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Strength and durability assessment of high-strength concrete with weathered crystalline rock waste as a sustainable partial replacement for fine aggregate

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ABSTRACT

Sand mining from riverbeds has been a vital component of the construction industry for decades, providing a fundamental ingredient for concrete production. However, the indiscriminate extraction of sand from riverbeds led to serious environmental issues, like erosion of riverbeds, destruction of aquatic habitats and increased susceptibility to flooding which emphasizes the necessity of finding alternate materials. Recent studies on Weathered Crystalline Rock, a soft upper layer in quarries – often discarded as waste – have shown that WCR-sand could be a viable alternative to fine-aggregates in concrete thereby alleviating the environmental impacts caused by the extraction of natural resources. Five mixes of M65 grade concrete with sand replacement of 5%, 10%, 15% and 20% with WCR-sand were prepared, cured for maximum 90 days and tested for mechanical and durability properties. Results obtained led to the conclusion that WCR-sand can be a partial replacement up to 5% – theoretically and even up to 10% practically – of sand in concrete without affecting the mechanical and durability properties. This could potentially reduce sand-mining and rock-quarrying up-to 5 to 10% which not only helps curb the depletion of natural resources, a major environmental concern today, but aids in managing waste materials from quarrying.

Keywords: Weathered crystalline rock sand; Mechanical properties; Durability properties; Waste material; Sand-mining and environment.

1. INTRODUCTION

1.1. General

Concrete is second to none in the list of man-made materials used in the construction industry all over the world for both residential and commercial buildings [1, 2]. Its durability, aesthetic appeal, low maintenance cost and the ease with which it can be produced are the primary reasons of popularity. However, the production of concrete requires a significant amount of raw materials, mainly the aggregates both coarse and fine, which is obtained by crushing rocks and/or by extraction from riverbeds, sever contribution to the CO_2 emission during cement production, etc., cause many dangerous environmental issues. Due to these factors, sustainable materials and construction practices are gaining more and more attention round the globe [3]. At the same time, due to the advancements in concrete technology, High Strength Concrete (HSC) offers a mild relaxation to the environmental issues by reducing the cement and concrete production requirements and thereby reducing the above mentioned impacts [4–9]. Sand mining from riverbeds has been a vital component of the construction industry for decades, providing a fundamental ingredient for concrete production [10–13]. The indiscriminate extraction of riverbeds for FA has caused environmental degradation and an impact on natural water flow [14]. Moreover, the increasing demand for sand due to rapid urbanization exacerbates these issues, turning sand mining into a grave environmental concern [15]. Also, due to the increase in demand and decrease in supply of raw materials for concrete production, the cost of concrete is increasing day by day [16, 17]. Hence, the search for alternative sources has led to the use of different types of aggregates [18]. Additionally, the extraction process involves the use of heavy machinery and has been linked to noise pollution, air pollution, and soil degradation, some of the major environmental issues now a days.

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While manufactured sand (M-sand) has emerged as an alternative to river sand, it is vital to acknowledge that M-sand production, which often entails the quarrying of rocks, contributes to its own set of environmental issues [19]. The extraction of rocks from quarries leads to habitat destruction, dust emissions, and landscape alteration.

To address this intricate environmental dilemma, this paper proposes the utilization of waste materials such as WCR, a soft upper layer of rock typically discarded as waste from quarries. The research indicates that integrating WCR as a partial replacement for sand in construction materials could potentially reduce sand mining and rock quarrying at least by 5%. This innovative approach not only offers environmental benefits by curbing the depletion of natural resources but also helps in managing waste materials from mining operations.

Concrete and concrete products manufacturing often makes use of a variety of different forms of FAs, such as Crushed Rock Sand (CRS), Industrial By-Products (IBP), Recycled FAs (RFA), WCR (WCR) sand, etc. [20–25]. These alternatives may originate from natural materials or be derived from a wide variety of sources, such as recycled concrete, rocks, or waste products from manufacturing facilities. The production of these alternative FAs involves the use of processes such as thermal, mechanical, and chemical separation, as well as washing, crushing, and scrubbing. After that, they are used as replacements for river sand in concrete, either by being added to the mixture in its whole or in varying amounts. It has been shown that nations such as the United Kingdom, Sri Lanka, Saudi Arabia, and Singapore make use of offshore sand as well as dune sand in their building processes.

The process of industrialization results in the production of a substantial quantity of garbage, around 85 percent of which is disposed of in landfills [26–29]. On the other hand, there are so many landfills available, and rising worries about the environment mean that there is an increasing need to find productive uses for these waste products. In place of natural FAs in concrete, industrial by-products (IBP) such as blast furnace slag, waste foundry sand (WFS), coal bottom ash (CBA), cement kiln dust (CKD), wood ash (WA), imperial smelting furnace (ISF) slag and ferronickel slag may be used as a replacement to natural FA in concrete [30–32]. Various types of alternatives for FA and their corresponding sources are shown in Figure 1.

