FIRE PERFORMANCE OF RECYCLED AGGREGATE CONCRETE: CHALLENGES AND FUTURE PROSPECTS


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Dedicated to Prof. György L. Balázs
for his 65th birthday

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The substantial amount of building and demolition waste that is produced worldwide and that is frequently disposed of by dumping and landfilling, which causes social and environmental problems, is discussed in the article. In order to address this issue, recycling technology for C&D trash has been created, and waste from the construction and demolition industries is turned into recycled aggregate that is then used to create recycled aggregate concrete. This strategy might aid in addressing the raw material shortage, cutting waste, and promoting environmentally friendly building methods. The effectiveness of recycled aggregate concrete (RAC) against fire is also explored in the research. The combination of components used, as well as their quality and manufacturing, might affect how fire-resistant RAC is. Because RAC is made of a solid, inert material with less water than traditional concrete, it has been shown to have excellent fire-resistant qualities overall. However, compared to conventional aggregate concrete, RAC may show more spalling and suffer a larger decrease in strength when subjected to high temperatures. The impact of variables like moisture content and compressive strength on the danger of spalling is also highlighted in the paper. According to the study, sustainable concrete built with RAC may, with proper design, meet specified fire design goals, although it may function mechanically less well at extremely high temperatures than conventional concrete.

Keywords: Construction and demolition debris, sustainable concrete, fire resistance, spalling, mechanical performance, traits that prevent fires.

1. INTRODUCTION

Concrete the most common construction material in the world represents the main component of construction and demolition waste (Xiao, Lu, and Ying, 2013). The rapid urbanization in the world has resulted in a significant amount of construction and demolition (C&D) waste, which is commonly disposed of through dumping and landfilling. This leads to social and environmental issues, such as safety problems and pollution of soil and water. To combat this, recycling technology for C&D waste has been developed, and concrete and brick waste are recycled into recycled aggregate for use in preparing recycled aggregate concrete (Vázquez et al., 2014). The construction industry is identified as a major contributor to this issue, the European Union generating approximately 850 million tons of waste per year, or about 31% of overall production (Thomas et al., 2013). However, some researchers have found that the CDW accounts for over 35% of all waste produced in the EU, generating about 1000 million tons of waste per year (Hu et al., 2018). The construction activities in Europe have been growing at an increasing rate due to the increasing demand for raw materials and aggregate production and importation are no longer sufficient to provide all the needed raw materials, and lead to the depletion of natural aggregate resources. In France, quarries are being protected, and aggregate producers are struggling to find workable sites. On the other hand, demolition sites generate significant waste, which is often not reused and limited to road construction. The paper suggests recycling demolition waste as construction materials for structural concrete as a promising alternative, provided that the recycled materials meet the necessary mechanical standards. This approach could help to address the shortage of raw materials, reduce waste, and promote sustainable construction practices (Yuan et al., 2023). Using waste materials in construction aligns with the principles of sustainable development and numerous environmentally friendly production technologies incorporate waste materials as fillers or additions to concrete and other construction materials, such as asphalt. Among the options available, the use of concrete made with recycled aggregates from construction and demolition waste is particularly relevant. This approach has a dual benefit, as it reduces waste accumulation in landfills and limits the consumption of natural aggregates, indirectly controlling the environmental impact of opening new quarries. By reusing waste materials in construction, it is possible to promote sustainable practices and contribute to the circular economy, which can have positive environmental and economic effects (Adessina et al., 2019). However, the direct use of recycled aggregates (RAs) in making concrete is inefficient due to the high-water absorption and porosity of old mortar layer on recycled aggregate. Further, the interfacial transition zones (ITZs) in RAC are different from those of natural aggregate concrete

(NAC). In other words, the amount of RA utilized in RAC is one of the critical factors affecting its mechanical properties (Guo et al. 2018). Recycle aggregate concrete RCA has some distinct differences from natural aggregates (NA), including higher water absorption, higher Los Angeles wear, lower bulk and particle density, and more irregular geometry, which can be attributed to the mortar adhered to the aggregates. However, the rough texture and high porosity of RCA can lead to densification of the interfacial zone and improved performance in concrete (Thomas et al., 2013). Furthermore, concrete being a brittle material composed of aggregates and mortar, which has many microcracks and other defects. Visible cracks propagate from microcracks under load during the service life, reducing the load capacity of the structure at ambient temperature, the use of RAC in high-temperature conditions, such as during a fire, needs further study to ensure its bearing capacity and promote its use as a sustainable construction material (Guo et al., 2018). Fire performance is a critical factor that needs to be considered in RAC structures due to the material's brittleness. Therefore, further studies are necessary to promote the use of RAC in construction (Yuan et al., 2023).

2. PROPERTIES OF RECYCLED AGGREGATE CONCRETE

The ability to explain why RAC can differ significantly when used in concrete can be improved by having a better grasp of how the aggregate transforms after being used in concrete. The study involves discussion on various types of concrete and evaluating their physical characteristics such as absorption, density, porosity, and water permeability, as well as their mechanical properties including compression, tensile strength, Young's modulus, shrinkage, and creep, freezing and thawing etc.

