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Use of recycled concrete and rice husk ash for concrete: A review

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Abstract: The rapid development of populations and the demand for concrete consumption are generating the need to produce greater quantities of cement, which has negative effects on the environment. Approximately 0.87 kg of CO_2 are produced per cement production; in addition, the use of aggregates is generating great concern in the construction industry, due to the cost and restriction of aggregates. Similarly, the accumulation of recycled concrete aggregate (RCA) and rice husk ash (RHA) contributes to pollution. Therefore, the objective of this manuscript is to review the literature of recent years on the use of RCA and RHA and the effect it generates on the various properties of concrete. For this purpose, indexed articles were used, between the years 2017-2021, with a total of 80 indexed articles evaluated. The literary analysis shows the most outstanding results including these materials that, when 8% RHA is added, the concrete reaches a compressive strength of up to 70 MPa; as well as the flexural strength by adding a combination 50% RCA + 1.50% basalt microfibers where it increases up to 29.44%. On the other hand, when 15% RHA is added, a compressive strength of 48.8 MPa is achieved; in turn, the flexural strength with 10% seashell for the fine aggregate and 20% RHA for the cement, reaches a strength of up to 65 MPa. In conclusion, the behavior of concrete undoubtedly depends on the proportions of RCA or RHA; however, the percentages should not exceed 8% and 15%, respectively.

Keywords: Cement, recycled concrete, rice husk ash, concrete, mechanical properties

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1. Introduction

Concrete, due to the properties it possesses, has become the material most used by mankind, and over the years the use of the building material has proven to be suitable for the design of sustainable structures that promote the development of an entire country (Haket, 2017). Moreover, as construction activities in all countries today have increased exponentially, the demand for concrete in large-scale structures has increased exponentially; therefore, concrete must possess excellent properties in several aspects, such as high compressive and tensile strength, excellent ductility and high durability to resist the penetration of aggressive substances (e.g., chloride/sulfate ions or chemical agents) (Liu et al., 2021). However, the problems caused by neglecting the environmental impact of concrete manufacturing must be considered. Portland cement, as a key ingredient of concrete, implies an emission of 0.87 kg of carbon dioxide (CO_2) per 1 kg of production, leaving in evidence the effects that are notoriously harmful to the environment and that are often overlooked; adding that these pollutants in some way or another cause damage to human health (Li et al., 2020).

In addition to the above, renowned global institutions whose purpose is to care for human integrity and the sustainable development of an entire country have predicted a significant increase of 12% to 23% in cement production by 2050; therefore, they consider it necessary to quantify and understand the effects that the industry has on the environment, in order to begin to reduce them (Juarez & Finnegan, 2021). Cement production brings with it increased energy consumption worldwide, accounting for 7% of all industrial energy use (Zhang et al., 2021). In turn, carbon dioxide gas contributes about 63.33% of global warming (Adnan et al., 2022). In other words, the manufacture of large quantities of building materials leads to serious environmental deterioration (Nidheesh & Kumar, 2019). In response, industrial by-products such as rice husk ash have been identified as possible alternative binders to ordinary portland cement (OPC) in concrete (Saloni et al., 2021).

Existing literature showed the great potential of using rice husk ash (RHA) as cement replacement or additives (Tayeh et al., 2021). It has also been shown to be highly pozzolanic at 5%, 7.5%, 7.5%, 12.5% and 15% and can be used in the production of high performance cement as an additional cementitious material, since this agricultural by-product material when incorporated in concrete and compared to the standard specimen, the compressive strength of concrete with RHA was higher at various ages up to 7 days and 28 days of curing (Reddy et al., 2021). Also, it is considered that the preferred content range of RHA should be 10% to 20%, since through a deeper and clearer understanding of the mechanism of action of RHA in cementitious materials, it can promote environmentally friendly and sustainable application in cement-based materials (Wang et al., 2021).

On the other hand, massive urbanization has driven infinite construction, and this is associated with the continuous increase in construction activities, such as infrastructure projects, commercial buildings and housing programs, and thus will see a rapid increase in construction and demolition waste, resulting in unpleasant and fatal impacts on urban sustainability and survival in terms of economic values and environmental safety (Aslam et al., 2020).

In countries with rapid urbanization would generate large percentages of demolition waste, which would end up being dumped in landfills or unauthorized sites (Islam et al., 2019). Now, these wastes, generate high pollution rates. For example, in the USA, high concentrations of boron were found in 22 construction and demolition debris landfills (Xu et al., 2020). These wastes also reduce the percolation of rainwater that recharges the groundwater table and affects the integrity of the environment, resulting in landfill dumping contaminating soil, air and wáter (Sivamani et al., 2021).

Thus, in the quest to reduce negative environmental results, it is being sought to produce concrete with alternative elements, since aggregates extracted from quarries have their own environmental impact due to the depletion of natural resources (Kirthika et al., 2020). It is known that in some regions of the world it faces supply constraints, due to the overexploitation of natural aggregates in construction (Ioannidou et al., 2017). Thus, the search for alternative concrete ingredients remains an active area of research among scholars (Bhatti et al., 2021). The use of construction and demolition waste (CDW) in concrete is a feasible alternative that can decrease the environmental impact generated by the construction industry (Xu et al., 2018a). And at the same time it can promote sustainable construction (Zaben et al., 2021).

It has been shown that recycled aggregate (RA) can be considered as a feasible alternative material for natural aggregates and is feasible for use in self-compacting concrete (Martínez-García et al., 2020). Likewise, concretes made with complete replacement of natural aggregate with recycled concrete aggregates (RCA) can generate high quality concrete (Makul et al., 2021). On the contrary, it has been shown that any addition of fine aggregates coming from construction waste or also from demolition as a replacement of natural fine aggregates is detrimental to the functional properties (quality) of the resulting concrete, as researches conducted confirmed that for higher replacement proportions of RCA, the maximum loss of compressive strength was 13 % and 22 % at 28 and 56 days, respectively; this strength being lower than the standard sample (Hafez et al., 2020). Similarly, the use of RCA is said to negatively affect the workability, quality, and mechanical properties of concrete (Moghadam et al., 2021). In recycled aggregate concrete (RAC), polypropylene fiber (PP) and steel fiber (SF) are two most used types of fiber materials, which can improve the strength and toughness of RAC and compensate for the defects of RAC to some extent (Zhang et al., 2020).