The properties of concrete depend on several factors, including the choice of materials, mix design, and curing time. One critical component of concrete that affects the properties is the aggregate, which typically makes up 60–80% of the total volume and FA percentage is in the range of 30 to 40 by mass of the total aggregate [33]. The use of traditional FAs such as river sand or crushed stone has been associated with several environmental concerns, including resource depletion, ecosystem disturbance, and energy consumption. On the other side, the requirement of construction materials will be doubled by the year 2030. This has prompted researchers to explore the use of alternative materials such as recycled aggregates, waste materials, and locally available materials [34].

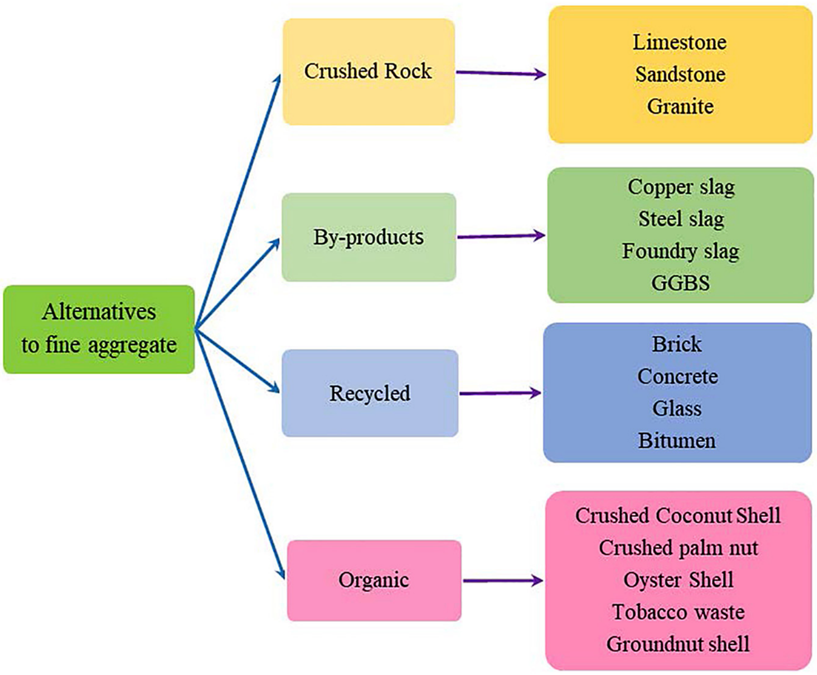

Figure 1: Different types of fine aggregate alternatives.

1.2. WCR as a potential alternative

The study in this paper presents a novel investigation into the potential of weathered crystalline rock (WCR) sand, a previously discarded waste material, as a sustainable replacement for natural sand in HSC, specifically focusing on M65 grade. Found abundantly in regions like Canadian Shield, Brazilian Shield, Siberian Craton, Ethiopian Highlands, etc., WCR-sand represents the soft upper layer of weathered rock formations, typically discarded as waste in quarries and earlier used as a material for tiny retaining bunds for agriculture in sloping terrains. Preliminary studies have hinted at its promising potential as a substitute for river sand or manufactured sand (m-sand). However, a comprehensive understanding of its impact on the mechanical and durability properties of HSC is crucial for widespread adoption.

1.3. Bridging the gap

Despite the pressing need for sustainable construction materials, research on WCR sand as a concrete constituent remains limited as its use is in beginning stage in construction industry. Existing studies primarily focus on its feasibility in lower-grade concrete mixes or its use as a partial replacement for natural sand. Furthermore, investigations delve into individual mechanical properties or specific durability aspects in isolation. This study addresses this gap by conducting a comprehensive evaluation of WCR sand's influence on the mechanical and durability characteristics of M65 grade concrete. It goes beyond merely assessing individual properties and delves into synergistic effects by testing various WCR sand replacement percentages (0%, 5%, 10%, 15%, and 20%) across a spectrum of tests encompassing:

- Mechanical Properties: 28-day compressive, split tensile, and flexural strength tests were considered for this study.
- Durability Properties of water cured specimens for 90 days: Water permeability, abrasion resistance, sulphate attack (both through compressive strength reduction and weight loss), and chloride penetration tests.

1.4. Significance and potential impact

The significance of this study lies in its approach to analyse the viability of WCR sand as a replacement for natural sand in HSC. By investigating both its mechanical and durability characteristics, the research depicts a comprehensive picture of this waste material's potential within the demanding realm of HSC applications. The findings hold the potential to:

- Reduce dependence on natural sand: By demonstrating the efficacy of WCR sand as a viable alternative, the study can contribute to alleviating the pressure on dwindling natural sand resources.
- Promote sustainable construction practices: Utilizing waste materials like WCR sand aligns with the principles of circular economy and reduces the environmental footprint of the construction industry.
- Offer economic benefits: By providing a locally available and potentially cost-effective alternative to natural sand, WCR sand can offer economic advantages for construction projects.
- Open doors for further research: The study paves the way for further research on optimizing WCR sand properties through pre-treatment methods and exploring its applicability in different concrete mix designs and applications.