2.1 Mechanical properties of recycled aggregate concrete, factors affecting the mechanical properties

Concrete consists of aggregate, which makes up 70-80% of its volume and is crucial for determining its properties. Coarse aggregate forms the framework of particles that bear the load in a concrete structure, while fine aggregate and cement paste fill in the voids between these particles, affecting the density, cement mortar amount, and performance of the concrete (Bui, Satomi and Takahashi, 2017). The greatest distinguishing aspect of RA is that, in contrast to NA, it is made up of original aggregate and attached mortar. The adhering mortar content tends to be inversely related to specific gravity and proportional to water absorption. The method of manufacturing, the strength of the parent concrete, and the quantity of uses all have an impact on the quality of RA. The mechanical characteristics and durability of RAC are influenced by the RA quality, and when the RA quality is poor or the replacement rate rises, RAC's performance suffers. The main distinction between RA and NA is that the former is composed of attached mortar and original aggregate. The content of the adhering mortar often correlates with water absorption and has an inverse relationship with specific gravity (Kim, 2022). Recycled aggregate concrete is not as strong or durable as natural aggregate concrete because the surface of the recycled aggregate sticks to the mortar, which changes its properties and creates a weak interface between the binder and the aggregate. This weak point depends on the relative strength of old and new mortar, as well as the mass of the interfacial transition zone. The recycled aggregate also has a "wall effect" that leads to a higher water-cement ratio, more pores and cracks, and weaker concrete. Nano silica has been found to accelerate hydration and improve the mechanical properties of the interfacial transition zone, resulting in stronger and less porous concrete. However, excessive use of nano silica can cause problems such as expansion of the silicate polymer, reduced compressive strength, and increased shrinkage and creep (Zheng, Zhuo, and Zhang, 2021). it was observed that the strength decreases as the proportion of recycled concrete aggregate in the mix increases. Specifically, there is an average drop of 13% in compressive strength when using 20% recycled concrete aggregate replacement, and a drop of 32% for 100% replacement. The compressive strength of recycled aggregate concrete is influenced by various factors, such as the amount of free water, cement content, and properties of the recycled concrete aggregate. Generally, replacing natural aggregate with recycled concrete aggregate is expected to decrease both compressive strength and elasticity modulus of the concrete, which may be due to lower strength of the recycled concrete aggregate or defects in the interfacial transition zones between the old and new mortar (Guo et al., 2018). The recycled aggregate typically consists of virgin aggregate with old cement mortar attached, which determines its properties along with the type and quality of the virgin aggregates, unbound stone, and any impurities present such as bricks, tiles, glass, asphalt, plastic, wood, and gypsum. The old cement mortar attached to recycled aggregate is often considered the primary reason for its poorer properties compared to natural aggregate, as it results in higher water absorption, porosity, crushing value, and Los Angeles abrasion value, and lower specific gravity. Compared to natural aggregates, the RAs exhibited lower density and 10% fines values. It appears that 10% fines value (TFV) is a more sensitive indicator of recycled aggregate strength than aggregate crushing value. A strong correlation exists between the density of concrete and the specific gravity of the aggregates used, with all correlation coefficients (R^2) exceeding 0.85. The compressive strength of concrete made with recycled aggregates was mostly lower than that made with natural aggregates, regardless of the water-to-cement ratio used. However, the strength of both types of concrete increased with age. Thus, high-quality RAs can be used to produce concrete with similar strength to natural aggregates. This increase in strength may be attributed to the attached cement mortar, which enhances the bonding between the RA and new cement paste, and the rough surface of the RAs, which improves the microstructure of the interfacial transition zone (Duan and Poon 2014). The presence of old mortar and contaminants, recycled aggregates often had worse characteristics than NA. The strength of the concrete is impacted by the presence of attached mortar in recycled aggregate. Nevertheless, silica fume solution impregnation and ultrasonic cleaning improve the strength properties of RAC by 15% and 7%, respectively. Treating RA giving beneficiation and improves its characteristics. Treatment of recycled aggregates primarily entails removing mortar that has clung to the aggregate's outer layer. The aggregate surface qualities were enhanced, and loose and weakly adherent mortar was eliminated as much as possible from treated aggregates. The compressive strength of treated recycled aggregate concrete was increased by 8–18% at the age of 28 days compared to untreated RAC due to better contact at the interfacial transition zone between treated RA and fresh cement paste. The latter age of prepared recycled aggregate concrete was shown to have good strength development. The surface treatment technique successfully eliminated the loose mortar particles, greatly enhancing the qualities of RA (Saravanakumar, Abhiram, and Manoj 2016). The most important property of concrete is its compressive strength, which impacts its mechanical strength, durability, and other characteristics. As the replacement rate of recycled aggregate increases, regardless of the type or quality of the aggregate, the compressive strength of concrete decreases. It is 95% likely that recycled aggregate concrete containing 100% coarse recycled concrete aggregate will have compressive strengths about 0.766 times lower than those of corresponding NAC specimens. However, in some cases, RAC exhibits similar or even slightly greater strength, especially when it contains RCA. This may be because the bond strength in the interface transition zone (ITZ) between the old, attached mortar and new cement paste is improved for some reason (*Fig*. 1). Overall, increasing the amount of RA used in concrete is generally unfavourable to its compressive strength, but incorporating a small proportion of recycled aggregate can sometimes increase strength. Like ordinary concrete, the compressive strength of RAC decreases with an increase in the water-cement ratio, and it varies greatly at lower ratios. To achieve similar compressive strength values as NAC, the water-cement ratio of RAC should be 0.05-0.1 lower, which is due to the low water utilization ratio of the ITZs between old, adhered mortar and aggregate. While the performance of RAC is generally inferior to NAC, simple and low-cost approaches such as adjusting the water-cement ratio, aggregate water content, mixing method, and admixture can improve its quality to some extent. It is not practical to remove old, adhered mortar to improve the properties of RAC (Bai et al., 2020). The remaining mortar and ITZs in RCA with extended service times are weaker, resulting in reduced compressive strength of the final concrete. However, the "internal curing effects" brought on by the saturated RCA may increase the compressive strength of recycled concrete. A model was created using the two-phase composite material theory to estimate the RAC elastic modulus by linking it to the NAC elastic modulus and taking residual mortar content into account. With a linear coefficient of 0.972 and a correlation coefficient (R^2) of 0.850, the projected values were found to be in fair agreement with the equivalent experimental results. The crucial parameter impacting the shrinkage behaviour of RAC was found to be residual mortar content (Geng et al., 2019).

When RAC's and NAC's indirect shear strengths are contrasted, In RAC and NAC, the indirect shear strength at 56 days was, on average, 8% and 5% greater than it was at 28 days. When comparing the growth of the compressive and indirect shear strengths, it can be seen that the compressive strength grew more quickly in the next two weeks after the indirect shear strength did in the first two. The average of the coefficient of variation values for the five mixtures was 2.73% for RAC and 2.60% for NAC. This difference is negligible, probably as a result of the aggregate's few sources being recycled. If concrete is obtained from various sources, this observation could not be valid. The comparison takes into account the compressive strengths of cubes, cylinders, and indirect shear. The strength of the RAC cube was, on average, 88.4% more than that of normal concrete. In a similar vein, RAC's cylinder compressive strength and indirect shear strength were, respectively, 92.2% and 87.7% of those of NAC. When recycled coarse aggregates are utilized, the strength often decreases by 10%. The large variation in strength reduction illustrates the impact of several elements, including the recycled aggregate's source, and highlights the necessity of testing local materials to determine their true behavior. In general, for RAC and NAC, respectively, the 56-day cube strength was 5% and 3% higher than the 28-day strength on average. Like to NAC, RAC can have its strength boosted by reducing the water-to-cement ratio if water reducers are used to provide sufficient workability. The strength of the crushed concrete used to create the recycled aggregates does not limit the compressive strength of RAC (Rahal 2007). When compared to natural aggregate with the same particle size, it was discovered that recycled aggregate considerably absorbs more water. This is due to the fact that broken limestone is less capable of absorbing water than the old, connected mortar in recycled aggregate. The physical characteristics of recycled aggregate (density and water absorption) were inferior to those of natural aggregate. The strength of recycled concrete decreased with an increase in recycled aggregate percentage when it ranged from 0% to 66.7%. The strength of recycled concrete improved as the percentage of recycled aggregate grew, which was greater than 66.7%. In other words, concrete with a single type of coarse aggregate (0% and 100%) had a better strength than concrete with both recycled and natural material. This was due to the fact that, as compared to other replacement levels of concrete, the difference between the physical properties of aggregate groupings for concrete (0% and 100%) was less. Also, it was investigated. With a larger aggregate size, recycled concrete performed compressively better. This was mostly caused by the decreased amount of adhering mortar in the larger aggregate size (Kang and Weibin 2018). Other researchers observed the improvement of the mechanical properties even from a 50% RCA dosage (Abed and Nemes 2019). It was found that as the substitution ratio of crushed recycled concrete aggregate (CRCA) increased, the cracks on the non-loaded surface of concrete during compression failure decreased, while the tensile and shear failure sections of concrete became rougher and accompanied

Fig. 1: Aggregate New and Old ITZ

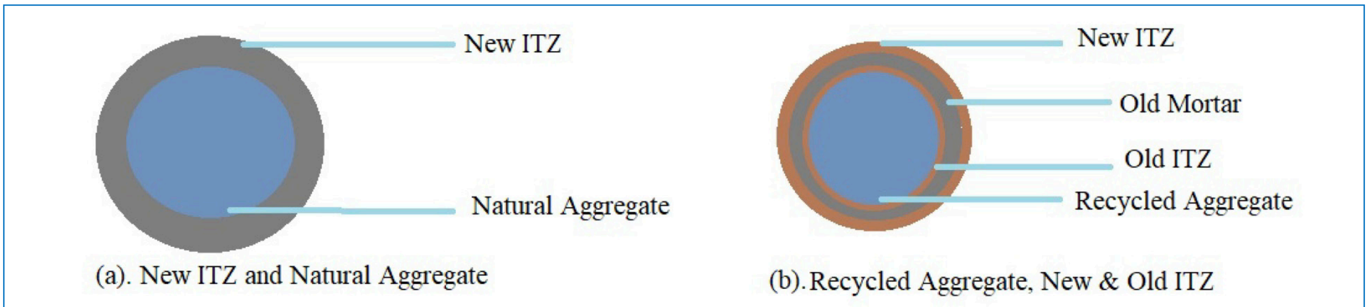

Table. 1: Effect of replacement rate of recycled coarse aggregate on residual compressive strength at the age of 28 days of concrete