There are also studies with RHA and recycled concrete as aggregates in concrete. It has been shown that concrete mixtures containing 100% coarse recycled concrete aggregates and 10% - 15% RHA satisfy the design requirements for structural application (Padhi et al., 2018).

This state-of-the-art review provides useful information on the reuse of RCA and RHA solid wastes, as a promising alternative to improve the physical and mechanical behaviors of structural concrete; showing the different proposals of use in substitution or addition of each concrete component, considering as parameters R w/c, adequate dosages, optimum temperature of RHA, and size of RCA, among others.

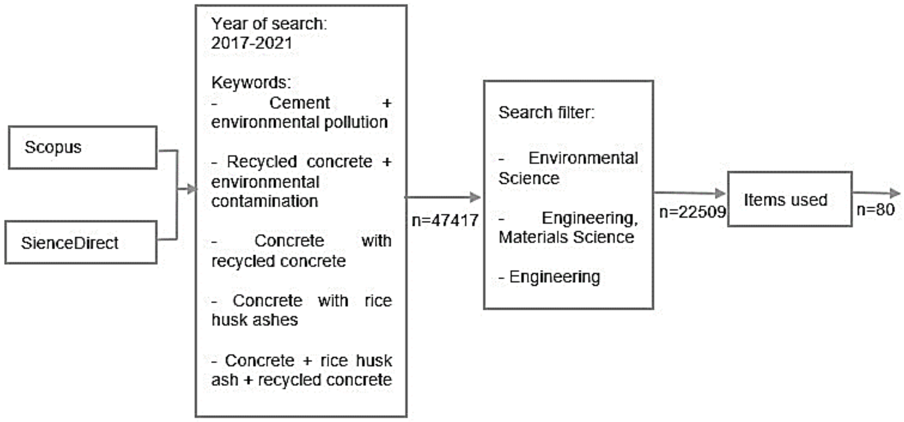

Figure 1. Process flow of obtaining processes and search parameters for publications.

Table 1. Results of research with filters.

Database	Year of search	Keywords	Documents without filter	Search filter	Documents with filter	Selected documents	Total
Scopus	2017-2021	Cement + environmental pollution	1224	Environmental science	573	5	36
		Recycled concrete + environmental contamination	16	Engineering, materials science	12	6	
		Concrete with recycled concrete	5585	Engineering	4184	15	
		Concrete with rice husk ashes	640	Engineering	419	9	
		Concrete + rice husk ash + recycled concrete	43	Engineering	28	1	
ScienceDirect	2017-2021	Cement + environmental pollution	14651	Environmental science.	6758	5	44
		Recycled concrete + environmental contamination	3255	Environmental Science, Engineering	2023	4	
		Concrete with recycled concrete	20135	Engineering	7637	22	
		Concrete with rice husk ashes	585	Engineering	276	11	
		Concrete + rice husk ash + recycled concrete	1283	Engineering	599	2	

Table 2. Distribution of articles by database and year of publication.

Database	Year in which the articles were published					Total
	2017	2018	2019	2020	2021	
Scopus	6	7	6	7	10	36
ScienceDirect	4	8	9	11	12	44
Total	10	15	15	18	22	80

2. Methodology

The present research was conducted using 80 articles published in high impact journals, indexed in databases such as: Scopus, and ScienceDirect, with the following keywords: cement + environmental pollution, recycled concrete + environmental pollution, concrete with recycled concrete, concrete with rice husk ash, concrete + rice husk ash + recycled concrete, between 2017 to 2021 as shown in Table 1, with the following results: 10 articles in 2017, 15 articles in 2018, 15 articles in 2019, 18 articles in 2020 and 22 articles in 2021 as shown in Table 2. The process elicitation flow and publication search parameters are shown in Figure 1.

3. Results and discussion

3.1. RHA and RCA waste production

The productions that generate these waste materials currently generate immense quantities that affect human health, damage the environment and its resources; this compilation of information is shown in Table 3.

Table 3. Results of research with filters.

Reference	Country	Quantities (Ton/year)	
		RCA	RHA
(Chakraborty & Thakur, 2021)	India	48	---
(Islam et al., 2019).	Dhaka city	1.28	---
(Selvaranjan et al., 2021)	Sri Lanka	---	0.88
(Gonçalves & Bergmann, 2007)	the federal state of Rio Grande do Sul	---	164.81
(Dytianquin et al., 2021)	UE	374	---
(Ghisellini et al., 2021)	Naples	1	---
(Santos & Tubino, 2021)	Brazil	44	---

Thus, the quantities extracted from some publications confirm the growing production of these wastes, as well as the majority production of rice consumption, which has repercussions on the production of rice husks, considering that approximately 200 kg of rice ash is extracted from 1000 kg of rice husks; this current rice production is shown in Figures 2 and 3, respectively.

Figure 2. World rice production statistics for the period 2009-2023. Source: (statista, 2023a).

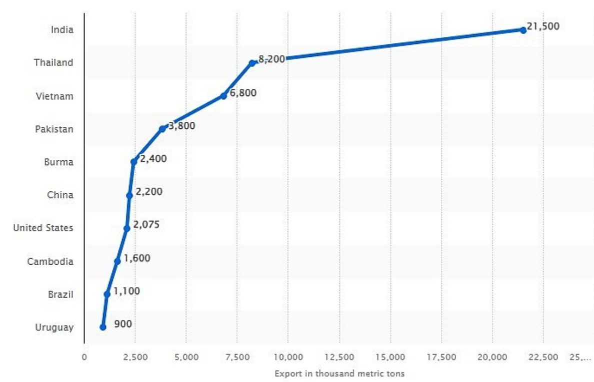

Figure 3. Major world rice exporting countries in 2022/2023. Source: (statista, 2023b).