The growing concerns about environmental sustainability and resource depletion demand innovative solutions within the construction sector. This paper, by exploring the potential of WCR sand as a sustainable substitute for natural sand in HSC, contributes to building a more resilient and environmentally responsible future for the construction industry. The investigation delves into both the mechanical and durability characteristics of WCR sand concrete, offering a comprehensive understanding of its viability and paving the way for further research and implementation. By embracing waste materials like WCR sand, we can not only address the challenges of resource scarcity but also pave the way for a more sustainable construction future.

2. MATERIALS AND METHODS

2.1. Materials

Ordinary Portland Cement (OPC) conforming to IS: 12269-2013 [35] has been used in this research program as the binding material. Crushed rubble as per IS: 383-1970 [36] recommendations are used as coarse aggregate whose size varying between 20 mm and 4.75 mm. Due to the scarcity of river sand, M-sand, satisfying

Table 1: Gradation of WCR.

SL. NO	IS SIEVE DESIGNATION (mm)	WEIGHT RETAINED IN GRAMS	% WEIGHT RETAINED	CUMULATIVE % RETAINED	% FINER	GRADING ZONE II
1	4.75	93.06	3	3	97	90–100
2	2.36	527.34	17	20	80	75–100
3	1.18	155.1	5	25	75	55–90
4	0.60	1085.7	35	60	40	35–59
5	0.30	930.6	30	90	10	8–15
6	0.15	310.2	10	100	0	0–10

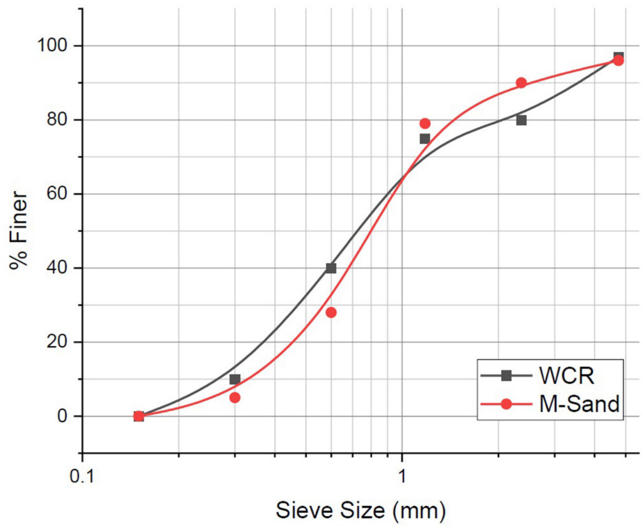

Figure 2: Comparison of WCR sand and M-sand w.r.t. percentage passing.

the conditions in IS: 383-1970, of size less than 4.75 mm was used as the FA in the control mix and WCR sand obtained from local area conforming to IS: 383-1970, was used as a partial replacement of M-sand. WCR sand was made by crushing the upper soft layer of rock or rubble, washed thoroughly to remove any debris or mud and dried well in the sun. The sand is sieved using standard sieves, the data is tabulated in Table 1 and the grading curve obtained corresponding to the data is compared with that of M-sand and is shown in Figure 2. WCR sand heaped in a container is shown in Figure 3.

In addition to the above constituent materials, GGBS which is a by-product of blast furnace operation and alcofine, a fine powdered form of GGBS (both collected from local suppliers) were also added for improving the performance of the M65 concrete with respect to various parameters. Properties of the different materials used in this study are given in Table 2.

To reduce the water cement ratio, which is a necessary factor in the mix design of high strength and ultra-high strength concretes, superplasticiser, Auramix 500, with a dosage range of 0.3 to 2.0 kg per kg of cementitious material is also used in this study.

2.2. Mix proportions

From a preliminary evaluation on the percentage replacement of WCR sand in concrete, it was seen that the mechanical strength properties were declining with increase in WCR sand percentage. Hence in this study, five variations of the HSC design mix were done with 100% M-sand, 95% M-sand and 5% WCR sand, 90% M-sand and 10% WCR sand, 85% M-sand and 15% WCR sand and 80% M-sand and 20% WCR sand and the mixes were designated as WCR00, WCR05, WCR10, WCR15 & WCR20 respectively keeping in view of the recommendations as per IS 10262:2019 [37]. Details of the mix proportions are given in Table 3.

Figure 3: WCR sand (a) sand heap (b) rock texture.

Table 2: Physical properties of cement, aggregates and other constituents.

PROPERTY	MATERIAL					
	CEMENT	M-SAND	WCR SAND	COARSE AGGREGATE	GGBS	ALCOFINE
Specific Gravity	3.14	2.67	2.67	2.76	2.08	2.21
Water Absorption (%)	–	4.1	4.9	0.51	–	–
Initial setting time (min)	69	–	–	–	–	–
Final setting time (min)	241	–	–	–	–	–
Particle size (μ)	–	–	–	–	–	4–6
Bulk density (kg/m³)	–	–	–	–	–	640

Table 3: Mix details of control mix, 5, 10, 15 & 20% WCR replacement.