Research	Replacement rate of recycled coarse aggregate				
	RC0	RC20	RC30	RC40	RC100
Zega, Antonio, and Maio 2011	43.6	42.7	41.4	-	-
Adessina et al. 2019	66	64	-	59	56
Kou, Poon, and Etxeberria 2011	43.8	34.3	-	-	-
Geng et al. 2019	34.5	30.2	-	-	-

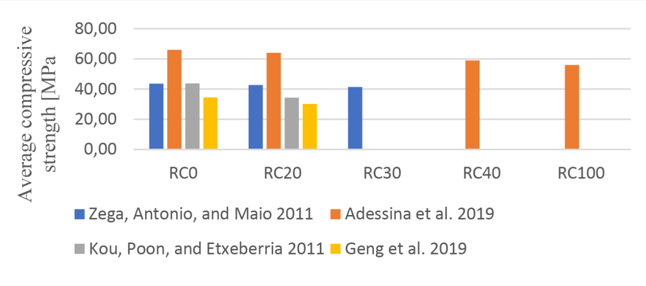

Fig. 2: Effect of replacement rate of recycled coarse aggregate on residual compressive strength at the age of 28 days of concrete (Adessina et al. 2019) (Zega, Antonio, and Maio 2011), (Kou, Poon, and Etxeberria 2011), (Geng et al. 2019)

by more concrete fragments, which were not affected by the substitution ratio of CRCA. Additionally, as the size of the concrete specimen increased, the integrity of concrete after compression failure increased. When the side length of the concrete cube was 150 mm, the substitution ratio of CRCA had the least impact on the compression failure of concrete. Moreover, as the substitution ratio increased, the peak compressive stress and peak tensile stress of RAC gradually decreased, the splitting limit displacement decreased, and the splitting tensile modulus slightly increased. As the substitution ratio of CRCA increased, the impact of the size effect on the peak compressive stress of concrete decreased gradually. The influence of size effect on the compressive strength of RAC was higher than that of ordinary concrete. Specifically, when the substitution ratios were 0% and 100%, the peak compressive stresses of RAC were reduced by up to 18.97% and 8.53%, respectively, due to the influence of the size effect (Du et al., 2021). When examined the relationship between the compressive strength of recycled aggregate concrete RAC and conventional concrete CC over three experimental phases, which were aged for 28 (a), 180 (b), and 365 (c) days, and also considered the effective water-to-cement (w/c) ratio. The results indicated that using 20% recycled aggregate RA content did not significantly impact the compressive strength of the concrete compared to CC after 28 days. However, with 100% RA substitution, there was a significant decrease in compressive strength, and to maintain similar strength levels, it was necessary to reduce the w/c ratio by 0.05. Additionally, after 180 days, the difference between the compressive strength of CC and RAC was more significant for stronger concretes (Thomas et al., 2013). A new method for combining RA in concrete, which replaces only large-sized RA particles with NA in the coarse aggregates. This method was compared to the conventional method, which replaces the entire coarse aggregate mixture or fine aggregate combined with all particle sizes of NA. The results showed that compressive strength increased as the RA replacement percentage decreased, and the new combination method yielded significantly higher compressive strengths at 7 days compared to the conventional method. This was attributed to the angular and rougher surface texture of RA, which improved bonding and interlocking with the cement paste at an early age. At 28 days, the compressive strength of RAC with 100% RA decreased by 38% compared to that of natural aggregate concrete (NAC). However, the new method showed considerable increases in compressive strength at all replacement levels compared to the conventional method, with a maximum increase of 22.7% for 50% RA content. In general, the compressive strength of RAC using the new method was similar to that of NAC, with a maximum difference of 5.6% at 50% RA content. The splitting tensile strength of RAC was slightly affected by the replacement proportion of RA and combination method, with the new method yielding slightly higher strengths of approximately 5% compared to the conventional method. Overall, the study suggests that the new combination method is more effective in accelerating the compressive strength of RAC than the conventional method and recommends using up to 50% RA content with the new method (Bui et al., 2017). The above all discussion can be understood from the illustrated graph plotted below, this graph is the final combined results of several literatures and is plotted between the compressive strength of RCA after 28 days and the proportional replenishment rate of natural aggregate by recycled coarse aggregate, It is observed that the compressive strength of the recycled aggregate concrete increases as the replenishment rate of the recycled coarse aggregate increases but similarly shows some decrease in compressive strength at 100% replenishment rate of NA by RA which is admissible. This phenomenon of increase in strength of the RCA is because of the adhered mortar on the recycled aggregate and presence of the double ITZ in RCA. The given *Table 1. and Fig. 2* summarizes the results of the previous experiments.

2.2 Durability

The fundamental durability traits of recycled aggregate concrete, such as water absorption, chloride permeability, porosity, freezing and thawing, were covered in this review paper. A crucial aspect of concrete's long-term durability is its capacity to function in all challenging circumstances, including extreme heat. Furthermore, covered is concrete's performance at high temperatures, which is a crucial factor.

2.2.1 Chloride permeability

Chloride ingress is the primary form of environmental attack on reinforced concrete exposed to chlorine salt environments, leading to corrosion of reinforcing steel bars and a reduction in durability. There are two commonly used tests to measure the chloride permeability of concrete: the conventional chloride diffusion test and the accelerated chloride diffusion test. The majority of NAC diffusion coefficients fall within the range of 110×10^{-12} m^2/s, with the upper limit of chloride diffusivities increasing with w/c. RAC diffusion coefficients, on the other hand, range from 116×10^{-12} m^2/s, showing larger variability than NAC, likely due to the influence of old attached mortar and old ITZ, which vary more than new mortar and new ITZ. The replacement percentage of RCA also has a linear impact on chloride penetrability, with recycled aggregates slightly increasing the coefficient of permeability and chloride diffusion coefficient but remaining within acceptable values for durable concrete. The resistance of chloride ion penetrability can be improved by using fly ash as a partial replacement of cement and recycled aggregate concrete displays greater resistance as curing age increases. Reducing the w/c ratio can also improve chloride impermeability (Xiao et al., 2013), indicating that in a chloride environment, RAC (recycled aggregate concrete) prepared with a low w/c (water-to-cement) ratio performs better than NAC (natural aggregate concrete). This may be due to the higher presence of C-S-H (calcium silicate hydrate) gels in RAC, which facilitate binding with chloride. The binding of chloride in concrete can occur through a chemical reaction between chlorides and hydrated cement aluminates, or through physicochemical adsorption in the CSH. Chlorides from an external source can be bound by the new cement paste in the RAC, as well as the old mortar adhered to the RCA. The use of a new method for mix proportioning in RAC leads to comparable diffusion performance for chlorides, similar to that of NAC and conventional RAC, while significantly reducing the cement content of the mix. This represents a noteworthy advancement in terms of sustainability (Vázquez et al., 2014). The substitution of NA in recycled aggregate concrete (RAC) had a greater effect on reducing chloride penetration as the w/c ratio in the RAC mix increased. This suggests that the w/c ratio used in RAC plays a role in enhancing the RCA's diffusivity (Yuan et al., 2023). The recycled aggregate size ranging from 5-10 mm offers greater resistance to chloride permeability (Duan and Poon, 2014). Demonstrates that the amount of recycled concrete, in the microstructure affects the ability of the sample to resist chloride penetration. When the recycled aggregate contains more mortar, the resulting concrete is more porous, leading to a rapid increase in cumulative chloride concentration. The replacement rate is also related to an increase in the chloride diffusion coefficient, which is influenced by the porosity of the recycled concrete. the new mortar has a higher diffusion coefficient than the reconstructed attached mortar, which is primarily due to the content and lack of damage of the reconstructed mortar. However, it is important to note that the real chloride diffusion coefficient of the attached mortar in the recycled concrete aggregate is expected to be higher than that of the reconstructed attached mortar due to the presence of micro-cracks and interface effects (Adessina et al., 2019). It is suggested there is approximately a 95% probability that the total accumulated charge of Recycled Aggregate Concrete (RAC) with 100% coarse Recycled Aggregate (RA) content exceeds that of Normal Aggregate Concrete (NAC) by a factor of about 2.07. The influence of fine RA on chloride penetration is more noticeable than that of coarse RA because of the greater amount of adhered mortar and clay content. Like regular concrete, the chloride penetration resistance of RAC decreases as the w/c ratio increases and increases with curing age. When compressive load is applied, the chloride diffusion coefficient of RAC initially decreases and then increases as the compression load increases. The maximum reduction in the chloride diffusion coefficient of RAC was approximately 40% at stress ratio of 0.51, which is more responsive to compressive loading compared to NAC (which was 25%) due to the higher porosity of RA. RAC made with RA sourced from higher-strength concrete showed lower chloride penetration than the concrete made with lower strength RA due to its lower water absorption (Guo et al., 2018). In general the durability of recycled aggregate concrete (RAC) used in construction needs special attention, especially regarding chloride penetration. Since the distribution of recycled coarse aggregates (RCA) is random, a five-phase RAC model is suggested to predict the effective diffusion coefficient of chlorides in RAC. This model includes new mortar, adhering old mortar, new interfacial transition zone (ITZ), old ITZ, and original natural coarse aggregates. It focuses on critical factors such as the volume fraction of RCA, the adhesion ratio of old mortar, the chloride diffusivity of adherent old mortar, the thicknesses of old and new ITZs, and the chloride diffusivity of old and new ITZs, and how they affect each phase and the effective diffusion coefficient of chlorides in RAC. Results show that the effective diffusion coefficient varies depending on the quality of adherent old mortar, the adhesive ratio of old mortar, the thickness of ITZs, and the chloride penetration resistance of ITZs. However, the model is only applicable to fully replaced RCA concrete since the model's multilayer spherical approximation (MLSA) cannot accurately predict the smear effect between RCA and natural aggregates (NA) in concrete with both RCA and NA (Hu et al., 2018).