3.2. Concrete with recycled concrete

3.2.1. Mechanical properties

3.2.1.1. Compressive strength

Gholampour and Ozbakkaloglu (2018) prepared a study on the long-term properties of concretes made with recycled aggregates of different strengths of the base concrete. For this purpose, they manufactured a total of six batches of concretes with recycled aggregate concrete (RAC). Tests were carried out to establish the compressive, splitting tensile, elastic modulus, workability, drying shrinkage and creep performance of each batch. Their experimental results showed that the compressive strength of high-strength RAC containing high-strength recycled concrete aggregates of 110 MPa is slightly higher than that of conventional high-strength concrete prepared with the same w/c ratio.

Chen et al. (2019) in their research used three parameters: the % recycled coarse aggregate (RCA) replacement (γ), lateral confining pressure (σ3) and the age of the concrete from which the RCA was obtained were considered in the tests, in order to discuss the effects of these parameters on the failure behavior of RAC, compressive strength, elastic modulus and stress-strain curves of RAC. The results of their experimental studies dated that: When the lateral confining pressure σ3 is 12 MPa, the RAC specimen experienced brittle failure. When the lateral confining pressure σ3 is >12 MPa, the RAC failure became more ductile.

Zheng et al. (2019) elaborated an experimental investigation where they studied the effect of replacing natural coarse aggregate (NCA) with recycled concrete aggregate (RCA) or recycled clay brick aggregate (RBA) on the compressive mechanical behavior of concrete in its solid state. Two grades of concrete, C25 and C50, were studied. The results found that when the NCA was replaced by 100% RCA, the reduction of the 28-day compressive mechanical behavior was only 7.2% and 9.6% for C25 and C50 recycled concrete. They also indicated that concrete with RCA performs better than concrete with RBA.

Berredjem et al. (2020) compared the long-term mechanical strengths (one-year period) of NA composite concrete and concrete incorporating RCA that were preserved in different types of water baths: tap water, demineralized water, and salt water. In the second step, they looked at durability indicators such as accessible water porosity, ammonium nitrate leaching, helium gas permeability and capillary water absorption. Their results showed that the use of RCA affects the mechanical properties of concrete in either compression or splitting tensile.

Velay-Lizancos et al. (2018) studied the influence of fine and coarse aggregate (as a whole) of recycled concrete on concrete, having greater emphasis on the variation of E-Modulus kinetics and the relationship it has with compressive strength and non-destructive testing. For this purpose, they replaced natural aggregates with recycled aggregates in proportions of 0% (it was the reference concrete) and (8%, 20%, 31%), of the total amount of aggregates. The researchers concluded that, at early ages, the relationship between compressive mechanical behavior and elastic modulus is affected by the amount of recycled aggregate.

Bui et al. (2018) proposed a method with the aim of improving the mechanical behavior of RAC by employing sodium silicate and silica fume. Their experimental studies concluded that the amount of silica fume and the w/c ratio impaired the mechanical properties of the treated RAC. It was also shown that the combination of sodium silicate and silica fume accelerated the strength development of RAC at an early age and was comparable to natural aggregate concrete. Table 4 shows a summary of the above mentioned investigations detailing the compressive strength of concrete according to its proportions.

3.2.1.2. Resistance to caking

Pacheco et al. (2019) the objective of their research was to analyze what influence recycled concrete aggregates have on the mechanical behavior and variability of concrete and performed comparative evaluations with the objective of predicting in a standard way the variability of concrete containing natural aggregates. They concluded that the properties of high-strength concrete with coarse recycled aggregates or coarse crushed limestone were significantly more variable than those of all other mixtures tested.

Table 4. Compressive strength of concrete, according to its proportions.

Material of construction	Water/cement ratio	Percentage of RCA	Compressive strength (MPa)	References
Concrete + RCA	0.41	70% RCA	22.50 MPa	(Chen et al., 2019)
	0.35	25% RCA	50.00 MPa	(Zheng et al., 2019)
	0.47	25% RCA	47.00 MPa	(Berredjem et al., 2020)
	-------	8% RCA	70.00 MPa	(Velay-Lizancos et al., 2018)
	0.45	30% RCA	55.00 MPa	(Bui et al., 2018)

3.2.1.3. Flexural strength

Seara-Paz et al. (2018) conductedan investigation where they analyzed the flexural behavior of recycled concrete that was subjected to increasing loads until failure, for this purpose they elaborated eight reinforced concrete beams with recycled coarse aggregates, the water/cement ratios they used were 0.50 and 0.65 with replacement percentages of 0%, 20%, 50% and 100%. Their experimental results showed that all reinforced concrete beams failed in flexure because of longitudinal steel deformation and subsequent crushing of the concrete in the compression zone.

Alnahhal and Aljidda (2018) investigated the effect of the use of recycled concrete aggregates from construction and demolition (C&D) waste combined with basalt macrofibers (BMF) on the bending behaviour and maximum capacity of reinforced concrete beams (RC) both analytically and experimentally. It was demonstrated that when using RCA in the concrete mixtures in relation to the bending of the tested beams was relatively small even with a total replacement. Likewise, the impact of the use of RCA was reduced for beams with concrete mixtures containing 1% or more basalt microfibers.

Brandes and Kurama (2018) in their research studied the effect of recycled concrete aggregates to determine the ultimate load behavior of shear-critical precast/prestressed concrete beams. For this purpose, they used two sources of high-quality RCA to replace natural crushed limestone at 50% and 100% by volume. Their findings regarding the use of RCA resulted in a reduction in beam cracking load and initial beam stiffness. The maximum reductions were 21% and 25% for cracking load and beam stiffness, respectively. Table 5 shows a summary of the above mentioned investigations detailing the flexural strength behaviour of concrete with the addition of RCA.