SL. NO.	MATERIAL	WEIGHT (kg/m³ OF CONCRETE)				
		WCR00	WCR05	WCR10	WCR15	WCR20
1	Cement	450	450	450	450	450
2	F.A	732	695.4	658.8	622.2	585.6
3	C.A	1191	1191	1191	1191	1191
4	WCR	0	36.6	73.2	109.8	146.4
5	Alcofine	40	40	40	40	40
6	GGBS	150	150	150	150	150
7	Admixture	4.8	4.8	4.8	4.8	4.8
8	Water	185	185	185	185	185
Mix Ratio		1:1.62:2.64				

2.3. Methods

2.3.1. Mechanical properties

2.3.1.1. Compressive strength test

M65 concrete with FA partially replaced by WCR sand at varying percentages of 0, 5, 10, 15, and 20 was used for this test. 15 150 mm cubes three for each variations were casted. The mix was prepared in a laboratory concrete mixer, roughly around 3 minutes of dry mixing to achieve a uniform colour for the mixture followed by 2 minutes of wet mixing.

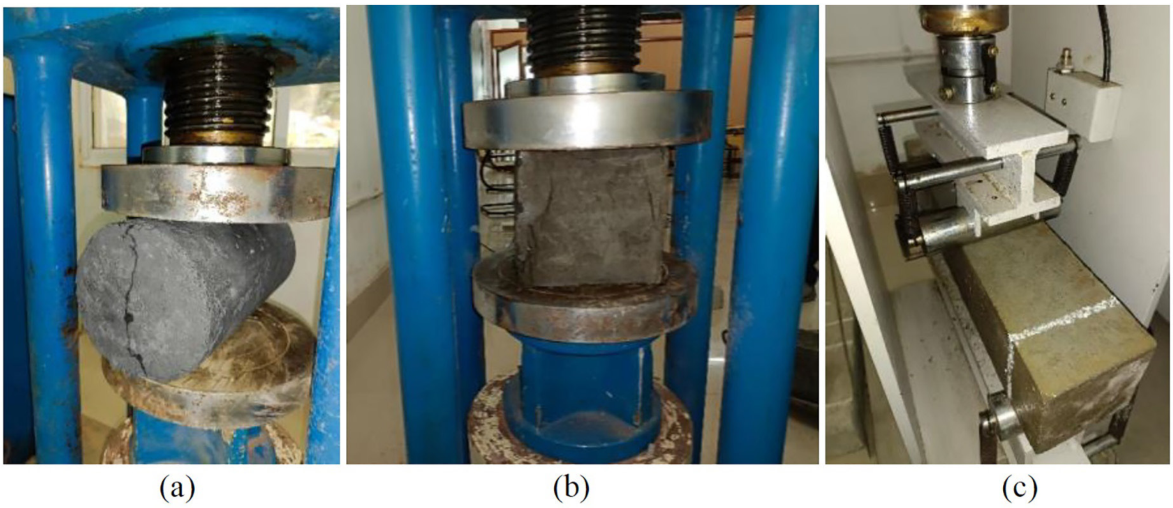

Figure 4: Testing for mechanical strength. (a) split tensile strength (b) compression test (c) flexure test.

The casted cubes were cured for 28 days in a moisture-controlled environment to ensure proper hydration of the cement particles. After the curing period, the cubes were tested for compressive strength according to Indian Standard IS: 516-1959 [38]. The load was applied gradually at a rate of approximately 140 kg/cm^2 per minute until the specimen's resistance to the increasing load decreased significantly or the specimen failed.

2.3.1.2. Tensile strength test

Totally 15 cylinders of 150 mm diameter and 300 mm height were prepared, 3 for each variations of the mix corresponding to the replacement of M-sand by WCR sand for the split tensile test of concrete. The specimens were kept in a curing tank for 28 days to ensure proper hydration of the cement particles.

Post the curing period, the cylinders were tested in accordance with the Indian Standard IS: 5816-1999 [39]. The load was incrementally applied at an approximate rate of 140 kg/cm^2 per minute until a significant decrease in the specimen's resistance to the increasing load was observed or until the specimen failed.

2.3.1.3. Flexural strength test

The dimensions of the beam specimens were 100 mm × 100 mm × 500 mm (width × depth × length) as per the code stipulations for nominal size of coarse aggregate less than 19 mm and 15 numbers of specimens were casted to represent each variation of the replacement percentage. The specimens underwent a curing process for 28 days within a controlled moisture environment to ensure optimal hydration of the cement particles.

After the curing period, the beam specimens were tested for their flexural strength. Load was incrementally applied at an approximate rate of 180 kg/cm^2 per minute until a significant decrease in the specimen's resistance to the increasing load was observed or until the specimen failed. Figure 4 below shows the pictures of the various mechanical properties being tested.

2.3.2. Durability properties

2.3.2.1. Water penetration test

Specimens of 150 mm cubes – three for each variations were prepared with the M65 grade concrete replacing M-sand by WCR sand in various percentages – were made and cured for 90 days. The cubes are tested for water penetration test as per the specifications laid down by IS: 516 -2018 Part 2. This test consists of determining the depth of penetration of water under pressure by the following procedure:

a. Specimens were water cured for 90 days according to the recommendations of IS 1199:1959 Part 5 [40].
b. Surface of the specimen to be exposed to water is roughened using a wire mesh.
c. Apply water pressure or 500 KPa for a duration of 72 hours.