2.2.2 Porosity

There is a connection between the open spaces within RAC and control concrete (CC), and this was investigated in three experimental phases over the course of 28, 180, and 365 days, as well as the effective water-to-cement (w/c) ratio. Generally, the RAC's accessible spaces, in contrast to CC, increases with a higher w/c ratio and substitution degree. Using RA has a negative effect on the durability of non-compact cement paste concretes. Furthermore, incorporating RA leads to an increase in porosity that is dependent on the w/c ratio and degree of substitution (Thomas et al. 2013). Both normal aggregate concrete and recycled aggregate concrete using two different sources of recycled coarse aggregate RA (one obtained from crushed granite and another crushed concrete rubble from demolished building), exhibited similar levels of porosity after 28 days of curing. However, significant variations in porosity were observed among the different types of concrete after 5 years of water curing. The concrete made entirely from crushed concrete aggregate had the lowest porosity after 5 years of curing, with a 45% reduction in porosity compared to 28 days. In contrast, concrete made with recycled aggregate containing mainly natural stone (granite) had the highest porosity after 5 years of curing, with only a 7% reduction in porosity compared to 28 days. The use of crushed concrete in the recycled aggregate significantly enhanced the long-term interfacial properties of the new concrete, most likely due to the extended self-cementing effects of the old cement mortar and the interaction between the new cement paste and the old cement mortar (Kou et al. 2011). It was found that the total porosity measured by X-ray computed tomography (XCT) increased with the ratio of substitution due to the adhered mortar of the aggregate, but the increase was different for saturated and dry aggregate. The increase in porosity was more significant for the saturated recycled aggregate, where the water absorbed increased the water/cement ratio, resulting in reduced mechanical properties. The recycled aggregate concrete made with saturated recycled aggregate had a higher number of larger pores and an open microstructure. The macro porosity of recycled aggregate concrete, shows an increase in macropore density with the height of the specimens, an exponential trend of the number of pores with their size, and a higher increase in the number of small pores and also larger pores in the perimeter of the sample, which increased with the substitution ratio were also observed (Thomas et al., 2019). It appears that at substitution rates of 20%, 30%, and 60%, there is no significant change in porosity (2%, 4%, and 11% respectively) when compared to the original mixture (NAT). Compared to natural aggregates, RA are more porous and have old cement paste attached to their surface, resulting in a different microstructure of the Interfacial Transition Zone (ITZ) in RAC than that of traditional concrete. As the RA content increases, the total and average porosity diameter of the concrete increases (Arredondo-Rea et al., 2019) The RCs' replacement factor *r*, which refers to the pore radius, is associated with both total volume and pore size. Its impact is more pronounced in younger concrete and diminishes as it ages. The reason for this effect is attributed to the creation of new products that reduce the number and size of pores. Given the wide range of pore sizes in concretes ranging from 1 nm to 1 cm. The most significant differences observed in the samples analyzed were related to two parameters, the first being the threshold for a larger pore radius, which increases as the replacement of NA by RCA increases, and the second being the detection of areas with major quantitative changes, where the pore volume from pores with a radius less than 30 nm increases (Smart and Jerman 2002). As the temperature exposure increased, the mortars' porosity and average pore diameter increased. The RA concrete had higher porosities than natural aggregate concrete before being exposed to high temperatures, likely due to the presence of old mortars. Concrete made with Portland cement had lower porosities than those made with 55% GGBS55 (ground granulated blast furnace slag) and 35% FA, but the average pore sizes of Portland cement concrete were higher than those of GGBS55 and FA concretes. After exposure to 300 °C, the increase in porosity of FA and GGBS concrete was lower than that of Portland cement concrete, possibly due to the pozzolanic reactivity of FA and GGBS, resulting in generally smaller average pore diameters (Eckert and Oliveira, 2017).