3.2.1.4. Abrasion resistance

El-Hassan et al. (2019) in their research studied the properties of permeable concrete made from recycled concrete aggregates. The replacement levels of natural aggregates by RCA were (0, 10, 20, 20, 40, 40, 70 and 100%). They also incorporated slag to improve the performance and sustainability of the concrete mixes. Their conclusions regarding the abrasion resistance of pervious concrete were that it is mainly influenced by the replacement of RCA. Also, higher mass loss was observed with more NA replaced by RCA. But, up to 20% RCA could be used without significantly affecting the abrasion resistance of cement-based concrete. The addition of 50% slag could increase this RCA replacement to 40%.

3.2.1.5. Chloride ion resistance

Kurda et al. (2017) prepared a detailed literature review with the aim of studying the combined effects of incorporating high amounts of fly ash (FA) and recycled concrete aggregates in concrete. They studied the fresh and hardened properties of concrete where fine and coarse RCA were used as partial or total replacement of fine and coarse natural aggregates (NA), respectively, and where high contents of FA are incorporated as binder or filler. They concluded that replacing 100% of natural aggregates with RCA produces a negative effect on concrete performance related to resistance to chloride ion attack, but this can be changed by incorporating 20% FA.

Ismail et al. (2017) in their research aimed to evaluate how different types of curing conditions influence the short- and long-term mechanical strength in terms of resistance to (compressive and flexural) likewise durability (water absorption, intrinsic air permeability, total porosity, among others) of RAC modified with treated RCA. It was concluded that not much difference was detected between the TR (RAC composed of treated coarse RCA) and CO (control concrete) series specimens in terms of water absorption under all exposure conditions.

Chen et al. (2020) investigated on the carbonation durability of two generations of 100% RAC (recycled coarse aggregate concrete) with the effect of chloride ion corrosion. For this purpose, they analyzed the evolution of the quality of recycled coarse aggregate concrete with the increase of recycling cycles, and both the carbonation depth, also its compressive strength as well as the porosity of RAC before and after chloride ion corrosion were measured. The authors state that chloride ion corrosion negatively affected the carbonation behavior of RAC, and the negative effect was more severe with increasing corrosion time and recycling periods. Chloride ion corrosion led to the increase of RAC porosity, becoming the fundamental reason for the deterioration of carbonation resistance.

Yue et al. (2020) prepared a paper where they investigated the degradation behavior of multiple ITZs in RAC subjected to an aggressive ionic environment. The microhardness and microstructure of multiple ITZs in RAC were studied after aggressive ionic attack, and the effects of the strength of new and old concrete on the properties of multiple ITZs in RAC were investigated. The results detail that there was a slight increase in the microhardness of ITZs after having a short duration sulfate attack, meanwhile the microhardness of ITZs decreased by further increasing the days of sulfate attack. Also, there was a binomial relationship between the microhardness of multiple ITZs and the duration of sulfate ion attack.

Table 5. Flexural strength performance of concrete with the addition of RCA.

Material of construction	Water / cement ratio	Percentage of RCA	Flexural strength	References
Concrete + RCA	0.50	20% RCA	All reinforced concrete beams failed in flexure because of longitudinal steel deformation and subsequent crushing of the concrete in the compression zone.	(Seara-Paz et al., 2018)
	0.65	100% RCA		
	-------	50% RCA + 1.50% Basalt macrofibers	The flexural strength of the concrete increased by 29.44% when these percentages were added, since it reached a flexural strength of 6.19 MPa	(Alnahhal & Aljidda, 2018)
	0.34	50% RCA	The maximum reductions were 21% and 25% for cracking load and beam stiffness, respectively.	(Brandes & Kurama, 2018)
	0.38	100% RCA		

3.2.2. Physical properties

3.2.2.1. Workability

Bidabadi et al. (2020) in the first phase of their study, tested different recycled concrete mixes with different levels of replacement of fine and coarse recycled aggregates respectively, instead of natural fine and coarse natural aggregates. The authors demonstrated that the replacement of fine aggregates at the 30% level has no significant negative effect on the fresh and hard properties of concrete, such as fresh density, workability, and compressive strength, considering this mix design as the optimum recycled mix design.

Plaza et al. (2021) analyzed the effect of simultaneous substitution of 0% to 100% of natural coarse aggregate by recycled concrete and of natural fine aggregates by 50% recycled concrete or construction and demolition waste mixed fine aggregates. These new secondary raw materials were characterized and an analysis of the effect of their use on the fresh and solid properties of the resulting eco-concretes was followed. The results express that the workability of recycled concrete is not affected when using recycled aggregates, independently of the nature or replacement ratio of the latter; all the mixtures studied exhibited soft consistency.

Cantero et al. (2018) evaluated the behavior of structural concretes containing (20, 25, 50, 50, 75, and 100%) recycled coarse aggregate mixed. The study variables of the researchers were: the workability of the concrete in fresh state, the air content, as well as the density, mechanical behavior in compression, flexure, and tension of the hardened concrete. The results regarding the workability of concrete did not negatively affect the use of 100% mixed recycled aggregate.

3.2.2.2. Electrical resistivity

Singh and Singh (2019) as a first step, in their study, was to quantify the electrical resistivity of self-consolidating concrete (SCC) made from coarse reused concrete aggregates (CrRCA) and fine reused concrete aggregates (FnRCA) in alternate replacements of coarse natural aggregates (CNA) and fine natural aggregates (FNA) respectively. As a second step, they evaluated the effectiveness of silica fume (SF) and metakaolin (MK) to balance the loss of SCC performance because of replacing natural aggregates with recycled aggregates, measured in terms of electrical resistivity. The authors observed that the electrical resistivity of the SF/MK blended SCC combination made with 50% (CrRCA) and 100% (FnRCA) was higher than that of the control SCC combination at all curing stages.

3.2.2.3. High temperatures

Garcia-Troncoso et al. (2021) in their study, their objective was to investigate the properties of self-compacting concrete, using three different types of aggregates namely recycled concrete aggregate (RCA), recycled concrete block aggregate (CBA) and recycled brick aggregate (RBA). The researchers evaluated different properties of the concrete, and evaluated the elevated temperature resistance of the SCC, which carried the several types of recycled aggregates in its structure. They strongly recommend the use of RBA as aggregate to achieve higher temperature resistance of SCC, since SCC-RBA can maintain its integrity and has an ideal compressive mechanical performance of 21.8 MPa even after exposure to an elevated temperature of 800°C.