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d. Immediately after the test, the specimen is split in the plane perpendicular to the plane on which the water was applied.
e. Average of the maximum depth of water expressed to the nearest mm of penetration for three specimens are recorded.

2.3.2.2. Rapid chloride penetration test

For each replacement level, cylindrical specimens of 100 mm diameter were prepared and subjected to a curing process for 90 days within a controlled moisture environment to ensure optimal hydration of the cement particles.

After the curing period, 50-mm thick slices of the specimens were tested for their chloride resistance. An essential component of the durability of concrete is its resistance to chloride ion penetration, which may be evaluated using the ASTM C1202-19 [41] standard. Using this test procedure, the specimens are subjected to a 6-hour electrical current monitoring period. The specimen has two ends, one submerged in a sodium hydroxide solution and the other in a sodium chloride solution, with a potential difference of 60 V DC maintained between them. It has been discovered that the specimen's resistance to chloride ion penetration is correlated with the overall charge passed, measured in coulombs.

By submerging the concrete samples in a sodium chloride solution and measuring the depth of penetration, the samples' resistance to chloride ion penetration was evaluated.

2.3.2.3. Sulphate resistance test

Sulphate resistance of concrete – an important durability test because of its relevance in the case of concrete structures exposed to severe environmental conditions like offshore structures- can be conducted in many ways with different specimen specifications. ASTM C1012 – 2019 recommendations are followed in this study. In this, three cubes of size 150 × 150 × 150 mm cubes for each of the replacement variations were casted, water cured for more than 90 days. The resistance of concrete to sulphate attack is determined on the oven dried (24 hours) specimens by immersing in 3% sodium sulphate solution. The solution is agitated every day and were changed the solution every month to ensure uniformity to the mix. After the specified period of immersion, specimens are taken out and weight loss and the compressive strength of the concrete cubes are determined.

2.3.2.4. Abrasion resistance

Test for abrasion resistance is done as per the stipulations given in IS: 1237-2012 [42] using Dorry's abrasion testing machine. Three specimens for each variations of sand replacement with dimensions 70 × 70 × 40 mm were casted, cured for 90 days and dried at 110 °C for 24 hours before testing and weighed to the nearest 0.1g and noted it as w_1. After spreading the abrasive powder in the guiding path of the machine, the specimen was placed and loaded with 30 kg, rotated the disc at the rate of 30rpm for 22 revolutions. Fresh abrasive powder was then added, rotated the specimen 90° about the vertical axis and repeated the rotation for 220 revolutions, altogether. Taking the specimen from the holder weighed it again to note the reading as w_2. The average thickness loss of the specimen is determined using the following formula in which A is the surface area, v_1 is the initial volume of the specimen.

$$t = \frac{(w_1 - w_2)v_1}{w_1 \cdot A} \tag{1}$$

All tests were conducted in a controlled environment, and the results were recorded for further analysis. The tests were repeated for each percentage of WCR sand to study the effect of its inclusion on the properties of the M65 concrete. The results were then compared and analysed to draw conclusions about the performance of the modified concrete. Figure 5 given below shows the images of various durability tests conducted on the specimens.

2.3.3. Scanning electron microscopy of the mixes

Scanning Electron microscopy (SEM) analysis was conducted to evaluate the morphology of the mixes. Specimens that had been crushed during the experiments were sampled. The provided sample stub underwent a cleaning process utilizing ethanol, followed by the attachment of a carbon tape. A fraction of the sample was subjected to a conductive gold coating process utilizing a sputter coater subsequent to its installation with adhesive carbon tape. The samples that had been coated were positioned within the chamber, and the scanning

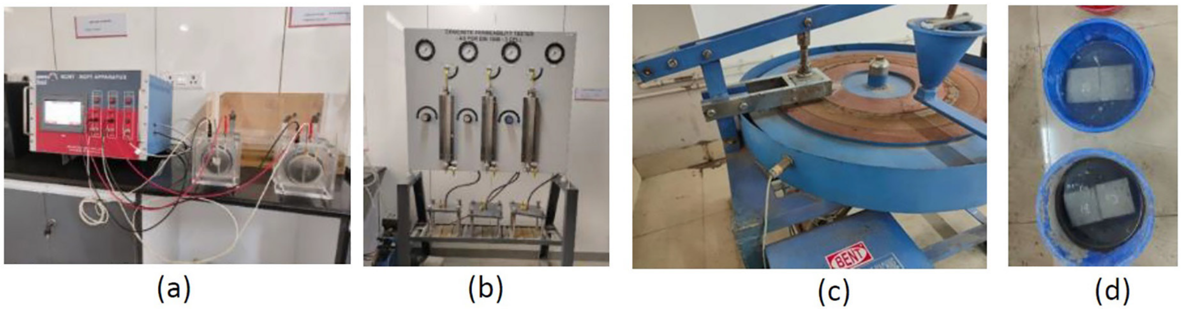

Figure 5: Images of durability testing (a) RCPT (b) water permeability (c) abrasion resistance (d) sulphate resistance.

electron microscope (SEM) was utilized to capture micrographs. The specific instrument employed for this purpose was the TESCAN VEGA–3.