2.2.3 Water Absorption

The presence of pores in aggregates means that dry particles can absorb some water. The amount of water absorbed depends mainly on the number and continuity of the pores, while the rate of absorption is influenced by pore size and continuity, as well as particle size. When using aggregates in a concrete mix, any unsaturated aggregate will absorb some of the mixing water, while free moisture on the surface of the particles will also contribute to the mix. To calculate the effective water/cement ratio and mix proportions by weight, the saturated surface dry condition is used as a reference point. However, recycled aggregates can be challenging to work with because their irregular shape makes it difficult to eliminate all free water after soaking. To measure the water absorption coefficient over time for both natural and recycled aggregates, it is best to observe the rate of capillary rise and measuring the change in mass of the sample over time but the standard 24-hour soaking time is insufficient for measuring water absorption in recycled aggregates, as it only accounts for 60-70% of the total absorption obtained after longer soaking periods (Materials, 2017). The ability of water to pass through a material increases as the ratio of water to cement (w/c) increases and as the proportion of Recycled Aggregate used in the material increases. The absorption coefficient of RAC increases with both the w/c ratio and the extent of recycled aggregate (RA) substitution. For instance, when the w/c ratio is 0.65 and the RAC contains 100% RA, the absorption coefficient increases from 6.2% to 8.4% compared to the CC. This represents a 35% increase in absorption (Thomas et al., 2013). The water absorption rate of RAC concretes is 15% greater than that of CC, but the water absorption rate of concretes made with varying amounts of recycled fine aggregates remains the same. Therefore, it can be inferred that the coarse aggregate has a significantly greater impact on this characteristic (Zega et al. 2011). The ability of recycled aggregate concrete (RAC) to resist water penetration is mainly influenced by factors such as the content of recycled aggregate (RA), the ratio of water to cement (w/c), the original strength of the waste concrete, the age of curing, and the presence of mineral admixtures. When the proportion of RA in RAC increases, its water resistance decreases. This is because the attached mortar and cracks in the waste concrete can provide a pathway for water to penetrate the RAC, and as the w/c ratio increases, the water absorption of RAC also increases. The impermeability of RAC is also affected by the particle size of the RA. Larger coarse aggregates have less surface area and attached mortar content, which reduces the water required for concrete and improves its strength. However, larger particles can also increase defects within the RAC. Mineral admixtures have been utilized to enhance the impermeability of RAC by filling the pores and creating a mesoscale pozzolanic reaction. So, incorporating a specific quantity of mineral additive is a successful approach for enhancing the interface composition and overall functionality of RAC (Guo et al., 2018). The water absorption in RCA within 24 hours is a combination of two factors, the capillary absorption of any leftover cement paste and the initial absorption of the natural aggregates. The two samples of RCA with the same 24-hour absorption rate can have significantly different absorption kinetics, which can impact the slump loss of concrete made with dry RCA. This behavior is strongly linked to the porosity of the paste, which is similar to the capillary absorption of regular concrete (Habert and Roussel, 2014). The absorbent qualities of aggregate depend on the degree of particle porosity or the average value of a mixture of high and low absorption materials. Coarse aggregate has a higher water absorption rate due to the higher absorption rate of cement mortar attached to the aggregate particles. Recycled aggregate is typically more absorptive than natural aggregate, with water absorption rates ranging from 3-10% and less than 1-5%, respectively. Therefore, it is crucial to understand the water absorption rates of recycled aggregate during the mix design stage. British Standards Institution (BSI) for measuring water absorption of aggregate is prominent. The BSI approach requires surface-drying the aggregate with a cloth or towel, which may detach some cement paste sticking to the surface of the aggregate, leading to a significant reduction in the oven-dried mass of aggregate and a less accurate testing result. To overcome these issues, the author proposes a new approach called real-time assessment of water absorption (RAWA), which provides a simpler and more accurate way to obtain water absorption rates at different time intervals without the need to soak and dry the recycled aggregate sample. RAWA avoids the removal of cement paste during the soaking and drying process of the recycled aggregate sample and provides a more genuine water absorption rate. The method has been tested and proven to be a good alternative for measuring water absorption of recycled aggregate (Tam et al., 2008). increasing the amount of Recycled Aggregate in concrete leads to a rise in water absorption and a decrease in density. The measured difference in water absorption between NAC and RAC is similar to the calculated difference, indicating that the cement slurry couldn't decrease the aggregate absorption capacity by sealing the pores. However, there is a noticeable difference between the measured and calculated densities. The calculated density decrease from NAC to RAC is on average 45% higher than the measured ones, suggesting that the mortar seals some superficial pores of the aggregates, especially in lower density aggregates. Concretes durability is linked to water absorption, and hence RAC should be protected from moisture in harsh environments. The water flow capacity in the hardened state allows internal curing via saturated aggregates, reducing shrinkage cracking. It is worth mentioning that low aggregate density has positive effects on concrete structures, such as reducing the dead weight of the structure, thermal conductivity, and thermal bridges, which improves the insulation capacity of the building. The staged mixing approach can be followed to decrease the ITZ water flow of RAC to a negligible amount in its fresh state. Incorporating extra water during the two-staged mixing approach for RAC can mitigate the adverse effects of recycled aggregate water absorption in concrete technology, provided the pre-wetting time is 5 min. However, these procedures are not recommended for natural aggregates since significant swelling in the slump test was found, which breaks the bonds and increases the effective w/c ratio (Eckert and Oliveira, 2017). The absorption of water by recycled aggregates (RAs) depends on the effective water to cement ratio (w/c), which affects the workability of the concrete mix and the performance of the hardened concrete. The size of the RAs affects the rate at which water is absorbed due to the different specific surfaces. There are two stages of water absorption, a rapid stage and a slow stage. During the first stage, the rate of absorption increases as the size of the RAs decreases. The three-dimensional Terzaghi capillary water rise model can be used to express the rapid water absorption stage, which ends when the wetting front reaches the center of the RAs particles. The slow water absorption in the second stage is caused by air bubbles not being separated from the opening of large pores in a timely manner, which increases the buoyancy force of the sample, and water-air displacement in the large pores slowing down due to a decrease in capillary pressure. The difference in capillary pressure between small and large permeable pores drives the water absorption of RAs immersed in water, and the capillary pressure in large pores can usually be ignored due to their diameters being several orders of magnitude larger than the most probable value of the RAs pores' diameters. The size of the RAs affects the rate of water absorption due to the different specific surfaces (Liang et al., 2021). The water permeability of recycled aggregate concrete (RAC) is weak compared to natural aggregate concrete (NAC), with a value of around 10-20 m^2. Self-healing may also play a role in reducing water permeability and improving durability in real conditions, making it a potential factor for assessment (Zaharieva et al., 2003). Moreover, after being exposed to temperatures below 500 °C, the capillary absorption coefficients of recycled aggregate concrete (RAC) were found to be higher than those of natural aggregate concrete with all types of binders used. This is most likely because the RA has higher porosity and a larger amount of total mortar. However, when exposed to 800 °C, the concrete prepared with 100% RA had a lower water absorption coefficient than natural aggregate concrete due to the more suitable CTE (coefficient of thermal expansion) of the RA with the new cement paste-mortar, resulting in less cracking. Additionally, regardless of the type of binder used, the concrete mixtures made with 100% RA showed the smallest increase in capillary absorption coefficient (compared to 25 °C), followed by those with 50% RA and natural aggregates (Cong, Sun, and Etxeberria, 2014).

2.3 Freeze and Thaw Resistance

One of the harshest and most damaging environmental effects on concrete is exposure to freeze-thaw cycles. A critical issue that can result in significant concrete deterioration is the harm that freezing and thawing cycles have on concrete structures in cold climates. Many physical characteristics, including matrix porosity and aggregate qualities, affect how resistant concrete is to freezing and thawing. In freeze-thaw cycles, the water initially enlarges within the pores after freezing, and if the necessary volume is greater than the available space, the surplus water is expelled by expansion pressure when the pressure is greater the material resistance, which causes local cracks to develop. Nonetheless, continuous freeze-thaw cycles in a humid atmosphere cause water to enter fractures during the thaw stage and freezes again later, leading to increasing degradation over time. This shows that it is possible to build RAC that provide equivalent workability in comparison to traditional concrete mixture including only natural aggregates. Taking into account the RCAs' water absorption capacity (which accounts for 50% of the total absorption value) and individually determining each proportion. These findings support compressive packing approach's superior ability to forecast the compressive strength of various recycled and natural concrete of different strength group. The mechanical and physical performance of normal strength concretes are more affected by the degradation cycles than are high strength combinations. The key mechanical parameters following freeze-thaw degradation (compressive strength, elastic modulus, and tensile strength) are proposed as a function of the initial open porosity of the concrete by way of a freeze-thaw degradation-law for RAC. Compressive strength after cycles separated by reference and its relationship Compressive strength is a function of the concrete's initial open porosity, and this relationship holds true for elastic modulus and tensile strength as well. According to research, the presence of mortar that is affixed to concrete generates a "delta" of increased degradation after 300 cycles. The distinction between natural and recycled concrete's ITZs (between aggregate and new paste) can be explained (one between aggregate and new paste and another between old paste and original aggregate). More damage occurs in RACs than NACs as a result of having more ITZs (Rangel et al., 2020). The deterioration of recycled concrete specimens constantly exposed to up to 56 freeze-thaw cycles (with freezing performed at 18 °C in air and thawing in water at 20 °C until the core temperature reached 6 °C), the concrete's initial strength determines its capacity to withstand the hydrostatic pressures produced by the degradation process. This describes how the type of RCA, their quality, and any potential processing procedure affect the performance of RAC as a result. For instance, treated RCA (RCA that has been cleaned before mixing) produces RAC that is more durable than untreated concrete mixtures, which, according to the authors' view, is due to a higher initial strength (and compactness). This is advantageous in reducing damage brought on by freeze-thaw cycles (Richardson, Coventry, and Bacon 2011). The interior structure of RAC remains generally tight with few micropores and cracks during the initial freeze-thaw interval (100 cycles). On the other hand, after 400 cycles, there were more pores and microcracks present, and the link between the aggregates and mortar weakened. It was no longer feasible to differentiate the ITZs within the mixture when samples failed in the late freeze-thaw interval 800 cycles, indicating that the concrete had become exceedingly porous (Zhu et al. 2019). The existing microcracks tend to grow as concrete is repeatedly subjected to free-thaw cycles after examining the mechanical properties of concretes with 30 MPa compressive strength subjected to different freeze-thaw cycles (0, 5, 15, 30, 50, 75, and 100 cycles). In addition, both the lowest freezing temperature and the number of free-thaw cycles have a detrimental effect on the residual compressive strength (Wang et al., 2020). Partially substituting fly ash for cement does not improve the freeze-thaw resistance of RCA concrete. It is anticipated that when the curing time is extended, the qualities of the mixes containing fly ash will become more favorable. It is crucial to stress that lower readings in specimens with additional cementitious materials do not necessarily indicate that these specimens are more susceptible to freeze-thaw assault. However, RCA-concrete mixes proportioned by the traditional mix design approach (100% RCA content) or by the EMV method (63.5% and 74.3% RCA content for RCA-concrete prepared with RCA-MO and RCA-VA, respectively) have strong resistance against freeze and thaw when used as a performance indicator. However, the EMV technique provides concrete with greater resilience to freeze-and-thaw action than RCA-concrete proportionate by conventional mix design method (Abbas et al. 2009). As the water/cement ratio fell, the weight loss reduced significantly and very consistently, with 50% recycled material and 50% saturation, the specimens showed remarkably good performance. Most of the RCA-containing mixes outperformed the control mix. The fact that the RCA encouraged the creation of a denser and more solid contact may be one factor in this performance's success. Semi-saturation of the 50% RCA had the greatest results among the groups including RCA, while full saturation and semi-saturation of the 50% RCA improved the concrete's durability. These numbers were remarkably similar to those seen in the control group. These results were also supported by the mechanical tests conducted for this investigation. The efficacy of concrete containing RCA was approximately equivalent to that of cement concrete only virgin aggregate after exposure to 300 freeze-thaw cycles, particularly for mixtures containing 50% RCA at a 50% saturation point (Yildirim, Meyer, and Herfellner, 2015).