Alrajfi et al. (2021) prepared an experimental study where they evaluated the structural performance of RC beams made of natural aggregate, recycled aggregate concrete and reclaimed asphalt pavement concrete (RAP) at both normal and elevated temperature. The replacement ratios they used were NA was replaced by RAC at 20% and 40%. They also used three replacement combinations of RAC and RAP. It was concluded that using RAC as a replacement for NA with a ratio of 40% decreased the loading capacity by 10% and 15% at normal and elevated temperature, respectively.

Meng et al. (2017) for their research fabricated 100 cylindrical specimens with the motive of studying the triaxial compressive mechanical performance of recycled aggregate concrete, they used different replacement rates of: (0, 30, 70 and 100%), the triaxial stress for their experimental work was as follows: (0, 5, 10, 10, 15 and 20 Mpa), after exposure to different elevated temperatures of: (20, 200, 300, 400 and 500 °C). They concluded that the triaxial strength of the samples is almost equal when the temperatures do not exceed 400 °C.

Pliya et al. (2019) the objective of their work was to study the high temperature performance (20°C-600°C) of high strength concrete (HSC) which is composed of different amounts of recycled coarse aggregate subjected to different heating rates, the water/cement ratio they used was 0.3 for all samples, the study variables were compressive strength, heating rate and loading condition (with and without preloading). Their results show that the compressive mechanical performance of concrete with 15% and 30% recycled aggregates at room temperature was not significantly affected with respect to concrete with 100% natural aggregates. At a lower heating of 1.5°C/min, the compressive mechanical performance indices at 500°C were similar for both RCA mixtures.

Amiri et al. (2021) the purpose of their experimental study was to investigate the influences of simultaneous replacements of cement by residual rubber powder (WRP) and coarse aggregate by recycled concrete aggregate (RCA) and their influence on concrete durability and mechanical properties. For that, they prepared concrete specimens containing the WRP with the replacement proportions of (0, 2.5 and 5%) by weight of cement, and for the RCA with the replacement levels were (0, 25 and 50%) of coarse aggregate. Also, different amounts of water to binder and binder content were used. The experimental results showed that there are no very noticeable differences between the durability performances of the concrete specimens containing the rates (WRP, RCA) of (2.5%, 25%), (5%, 25%) and their reference concretes. It was also demonstrated that the negative effects of RCA are neutralized by the positive effects of WRP in terms of durability performance.

3.2.2.4. Acoustic properties

Wang & Du (2020) elaborated a type of recycled granulated rubber concrete (RCC) which was made from recycled aggregates and rubber materials, for this they considered different study parameters, they made a comparison and analysis of the physical, as thermal and also acoustic performance of normal concrete (NC), concrete which in its composition carried recycled aggregate (RC) and RCC. They concluded that, with the increase of the amount of rubber, RCC has better sound absorption performance than RC and NC; when the replacement rate of rubber is 30%, there is a higher sound insulation coefficient and noise reduction and better sound insulation effect in the frequency range of 250 Hz to 2000 Hz.

Xu et al. (2018b) in their research elaborated experimental studies in order to determine the bond between recycled aggregate concrete and ribbed steel bars, for this purpose they used the acoustic emission (AE) technique. The researchers in the extraction tests considered four different amounts of recycled aggregate replacement which were (0, 50, 60 and 70%). Their experimental analysis results show that the internal damage of RAC is more severe and dispersed both in space and time, which is due to the initial defect of recycled aggregate. By using the AE monitoring method, the dependence of the RAC joint failure mechanism on the recycled aggregate replacement rate could be explained.

Men et al. (2020) in their study performed uniaxial compression test and test application of acoustic emission (AE) technology of recycled coarse aggregate concrete specimens at the same time. Variations of compressive strength and AE parameters (counts and energy) were studied by using specimens with different loading rates, maximum aggregate sizes and water-cement ratios (WC). The authors, based on AE parameters, used a novel approach called cumulative stage ratio (SCP analysis was proposed) where they discussed the compressive failure process and AE performance of RAC with different conditions. Concluding that the increase of water-cement ratio also causes the change of AE counts and energy in the stable ITZ (interfacial transition zone) microcracking and unstable cracking of concrete, contrary to the change caused by loading rate. Table 6 shows a summary of the above mentioned investigations detailing the high temperature and acoustic properties of concrete with RCA incorporation.

3.3. Rice husk ash concrete

3.3.1. Mechanical properties

3.3.1.1. Compressive strength

Kanthe et al. (2018) did a research where they describe the combined effect of fly ash and the use of RHA on the properties of concrete as partial replacement for cement and have high pozzolanic strength, they used the mix composition with 10% RHA along with 10, 20 and 30% FA as partial replacement of cement, they studied the compressive mechanical performance, workability and durability performance. The researchers showed that the highest compressive strength was achieved with 10% RHA and 20% FA used.

Le et al. (2018) in their study detailed that RHA is classified as a highly reactive pozzolan. It has a very high silica content, like the less expensive and locally available silica fume as a mineral admixture in concrete. It is concluded that the addition of RHA to HPFGC significantly improves the compressive mechanical performance, especially when the concrete is made with 20% RHA.

Table 6. Physical properties of concrete with RCA incorporation.

Physical properties	References	Variants	Concrete behavior
High temperatures	(Garcia-Troncoso et al., 2021)	400°C	It reached a strength of 21.8 MPa; being the most suitable in the mechanical behavior of concrete.
	(Alrajfi et al., 2021)	20°C - 500°C	The mechanical properties decreased for the same substitution ratio of recycled aggregates which were 10%, 20% and 30% and with increasing temperature.
	(Meng et al., 2017)	500°C	Above 500°C high temperature, the triaxial strength gradually decreased, but the amplitude of the decrease is smaller than that of uniaxial strength.
	(Pliya et al., 2019)	20°C-600°C	Compressive strength at 15% and 30% at room temperature was not affected.
Acoustic properties	(Wang & Du, 2020)	30% replacement	Acoustic isolation in frequency from 250 Hz to 2000 Hz.
	(Xu et al., 2018b)	0%, 50%, 60% and 70%.	RAC internal damage is more severe and dispersed in both space and time.

