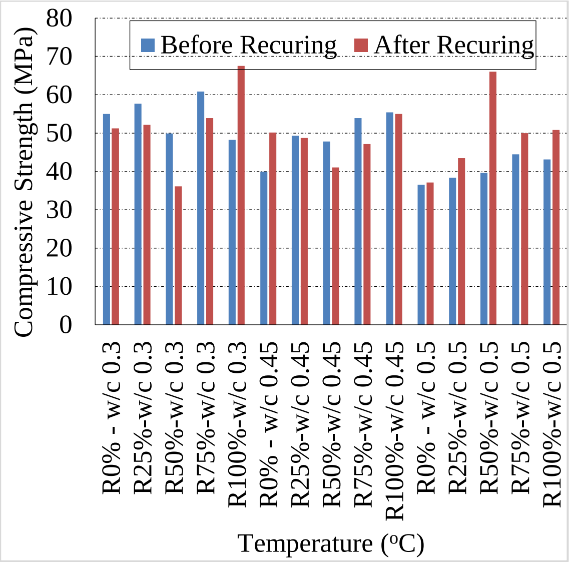



Fig.10 Residual Compressive Strength at 550ºC Temperature After Recuring RCA 40 Mpa

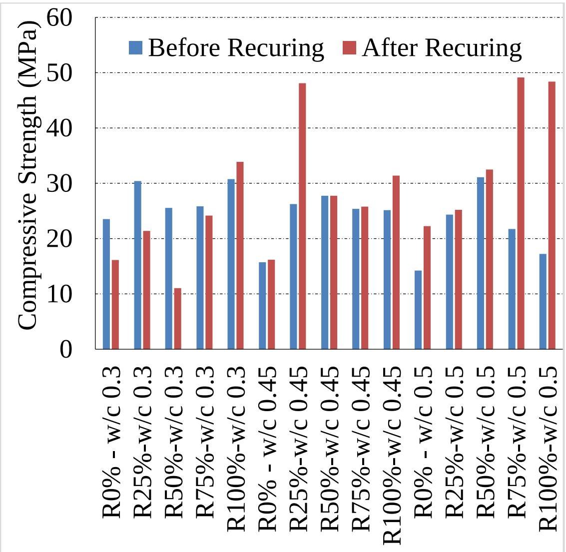



Fig.11 Residual Compressive Strength at 800ºC Temperature After Recuring RCA 40 Mpa

Previous research [20] has shown that recuring in water on concrete exposed to high temperatures can restore the concrete's strength to its original state before exposure to high temperatures. This healing can occur due to the regeneration of hydration products from calcium oxide (CaO) rehydration and the hydration of previously unhydrated cement particles. In this study, recuring was carried out by immersing the samples in water for 7 days. Re-curing is the process of restoring moisture to concrete after drying or thermal damage. In recycled aggregate concrete (RAC), re-curing plays a crucial role in improving crack characteristics and reducing the effects of dehydration.

Seven days of water re-curing restored 44–87% compressive strength in concrete with RCA 0–100%, w/c 0.45, and 0.5, but w/c 0.3 required longer due to its low permeability. More cracks and pores facilitate hydration recovery in regular concrete, while high-strength (w/c 0.3) concrete limits water penetration. For RCA 25 and 40, water re-curing after high temperature exposure can restore pre-fire strength and halt further degradation, significantly improving post-fire performance.

## 5. CONCLUSION

1. When RCA content increases (with similar strength), concrete experiences a greater loss in compressive strength at 800°C, with conventional concrete showing the sharpest decline.
2. Water re-curing for 7 days effectively halts degradation and restores 44–87% compressive strength in concrete (0–100% RCA, w/c 0.45 and 0.5), but mixes with w/c 0.3 require extended re-curing for optimal recovery.

## 6. ACKNOWLEDGMENTS

We gratefully acknowledge the Faculty of Civil and Environmental Engineering (FTSL), Institut Teknologi Bandung (ITB), for their financial support, which was essential to the completion of this research