3. FIRE PERFORMANCE OF RECYCLED AGGREGATE CONCRETE

In this review paper, the critical fire performance of recycled aggregate concrete was also covered. RCA's fire performance can change based on the precise combination of materials utilized as well as the RCA's quality and processing. Due to its construction from a solid, inert substance, RCA has generally been found to have strong fire-resistant qualities. Moreover, RCA often contains less water than conventional concrete, which can aid in reducing the risk of spalling and other types of damage during a fire (Dong et al., 2014). High temperatures frequently result in aggregate damage, a softening of the cement paste-aggregate bond, a softening of the cement paste because of higher porosity upon dehydration, a partial break - down of the calcium silicate hydrate the principal of cement hydration, and the development of cracking. Recycled aggregate should be utilized in the design mix rather than natural aggregate since it absorbs water more quickly. Recycled aggregate with a high crush value and resistance to abrasion may be a clear sign of weaker concrete. Concrete loses a considerable portion of its strength quickly when subjected to high temperatures, and recycled aggregate concrete exhibits this loss of strength earlier than natural aggregate concrete. With late-aged concrete compared to early-aged concrete, the percentage loss in concrete strength caused by high temperatures is less. Recycled aggregate concrete does suffer a greater loss than natural aggregate concrete, though. Recycled aggregate concrete has an excellent resistance to strength deterioration brought on by thermal stress, and its value is only 5% to 10% lower than ordinary aggregate concrete's (Kim, 2022). According to a statistical analysis of cracks, normal strength concretes primarily experienced cracking along interfaces, such as those between old paste and new paste or between old paste and natural aggregate. Nonetheless, it was noted that certain cracks in high strength matrix concretes crossed through the aggregate. According to the chemical studies, the hydration reactions in the old mortar at the LRCA were not quite finished. As a result, extra hydration reactions with the LRC concretes may have strengthened the existing mortar and provided more crack resistance. Due to higher moisture concentrations in the aggregates, Industrial recycled concrete aggregate (IRCA) concretes showed more mass loss after exposure to high temperatures and the possible cause is because of presence of impurities. The *Fig. 3* shows the crack pattern at high temperature for three different types of concrete viz, (a) IRC 0.6 concrete at 750 °C, (b) IRC 0.3 concrete at 450 °C, IRC 0.3 concrete at 450 °C respectively.

Spalling is the fundamental issue when analyzing the fire behavior of concrete structures. This phenomenon involves the violent or nonviolent separation of concrete particles from a concrete member's surface. Fire spalling can have a significant impact on the structural performance depending on the extent of the damage because it decreases the cross - sections and may even exposes steel rebars to the fire. This may result in a decrease in load-bearing capability, thermal insulation, and fire resistance. The overall weight loss of the sample (% of the initial mass of the sample), the spalled volume (percentage of the starting volume of the sample), the mean spalling depth (mm), and the maximum spalling depth were the four indicators used to assess the spalling after the fire (mm). Compared to NA-made concrete, RCA-made concrete showed more spalling. The degree of spalling increased slightly as the compressive axial stress increased. Spalling indicators (volume and maximum depth) showed strange behavior in relation to the replacement rate. First, the volume and depth of the spalling grew from 0% to 40%. The spalling signs were steady from 40% to 100%. The general behavior was not significantly altered by the replacement approach (direct replacement or strength-based replacement). Several characteristics, like the water content and compressive strength, that may increase the danger of spalling are impacted by the presence of RCA. Since concrete mixes with relatively low strength displayed a notably increased spalling, the compressive strength of concrete prepared with RCA had no effect on the spalling risk. Since mixes with a high-water content had greater spalling depths and volumes, the water content affected the spalling damage. More water content and less thermal cracking may be linked to an increased likelihood of spalling. The improvement in the mechanical characteristics of the concrete due to the smaller thermal mismatch may also be associated with a potential reduction in the probability of spalling (Fernandes et al., 2022).

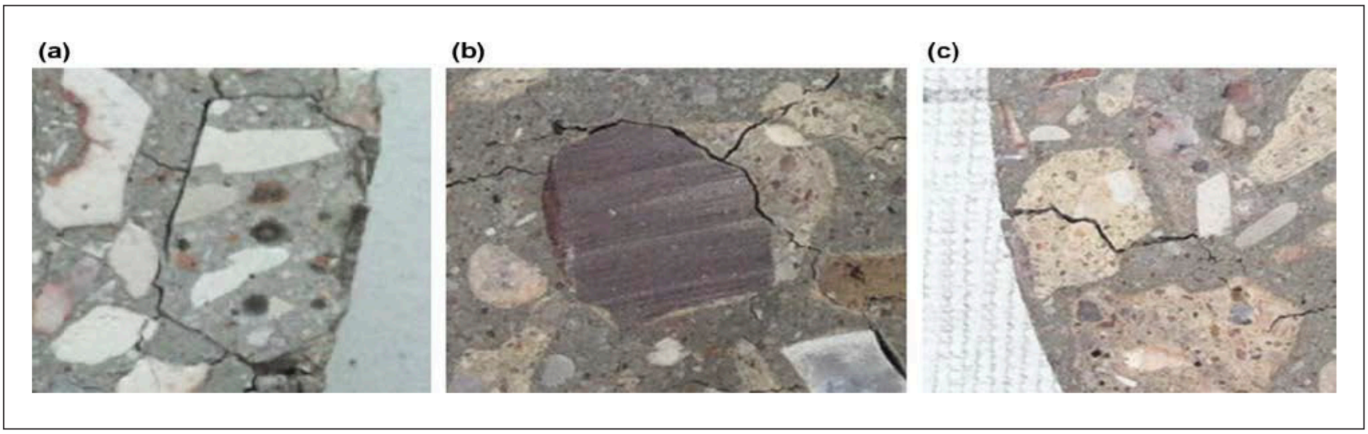

Fig. 3: Crack patterns observed after heating: (a) at ''new paste–old paste'' interface at 750 °C, (b) between siliceous aggregate and old paste at 450 °C, (c) through a calcareous aggregate at 450 °C. (Laneyrie et al., 2016)