3. RESULTS AND DISCUSSION

3.1. Chemical composition of WCR

The chemical composition of WCR is seen to be similar to naturally occurring rocks from the EDS analysis data. Comparison of EDS analysis report obtained for WCR and M-sand used in this study is given in Figure 6 and Figure 7. Table 2 shows the elemental details of the sample. Silica is the major constituent while other constituents like oxides of manganese, magnesium, iron, aluminium, etc., are in the line with that of river sand or m-sand. In many areas prior to quarrying rubble, this soft outer layer of rock is removed and disposed as waste. By using this, we can bring down the cost of construction and it will be a solution for the disposal of waste material from quarry. As deep quarrying is not needed, it is environment friendly. The surface texture of WCR is shown in Figure 3. The major components of WCR are Silicon Dioxide, Aluminium Trioxide, Ferric Oxide, Calcium Oxide and Potassium Oxide as shown in Table 4.

3.2. Mechanical properties

3.2.1. Workability

Slump test based on IS 1199:1959 [43] was conducted on the various mixes to assess the workability of the fresh concrete. Average values of 3 sets for each of the replacement percentages are shown below in Figure 8.

From the data it is seen that 5% replacement of sand with WCR slightly improves the workability, by around 3% which is a good sign. The reason for the better workability can be explained based on the comparison of microscopic images of WCR and M-sand. The microscopic images shows that the surface of M-sand is rougher than that of WCR, which definitely will reduce the workability. Refer Figure 9 for comparison of the microscopic images of both the FAs. The results obtained with studies of ASHISH [44], in which when marble powder was added to concrete as a partial replacement of cement, the workability reduced and in a similar fashion, the WCR-sand contains more fines and hence similar effects can be expected.

3.2.2. Compressive strength

Results of the compression test conducted on the specimens are shown in Figure 10. The results are similar – decreasing with increase in the percentage of WCR replacement – to that of crushed clay brick for sand replacement done by GARCIA-TRONCOSO *et al.* [45], OLOFINNADE *et al.* [46] and ZHU and ZHU [47].

The target mean strength corresponding to characteristic compressive strength of 65 N/mm^2 is 75 N/mm^2. Results of the test show that replacing sand with WCR, reduces the compressive strength and beyond 5% replacement, the target mean strength is not attained, but up to 15% of replacement, the concrete mix attains the characteristic compressive strength required. Water absorption test on the WCR sand shows that it absorbs more water by around 18% compared to M-sand as per Table 2. Hence, as the percentage of WCR sand increases, water absorption also increases. The more the water absorbed by constituent materials other than binding materials, the more will be the effect on the strength of concrete [48–50].

3.2.3. Splitting tensile strength

The results indicate a decrease in tensile strength as the percentage of sand replacement with WCR sand increases as shown in Figure 11 below. This trend suggests that WCR sand may not be as effective as the original FA in

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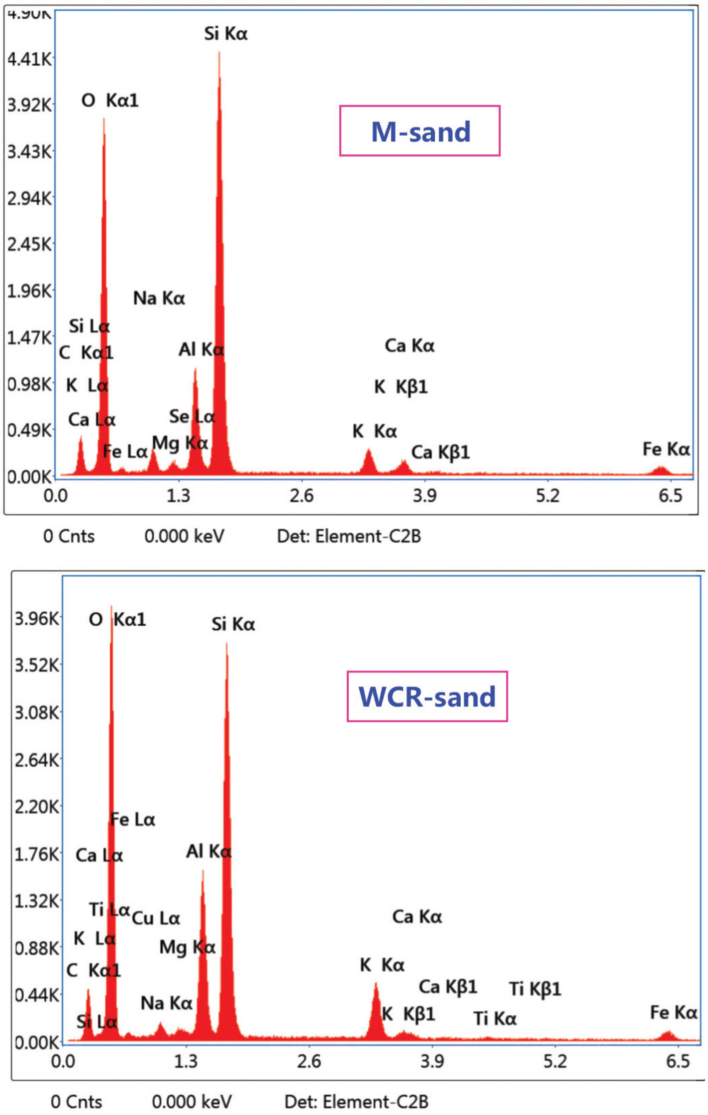

Figure 6: Comparison of EDX analysis result of WCR & M-sand for elements.