Sandhu and Siddique (2017), They did an investigation where in the manufacture of concrete they used RHA, this by-product is obtained by burning rice husks which is rich in amorphous reactive silica containing approximately 90% silica. The incorporation of 10-15% RHA as a partial replacement of cement improves the strength and durability properties of HAC.

Kang et al. (2019) in their study, RHA-based reactive filler was used in ultra-high-performance concrete (UHPC) to improve the mechanical properties without heat treatment. Experimental results show exceptional strength around 200 MPa after 91 days under ambient conditions (20 °C and 60% relative humidity).

Faried et al. (2021) investigated to highlight the effect of seven diverse types of nano rice husk ash (NRHA) on mechanical pulse rate. The RHA was fabricated by calcining rice husks at temperatures of 300, 500, 700 and 900°C at a constant burning time (for 3h). Then, it was kept cooling at a constant rate of 10- / min and different burning times of (9, 7, 5 and 3 h, respectively). After that, the product was milled to nanometer size where it significantly improved the mechanical performance upon compression at combustion temperature of 900 °C and 700 °C for 1% NRHA and at 500 °C and 300 °C for 3% and 5% NRHA.

Gill and Siddique (2017) studied the microstructural properties of self-compacting concrete (SCC) containing metakaolin (MK) and rice husk ash (RHA). For this they elaborated sixteen mixtures in total. First it was the control mixture, then three mixtures with 5%, 10%, 15% MK as cement substitution, then three mixtures were made with 10%, 20%, 30% RHA as a replacement for the fine aggregates and nine additional mixtures were made with different combinations of RHA and MK. The researchers arrived at the results that when MK and RHA were used independently, maximum compression results were obtained with 15% MK and 10% RHA replacement. Table 7 shows a summary of the above mentioned investigations detailing the behaviour of the compressive strength of concrete, according to its RHA proportions.

3.3.1.2. Tensile strength

Olutoge and Adesina (2019) investigated the use of RHA as an alternative to conventional cement in the manufacture of concrete, mortar, and masonry. Their experimental test results show that replacing conventional cement with RHA reduced the tensile strength of both compression and splitting of the resulting concrete. Saturated water absorption and apparent porosity were found to increase while bulk density was found to be reduced especially with a higher RHA content.

Kang et al. (2019) in their research they used RHA-based reactive filler in ultra-high-performance concrete to improve mechanical properties without heat treatment. Their experimental results show an outstanding strength around 200 MPa after 91 days, under ambient conditions (20 °C and 60% relative humidity). This was possible due to the promotion of the pozzolanic reaction by additional water and amorphous silica provided by the porous (i.e., internal curing effect) and reactive filler, respectively; therefore, the volume of the capillary pores was reduced.

3.3.1.3. Flexural strength

Varadharajan et al. (2020) aimed to replace cement with RHA in varying proportions from 0% to 20%. They also used marble waste powder (MWP) in concrete in substitution for fine aggregate in varying proportions from 0% to 30%. They also used hooked steel fibers and the amount they used was 1.5% by weight of cement to improve mechanical properties as well as permeability. Their experimental results showed that the optimum combination was (15% RHA, 1.5% hooked steel fibers and 30% MWP).

Panda et al. (2020) focused on studying the mechanical properties of crushed shell concrete by partial replacement of crushed shell with fine aggregate and partial replacement of RHA with cement. All tests were created by substituting (0, 10%, 20% and 30%) of fine aggregate with crushed seashells

Table 7. Compressive strength of concrete, according to its RHA proportions.

Material of construction	Water/cement ratio	Percentage of RHA	Compressive strength (MPa)	References
Concrete + RHA	----------	10% RHA- 20% FA	The strength was like that of the standard concrete	(Kanthe et al., 2018)
	0.33	5% RHA	55 MPa	(Le et al., 2018)
		15% RHA	62 MPa	
	0.41	15% RHA	48.8 MPa	(Sandhu & Siddique, 2017)
		20% RHA	40.2 MPa	
	-------	3% RHA	Increased its compressive strength by 9.4% to 120 MPa.	(Faried et al., 2021)
		5% RHA	Increased its compressive strength by 5.6% to 100 MPa.	
	0.44	10% RHA	43.4 MPa	(Gill and Siddique, 2017)
		20% RHA	36.2 MPa	
		30% RHA	30.3 MPa	
	0.65	5% RHA	38.9 MPa	(Olutoge & Adesina, 2019)
		12.5% RHA	20.8 MPa	

and replacing (0, 10% and 20%) of RHA with cement. Slump and other physical properties were studied, for tensile, compression and flexural mechanical properties were done after 7, 28, and 90 days of curing under water. The authors detailed that the maximum compressive, tensile, and flexural performance was achieved with 10% replacement of fine aggregate by crushed seashell and the optimum substitution ratio of RHA for cement was 20%.

Ali et al. (2021) in their research study the effect of RHA partially substituted for cement to produce lightweight aerated concrete. For this purpose, they used RHA with different replacement proportions by weight of cement, the proportions were (0, 2.5, 5, 7.5, 10, 12.5 and 15%). In addition, aluminum powder was added in the mixing process at 0.5% by weight of binder. It was concluded that the maximum mechanical behavior of concrete such as: compressive strength was 22.16%, split tensile with 20.41% and flexural with 22.31%, higher than the control mix in a period of 28 days, these results were achieved with 10% RHA replaced by weight cement.