For mechanical properties post-fire, sustainable concrete using coarse recycled concrete aggregate has received little attention to far (heated, cooled, and then loaded at-ambient temperature). It was found that the sustained strength and elasticity of the concretes under consideration decreased proportionally as the temperature rose. Moreover, the only discernible change across the concrete was a slight rise in strength as RCA concentration increased. The higher strength of the original RCA source and the higher curing conditions resulting from retained moisture in the source aggregate were both used to explain this behavior. This has significant ramifications for the practitioner since it makes it more difficult to identify probable mechanical property losses at high temperatures. In general, the thermal strain coefficient values were comparable. The main finding was that sustainable concrete with RCA had much lower mechanical performance at rising temperatures than conventional concrete. This does not imply that the sustainable concrete was ineffective, either. Even with a full RCA replacement, all sustainable concretes behaved above 35 MPa at 500 °C, exceeding the required 40 MPa strength of the concrete mix design. This observation shows that sustainable concretes with RCA might be able to achieve particular fire design goals with a good design (Gales et al., 2016). If the replacement amount is kept between 0% and 40% and done with hydrated old concrete, it is inferred that concrete with recycled coarse aggregate in it will behave similarly to natural aggregate concrete when exposed to temperatures between 25°C and 800°C. For dry conditions and saturated surface dry conditions, the average particle densities of natural coarse aggregate are 2895 kg/m^3 and 2935 kg/m^3, respectively, while for dry conditions and saturated surface dry conditions, the average particle densities of recycled aggregate are 2311 kg/m^3 and 2446 kg/m^3, respectively. As a result, recycled coarse aggregate (RCA) is lighter than natural coarse aggregate, which may be due to the addition of low-density cement paste to RCA. The volume % of leftover mortar will increase as the recycle aggregate particle size is increased; this invariably results in a decrease in the specific gravity and density of the aggregate particles. With rising temperatures, the densities of concrete containing granite (virgin aggregates) and recycled aggregates rise. Regardless of the % substitution of the virgin coarse aggregate (granite) with the recycled ones. It is believed that the relatively weak interfacial bond between the RCA and the solidified paste within the concrete matrix is what caused the initial reduction in strength from 25 °C through 100 °C and 200 °C. At temperatures between 200 °C and 400 °C, strength increased continuously. From 200 °C to 400 °C, the strength continued to gradually rise. The strength of the control samples gradually rose up to roughly 30%, but those with 15% and 30% RCA replacements showed 36% and 35% increases in strength, respectively. There may have been dehydration and heat expansion of the concrete. After then, the strength of the concrete cube began to decline steadily once more as the temperature approached 600 °C. In contrast to samples with 15% and 30% RCA replacements, which showed 5% and 2% strength reductions respectively, control samples gradually decreased by roughly 13%. The temperatures were approaching 600 °C when the fissures were discovered. Generally speaking, nothing changed until the temperature was well above 100 °C. There was an initial drop in strength from 100 °C to 200 °C which is suspected to be due to the relative weak interfacial bond between the RCA and hardened paste within the concrete matrix; a gradual increase in strength continued from 200 °C to 450 °C and steady drop occurred again after that up to 600 °C. Also, with temperatures higher than 400 °C the cubes showed further loss in weight and increased visibility and higher density of cracks. Beyond 600 °C, deterioration was relatively more severe and the mechanical properties of concrete (such as compressive strength) were largely affected by the temperature. The *Fig. 4* shows the crack lines formed on 15% recycled concrete after tempering for 2 hours at 400 °C (Salau, Oseafiana, and Oyegoke, 2015).

All concrete compositions' compressive strength declined as exposure temperature rose. The greater amount of recycled mortar used to adhere the recycled aggregates is what is contributing to the rise in the residual compressive strength for recycled aggregate concrete. Subsequently improving the thermal expansion characteristics of the cement paste and aggregates. Although the residual compressive strength of concrete mixes made with recycled aggregates was somewhat lower at 200 °C and 400 °C than that of the control mixture, the ratios of residual to early compressive strength increased for concrete mixtures that contained 20% extra materials in place of OPC, especially at greater exposure temperatures of 400 °C and 600 °C. The increase in residual compressive strength of blended concrete containing marble powder and rice husk ash was mainly due to pozzolanic reaction that result in the formation of supplementary hydration products. The production of additional hydration products as a result of the pozzolanic reaction increased the residual compressive strength of concrete mixtures comprising marble powder and rice husk ash. At high temperatures, recycled aggregate concrete's residual compressive strength was satisfactory and on par with the control mixture. When recycled aggregate concrete was subjected to elevated temperatures, there was no spalling or fragmentation. demonstrating the recycled aggregates' sufficient thermal compatibility with cement paste. When contrasted with the control mix, concrete mixtures containing a 30% substitution of recycled aggregates had splitting tensile strengths that were over 35% higher. Even

Fig. 4: Crack lines formed on 15% recycled concrete after tempering for 2 hours at 400 °C (Salau et al., 2015)

though the splitting tensile strength was reduced as recycled aggregates were added, the final strength was equivalent to that of the control mix. With 100% recycled aggregate concrete, the use of marble powder and rice husk ash as a 20% cement replacement resulted in a decrease in both compressive and breaking tensile strengths. When compared to 100% recycled aggregate conventional concrete without steel wires, the mixtures with 0.5% waste steel wires demonstrated higher splitting tensile strength and compressive strength. (Salahuddin et al. 2019). The compressive strength decreased by 6 to 8% when recycled material was used in place of natural aggregate. The excess cement paste in recycled aggregate, which led to a weak interface zone and lower density, has been recognized by Mehta in 1986 as the cause of these reductions in splitting tensile strength, which decreased by 8 to 12%. For concretes made using river gravel, crushed limestone, and recycled aggregate. When the various concretes were subjected to temperatures of 250 °C and 500 °C, there were no apparent cracks. However, the river gravel concrete specimens that surviving the exposure had several deep, wide fissures. This can be due to the river gravel concrete's high quartzite content, which was discovered by mineralogical investigation. The neighboring cement paste is typically thermally incompatible with the quartzite because it typically has a greater coefficient of thermal expansion. With fewer, smaller cracks, all the RCA and crushed limestone specimens withstood the exposure to 750 °C. The extremely slight cracks in the RCA concrete examples were shallower and narrower than those in the crushed limestone specimens. Because RCA contains a significant amount of mortar, it is expected that its coefficient of thermal expansion is similar to that of cement paste. In order to strengthen the physical bond between the cement paste and the aggregate, it also features a rough surface roughness. Generally speaking, it has been shown that concrete created from recycled concrete aggregate performs well at high temperatures and is equivalent to other types of concrete. When RCA concrete was heated to 750 °C, unlike river gravel concrete, no spalling or disintegrating was seen. Compressive and flexural strength as well as elastic modulus of concrete constructed using recycled concrete aggregate frequently decreased with temperature. For all raised temperatures, the residual to starting compressive and tensile strength ratios of concrete built using recycled concrete aggregate were higher than those of river gravel concrete. Comparing RCA concrete to crushed limestone concrete heated to 500 °C or higher revealed the same pattern. With the exception of RCA concrete at 500°C, all concretes' residual moduli of elasticity displayed similar tendencies (Sarhat and Sherwood 2011). The main factor influencing the features of the aggregates and the factor anticipated to influence the final properties of the RAC is the adhering mortar content inside the RCAs particles, thermal shock and image analysis, were used on concrete samples made with red binders and coarse RCAs to assess the adherent mortar content for the used coarse RCAs. In both situations, the volume of adhering mortar was roughly 48%. The mechanical performance that was still present after exposure to high temperatures show that RCAs can be used in place of natural aggregates. The data reported revealed how residual mechanical performance are not harmed throughout the heating procedures, but residual physical performance are influenced by the presence of RCAs. This makes it easier for water and vapour to migrate, which can lessen the likelihood of the spalling phenomenon (Beatriz da Silva, Pepe, and Toledo Filho 2020). The integration of recycled concrete coarse aggregates have no effect on the material's thermal responsiveness, despite the increased porosity and altered thermal characteristics of the matrix-aggregate interface when compared to reference concrete. Upon exposure to high temperatures, recycled concrete coarse aggregate showed variations in the studied residual mechanical parameters (compressive strength, splitting tensile strength, and elasticity modulus) that were roughly comparable to those shown by reference concrete. As a result, it appears that there is no correlation between the rate at which natural coarse aggregates (natural concrete aggregate) degrade and the rate at which recycled concrete coarse aggregate replaces them for the various exposure temperatures examined. As a result, when compared to ordinary concrete, the structural use of recycled concrete coarse aggregate has no restrictions in terms of post-fire residual mechanical qualities. As a result, when compared to ordinary concrete, the structural use of recycled concrete coarse aggregate has no restrictions in terms of post-fire residual mechanical qualities. As with conventional concrete, the mechanical properties of concrete are significantly decreased after exposure to high temperatures with growing replacement levels of natural concrete aggregate by recycled concrete coarse aggregate. The highest decreases of residual effectiveness took place for exposure temperature of 800 °C: 12.2% for compressive strength. As a function of the exposure temperature, reduction factors were proposed to assess the remaining mechanical properties of recycled concrete coarse aggregate (Vieira, Correia, and De Brito 2011). On reviewing the several literature results and plotting the graph between the rate of substitution of NA and post fire compressive strength. On comparing these graphs, it is observed that the compressive strength of recycled aggregate concrete is comparable to the natural aggregate concrete only when the substitution rate of natural aggregate by the recycled coarse aggregate is up to 30% and the fire resistance of the recycled aggregate concrete is admissible up to the temperature of 400 °C.