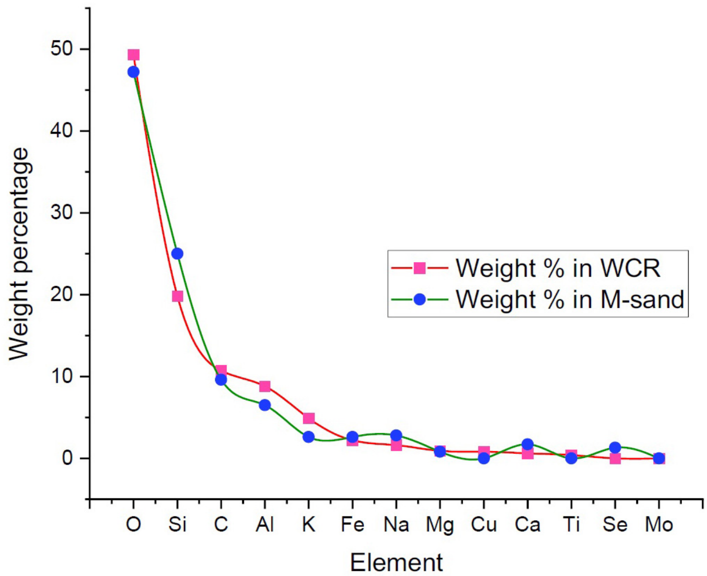

Figure 7: Comparison of EDX elemental analysis of WCR & M-sand.

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Table 4: Result of XRF analysis of WCR – major composition.

SL NO.	ELEMENT	PERCENTAGE
1	SiO_2	67.55
2	TiO_2	0.66
3	Al_2O_3	16.07
4	Fe_2O_3	3.81
5	CaO	2.12
6	MgO	0.71
7	Na_2O	2.68
8	K_2O	5.76

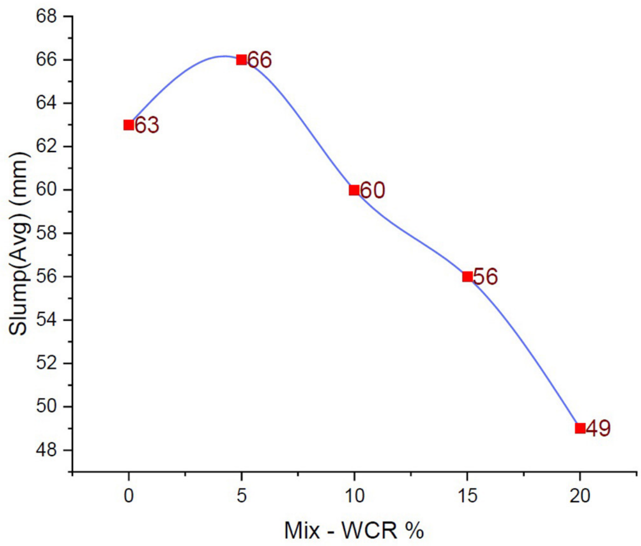

Figure 8: Slump values of various WCR percentages.

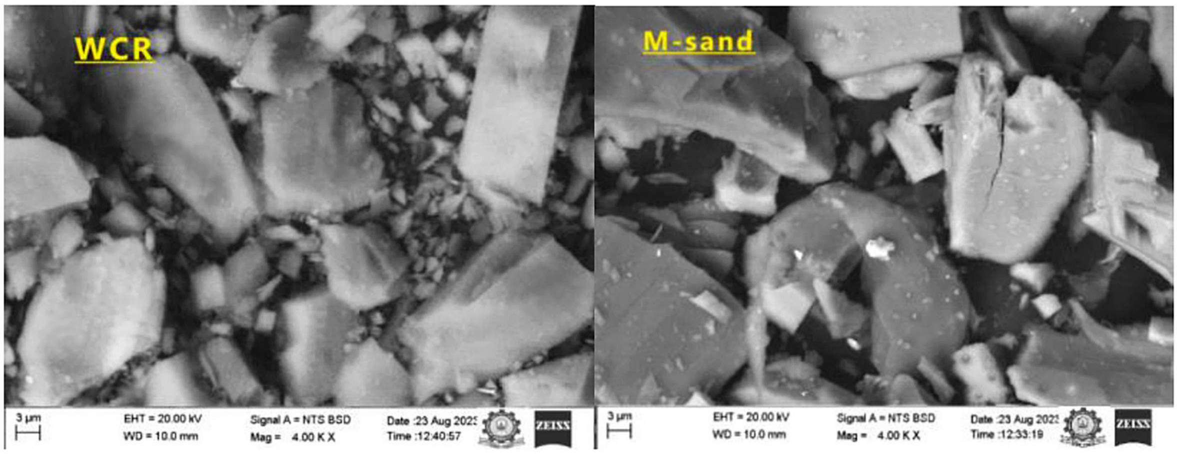

Figure 9: Microscopic images of surface texture of WCR and M-sand.

providing tensile strength to the concrete a higher percentages of replacement. But up to 5% replacement of FA can be considered as recommendable in alignment with the studies on concrete with waste foundry sand by JEYANTHI *et al.* [51] and the work of ASHISH [52], in which they added marble powder as partial replacement of FA in concrete.