Siddika et al. (2018) investigated different mechanical and physical properties of concrete using RHA as a partial replacement of cement. The researchers evaluated concrete specimens with different proportions of RHA as replacement of cement content and with different w/c ratio. The results related to the compression, flexural and tensile mechanical performance of the concrete specimens with 10% cement replacement with RHA concluded that they are comparable with the control specimens. Table 8 shows a summary of the above mentioned investigations detailing the flexural strength behaviour of concrete with the addition of RHA.

3.3.1.4. Abrasion resistance

Djamaluddin et al. (2018) the objective of their study was to investigate what is the effect of RHA addition that was collected from uncontrolled burning and without previous grinding (NRHA), this material was used as a replacement of cement in concrete. The properties studied were compressive mechanical performance, abrasion resistance expressed as weight loss, among others. The results in relation to abrasion resistance showed that by mixing NRHA with aggregate for a period of 8 min, the abrasion resistance improved by 10.35% at 28 days and 23.62% at 91 days over the control concrete.

3.3.2. Physical properties

3.3.2.1. Chloride resistance

Fapohunda et al. (2017) did an investigation on the use of materials that can replace cement in concrete. One of them is rice husk ash (RHA), which the researchers found suitable to partially replace Portland cement in concrete production, controlled incineration is necessary to produce RHA with a structure that can lead to structural concrete, the use of RHA resulted in higher water demand up to 10% replacement of cement by RHA will result in strength development comparable to that of control samples.

Sahoo et al. (2021) in their research studied the durability properties of concrete by incorporating silica fume (SF) and rice husk ash (RHA) in partial replacement of Portland slag cement (PSC). Their experimental results showed that all the mixtures in general of concrete with SF or RHA demonstrated higher resistance to chloride attack related, so the researchers

Table 8. Flexural strength behavior of concrete with the addition of RHA.

Material of construction	Water/cement ratio	Percentage of RHA	Flexural strength	References
Concrete + RHA	------	5% RHA	An average strength improvement of 9.9 %, 14.4 % and 18.9 % was observed for 5 %, 10 % and 15 % cement substitution with RHA	(Varadharajan et al., 2020)
		10% RHA		
		15% RHA		
	0.45	20% crushed shell per fine aggregate - 10% RHA per cement	Decreases flexural strength, up to 60 MPa	(Panda et al., 2020)
		10% marine shell per fine aggregate - 20% RHA per cement	Achieves an optimum flexural strength of 70 MPa	
	0.60	10% RHA	A flexural strength of 22.31% was achieved, superior to that of the control mix in a period of 28 days.	(Ali et al., 2021)
	0.60	10% RHA	Achieved a flexural strength of 16.56 MPa during 28 days of curing	(Siddika et al., 2018)
		15% RHA	It showed an increase in flexural strength of 27.68 MPa after 28 days of curing.	

deduce that this type of concrete can be used in structures that are exposed to saline environment.

Krishna et al. (2017) made an investigation of industrial wastes and agricultural by-products such as: fly ash and rice husk ash, silica fume, they used RHA as cement admixture in concrete and studied their properties and examined the strength and workability parameters of concrete. Four different substitution levels, namely 5%, 10%, 15% and 20%, have been selected and studied with respect to the method of substitution and it was evident that the incorporation of RHA enables the concrete to obtain high resistance to chloride attack.

Bheel et al. (2020) the object of their research was to study the characteristics of concrete by partially replacing cement with rice husk ash (RHA) and fly ash (FA). This study focuses on the performance of concrete. Cement was substituted in different proportions of RHA and FA combined with half replacement of RHA and FA. It was obtained in their results that with 5% RHA + 5% fly ash optimum strengths were achieved; however, as the RHA and FA content increased the concrete performance decreased.

Luo et al. (2021) in their research rice husk ash (RHA) has been considered as a suitable mineral admixture for cement. The effect of temperature is not well considered. Therefore, in their study they aimed to develop a method to evaluate the degree of hydration of blended cement that can consider the influence of temperature. The key to their method was to adopt a kinetic model of non-evaporable water (NEW) hydration to determine the final NEW content of blended cement when it is fully hydrated. According to the model fitting results when m = 3, the addition of RHA could reduce the apparent activation energy (Ea) of blended cement, the Ea values of OPC, RHA-1 cement, and RHA-2 cement are 37.64 kJ/mol.

Zareei et al. (2017) in their study presented the benefits resulting from different amounts of rice husk ash (RHA) on concrete indicators by five substitution ratios of 5%, 10%, 15%, 15%, 20% and 25% RHA per weight of cement also 10% micro-silica (MS) and thus to compare with a reference mix containing 100% Portland cement. The authors demonstrated that the incorporation of RHA into the cement aids low amounts of chloride ion penetration with ratios up to 928 Coulombs at 25% RHA replacement.

3.3.2.2. Workability

Thomas (2018) in their research elaborated a detailed literature review with the purpose of describing in detail some of the results that have been published related to the use of RHA as a supplementary cementitious material also the properties of such concrete in its fresh and hardened stages are studied. The results described by the authors detail that with percentages higher than 10%, workability is reduced as the RHA requires more water, but this can be corrected by increasing the dosage of superplasticizer.

3.3.2.3. Waterproof

Zhu et al. (2019) studied the influence of using RHA on the waterproofing and microstructural properties of ultrafine fly ash-based geopolymer (UUFA). For this purpose, they prepared and characterized quantities of RHA. Combining with the softening and surface softening coefficient by obtaining TG and FT-IR tests, etc., the mechanism was discovered. The results indicate that, to the densification of the structure, but also decline the existence of calcium hydroxide and promote gel formation, which makes a significant contribution to the improvement of the impermeable property.

3.3.2.4. High temperatures

Khaliq and Mujeeb (2019) in their study evaluated the residual mechanical properties of high strength concrete (HSC) incorporating 10% RHA and 10% bagasse ash (BA) as cement replacement in its structure, after exposure of this type of concrete to elevated temperatures. Their experimental results reveal that the residual mechanical performance of pozzolanic concretes deteriorates at temperatures above 200 °C. Table 9 shows a summary of the above mentioned investigations detailing the workability and high temperature behaviour of concrete with the incorporation of rice husk ash.