Fig. ***5*** summarizes the results of the previous experiments.

4. CONCLUSIONS

Recycled aggregate (RA) often contains adhered old cement mortar, which can alter its properties. This prior mortar can improve the adhesion between RA and fresh cement paste, contributing to increased strength. Additionally, the coarse surface of RAs can also contribute to this strength enhancement.

When 20% RA is used in concrete, it has a minimal impact on its compressive strength compared to traditional concrete or conventional concrete (TC/CC). However, when 100% RA is employed, there is a noticeable reduction in strength due to the inherent weaknesses and porosity of recycled aggregates.

The use of nano silica can boost the performance of

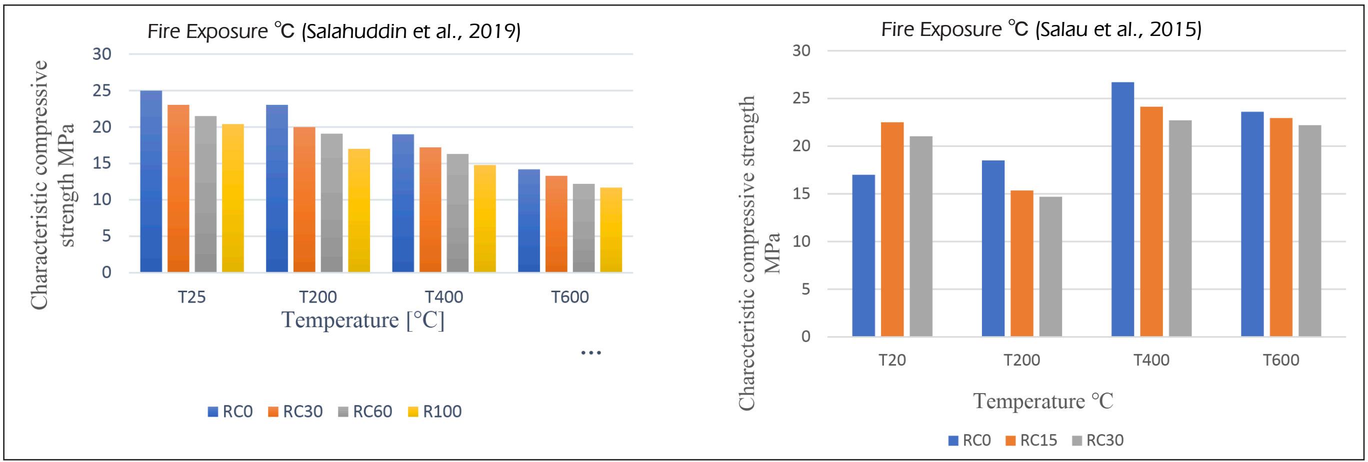

Fig. 5: Effect of replacement ration of coarse recycled aggregate on characteristic compressive strength after being exposed to elevated temperatures.

recycled concrete by expediting hydration and enhancing the interfacial transition zone (ITZ). Nonetheless, an excessive usage of nano silica can lead to problems such as reduced compressive strength.

Adjusting factors like the water-cement ratio, aggregate water content, mixing technique, and admixture can enhance the quality of recycled aggregate concrete (RAC). The water-cement ratio for RAC should be slightly lower than that for natural aggregate concrete (NAC) to attain equivalent compressive strength.

The quality of RA is influenced by manufacturing methods, the strength of the parent concrete, and its usage history. High-quality RA can slow down the deterioration of RAC, and up to 30% RA can be used as a replacement.

Recycled aggregates can elevate permeability and chloride diffusion coefficients, yet these values still remain within acceptable ranges for durable concrete. The degree of substitution with recycled coarse aggregates (RCA) has a linear effect on chloride penetrability.

In a chloride environment, RAC with a low water-cement ratio performs better than NAC, owing to the higher concentration of C-S-H gels.

The incorporation of crushed concrete in recycled aggregate significantly enhances the long-term interfacial qualities of new concrete.

RAC exhibits least water tightness due to its higher water absorption coefficient, which escalates with the water-to-cement ratio and the level of RCA substitution.

The absorption of free water by irregularly shaped recycled aggregates can influence the actual water-cement ratio and mix proportions.

The resistance to freezing and thawing in RAC is determined by matrix porosity and aggregate quality. During the initial freeze-thaw cycles, the internal structure remains tight, but it deteriorates over time.

The link between cement paste and aggregates can be damaged, the cement paste can become softer, and cracks can form as a result of high temperatures having a negative impact on concrete. Although its absorption rate and crush value must be taken into account to prevent weaker concrete, recycled aggregate is a potential choice for concrete mix design. Recycled aggregate concrete exhibits good resilience to thermal stress, it loses strength more quickly in high temperatures than natural aggregate concrete. Although recycled aggregate concrete experiences a larger overall strength loss than natural aggregate concrete, the percentage loss is still rather small. Compared to early-aged concrete, late-aged concrete loses less strength as a result of high temperatures. The enduring strength and flexibility of concretes both decrease as temperatures rise, though higher concentrations of RCA can marginally boost strength.

The mechanical properties of concrete at high temperatures can be impacted by RCA and other additives like marble powder and rice husk ash, which enhance hydration and residual compressive strength.

RCA concrete maintains its mechanical performance even after exposure to high temperatures, supporting its application as an alternative to natural aggregates and reducing the risk of spalling.

Incorporating recycled concrete coarse aggregates has no effect on the thermal responsiveness of concrete and does not restrict post-fire residual mechanical properties. Nonetheless, concrete does experience a decline in its mechanical characteristics at high temperatures.

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