## 7. REFERENCES

1. Vieira J P B, Correia J R and De Brito J, Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. Cement and Concrete Research, 41(5), 2011, pp.533–541. https://doi.org/10.1016/j.cemconres.2011.02.002
2. Beatriz da Silva J, Pepe M and Toledo Filho R D High temperatures effect on mechanical and physical performance of normal and high strength recycled aggregate concrete. Fire Safety Journal, (117) 2020, pp. 103222 https://doi.org/10.1016/j.firesaf.2020.103222
3. Safiuddin M, Alengaram U J, Rahman M M, Salam M A and Jumaat M Z, Use of recycled concrete aggregate in concrete, Journal of Civil Engineering and Management 19(6), 2013, pp.796-810. https://doi.org10.3846/13923730.2013.799093
4. Pepe M, A Conceptual Model for Designing Recycled Aggregate Concrete for Structural Applications, A Book Springer International Publishing, 2015 ISBN: 978-3-319-26472-1 https://doi.org10.1007/978-3-319-26473-8
5. Tam V W Y, Soomro M and Evangelista A C J, A review of recycled aggregate in concrete applications (2000–2017) Construction and Building Materials, (172), 2018, pp. 272–292

https://doi.org/10.1016/j.conbuildmat.2018.03.240

6. Chen Z, Chen J, Ning F and Li Y, Residual properties of recycled concrete after exposure to high temperatures, Magazine of Concrete Research 71(15), 2019, pp. 781–793 https://doi.org/10.1680/jmacr.17.00503
7. Pliya P, Hajiloo H, Romagnosi S, Cree D, Sarhat S and Green M F, the compressive behaviour of natural and recycled aggregate concrete during and after exposure to elevated temperatures, Journal of Building Engineering (38), 2021, pp. 102214 https://doi.org/10.1016/j.jobe.2021.102214
8. Kou S C, Poon C S and Etxeberria M, Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures, Cement and Concrete Composites, (53), 2014, pp. 73–82 https://doi.org/10.1016/j.cemconcomp.2014.06.001
9. Chen G M, He Y H, Yang H, Chen J F and Guo Y C, Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures, Construction Building Materials (71), 2014 pp. 1–15 https://doi.org/10.1016/j.conbuildmat.2014.08.012
10. Dong H, Cao W, Bian J and Zhang J, The fire resistance performance of recycled aggregate concrete columns with different concrete compressive strengths Materials, 7(12), 2014, pp. 7843–7860 https://doi.org/10.3390/ma7127843
11. Gales J, Parker T, Cree D and Green M, Fire Performance of Sustainable Recycled Concrete Aggregates: Mechanical Properties at Elevated Temperatures and Current Research Needs, Fire Technology (52), 2016, pp. 817–845
12. Zhao H, Liu F and Yang H, Thermal properties of coarse RCA concrete at elevated temperatures, Applied Thermal Engineering, (140), 2018, pp. 180–189 https://doi.org/10.1016/j.applthermaleng.2018.05.032
13. Sarhat S R and Sherwood Edward G, Residual Mechanical Response of Recycled Aggregate Concrete after Exposure to Elevated Temperatures, Journal of Materials in Civil Engineering, 25(11), 2013, pp. 1721–1730 https://10.1061/(ASCE)MT.1943-5533.0000719
14. Silva R V., De Brito J and Dhir R K, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production Construction and Building Materials, (65), 2014, pp. 201–217 https://doi.org/10.1016/j.conbuildmat.2014.04.117
15. Tošić N, Marinković S, Dašić T and Stanić M, Multicriteria optimization of natural and recycled aggregate concrete for structural use, Journal of Cleaner Production (87), 2015, pp. 766–776 https://doi.org/10.1016/j.jclepro.2014.10.070
16. Yang H, Zhao H and Liu F, Compressive Stress–Strain Relationship of Concrete Containing Coarse Recycled Concrete Aggregate at Elevated Temperatures, Journal of Materials in Civil Engineering, 31(9), 2019, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002851
17. Fernandes B, Carré H, Mindeguia J C, Perlot C and La Borderie C, Spalling behaviour of concrete made with recycled concrete aggregates Construction and Building Materials, (344), 2022, pp.128124 https://doi.org/10.1016/j.conbuildmat.2022.128124
18. Zega C J and Di Maio A A, Recycled concrete made with different natural coarse aggregates exposed to high temperature Construction Building Materials, 23(5), 2009, pp. 2047–2052 https://doi.org/10.1016/j.conbuildmat.2008.08.017
19. Bellová M, EUROCODES: structural fire design Procedia Engineering, (65), 2013, pp. 382–386 https://doi.org/10.1016/j.proeng.2013.09.059
20. Henry M, Darma I S and Sugiyama T, Analysis of the effect of heating and re-curing on the microstructure of high-strength concrete using X-ray CT, Construction Building Materials, (67), 2014,pp.37–46 https://doi.org/10.1016/j.conbuildmat.2013.11.007