3.3.2.5. Electrical resistivity

Ameri et al. (2019) the objective of their study was to optimize in self-compacting concrete (SCC) the RHA content, also the bacterial concentration, for that the cement was replaced by RHA in proportions of (0, 5, 10, 15, 15, 20, 25 and 30%) by weight of cement. Also, micro-silica (MS) was included in an amount of 10% by weight of the cementitious materials. The mixture with the optimum amount of RHA was supplied with bacterial cells with concentrations of 10^3 cells/ml 10^5 cells/ml and 10^7 cells/ml cells/ml to reduce the formation of microcracks. Their experimental results showed that the optimal amount of RHA with the maximum concentration of bacteria led to a 415% increase in electrical resistivity and reduced all permeability-related properties by up to 80% compared to the control mixture.

Cascudo et al. (2021) evaluated the pore solution by the ex-situ leaching method of an extensive variety of concretes which were modified with mineral additions and subjected to natural carbonation over a 14-year period of exposure in a typical urban environment. The total number of concretes studied were 6 different families, so that five of them used mineral admixtures in their composition and one situation represented the reference concrete which was without mineral admixtures. The following amounts were substituted by mass of cement: silica fume, 10%, metakaolin 10%, RHA 10%, fly ash 25% and blast furnace slag 65%. Their conclusions focus that the effect of carbonation decreases the electrical conductivity of the porous solution in all cases, and that mineral additions decrease the conductivity of the concrete porous solution

3.4. Concrete with rice husk ashes and recycled concrete

Rattanachu et al. (2020) in their study, rice husk ash (RHA) was ground to a high fineness then used to partially replace ordinary Portland cement (OPC) by 20% to 50% by weight of cementitious materials in order to improve the quality of concrete containing recycled aggregate. The variables they studied were the depth of chloride penetration, the corrosion resistance of steel, and the mechanical compressive performance of concrete with a mixture of fine and coarse recycled aggregates. Their results showed that the use of ground rice husk ash (GRHA) up to 50% of cement replacement in RAC offers higher chloride damage performance compared to recycled aggregate concrete (RAC) without GRHA.

Koushkbaghi et al. (2019) the object of their study was to determine the performance of mixes incorporating recycled concrete aggregate (RCA) and RHA in terms of mechanical performance and durability. The mechanical performance was analyzed in relation to the compressive and splitting tensile performance of the concrete. In addition, the authors studied durability properties such as water absorption, chloride diffusion and acid attack. Also, fibrous and non-fibrous concretes were made to study the effect of RHA and RCA. Their experimental results showed that the incorporation of RHA had a not-so-significant improvement in the splitting tensile strength of non-fibrous concrete. As for fibrous concrete, there was a considerable improvement because of the better bond that RHA formed between the concrete with the fibers.

Nuaklong et al. (2020) in their study used RHA with the aim of improving the performance of geopolymer concrete including fly ash with a calcium fly ash content manufactured from recycled concrete coarse aggregate. For this purpose, they evaluated and compared the mechanical properties and their fire resistance performance of geopolymer concretes with addition of RHA and Ns. The authors concluded that using recycled concrete as coarse aggregates in geopolymer concrete reduces its strength but increases the permeability and increases the workability of the concrete when it is fresh.

4. Conclusions

Based on the literature review, the following conclusions can be drawn:

Most of the research conducted worldwide shows that the addition of more than 70% RCA generates a decrease in its compressive strength, since it reaches a strength of 22.50 MPa; however, when 8% RCA is added, it obtains a higher strength of 65 MPa. On the other hand, with respect to its flexural strength, when adding percentages of 50% RCA + 1.50% basalt microfibers, an increase in the flexural strength of the concrete was achieved up to 29.44%. In addition to the above, it is evident that the mechanical characteristics achieved are not the most adequate; however, it was shown that when other materials such as basalt macrofibers or other alternative elements are incorporated, the mechanical behavior of the concrete improves. Next, in the physical properties of the concrete with the addition of RCA, it was observed that high temperatures influence the concrete; likewise, when percentages of 10%, 20% and 30% RCA were substituted, the workability of the construction material is not affected; at the same time, it was evidenced that the mechanical behavior of the concrete reached a compressive strength of 21.8 MPa, which is considered the most suitable.

The use of rice husk ash (RHA) as a partial replacement of cement in the production of concrete has positive effects on its mechanical properties; most authors agree that the optimum replacement percentage of RHA for cement would be between 10% to 15%; likewise, with 10% RHA a compressive strength of 43.4 MPa was achieved and with 15% a strength of 48.8 MPa was obtained; however, with percentages higher than 30%, a deterioration in its mechanical properties was evidenced, being 30.3 MPa. Similarly, in its flexural strength, the most optimum strength was obtained when 10% seashell per fine aggregate - 20% RHA per cement was mixed, since it showed an optimum flexural strength of 70 MPa. Then, in the physical properties of concrete with RHA related to workability, research shows that this type of concrete with up to a maximum of 10% RHA does not lose workability.

Finally, for the use of RHA and recycled concrete together in the production of concrete, the limited existing research shows that it is possible to use 100% recycled aggregate for

Table 9. Physical properties of concrete with the incorporation of rice husk ash.

Physical properties	References	% replacement of rice husk ash in cement	Results obtained for concrete with rice husk ash
Workability	(Thomas, 2018)	5% a 10%	With percentages higher than 10%, workability is reduced.
High temperatures	(Khaliq & Mujeeb, 2019)	10% RHA and 10% BA in concrete structure	Deterioration properties above 200 °C

the coarse aggregate and 10% to 15% RHA in substitution of cement; these substitution proportions would be optimal for structural applications.

There are many investigations that support the use of RHA in concrete and the use of recycled concrete as a concrete component, but these two variables are studied independently, so more research is recommended to study these two substitution variables in the same concrete mix design, for the reason that there is very little research that supports this very important topic of study.

Conflict of interest

The authors have no conflict of interest to declare.

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