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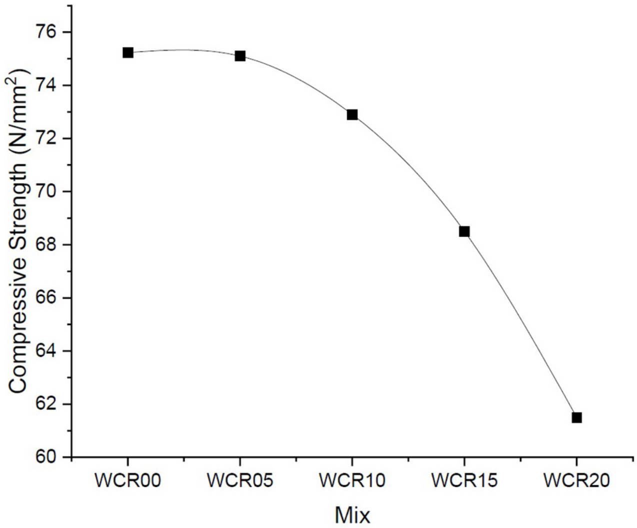

Figure 10: Cube Compressive strength of the samples.

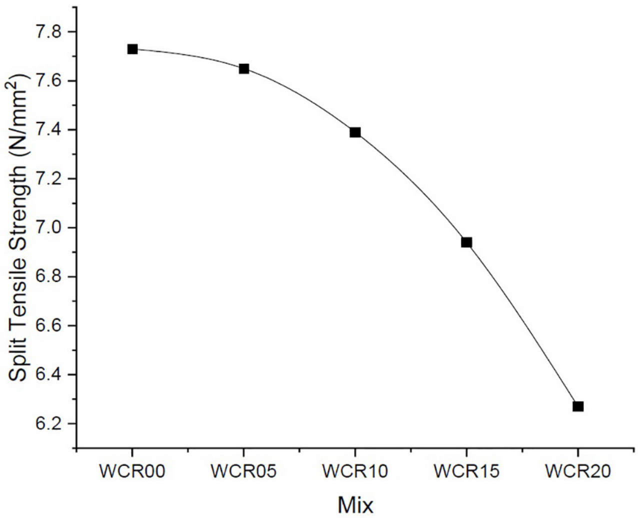

Figure 11: Split tensile strength of the samples.

The decrease in strength of the concrete with partial inclusion of WCR sand may be due to the decrease in water content as the water absorption of WCR is around 20% more than M-sand made from rock. The more the water absorbed from the mix by the constituent materials of the concrete, the more water content adjustment is needed during mix design.

3.2.4. Flexural strength

Three beams, with dimensions of 100 mm × 100 mm × 500 mm, were casted and after curing for 28 days, tested in accordance with the prescribed criteria specified in IS 516: 1959 (Reaffirmed 2018). Results obtained from the tests are shown in Figure 12 and it shows in agreement with the finding of LIHUA ZHU *et.al*, 2020; NATIVIDAD GARCIA-TRONCOSO, *et.al*, 2023; LOGANATHAN PATTUSAMY, *et.al*, 2023 [53] and in the present study the flexural strength is reduced by increasing the percentage of WCR for partial replacement of FA.

3.3. Durability properties

3.3.1. Rapid chloride permeability test

Test results of RCPT are shown in Figure 13 below. The chloride penetrability of concrete is decided by comparing the data from Table 5, which is an extract of the ASTM C1202-19, with that of the results from the test.

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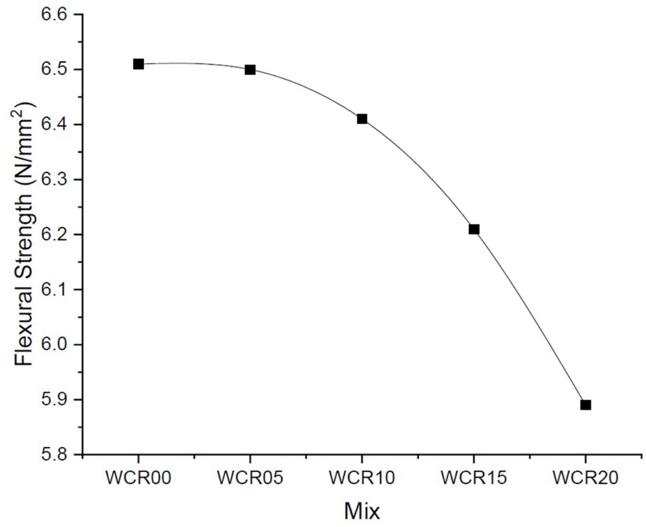

Figure 12: Flexural strength of the samples.

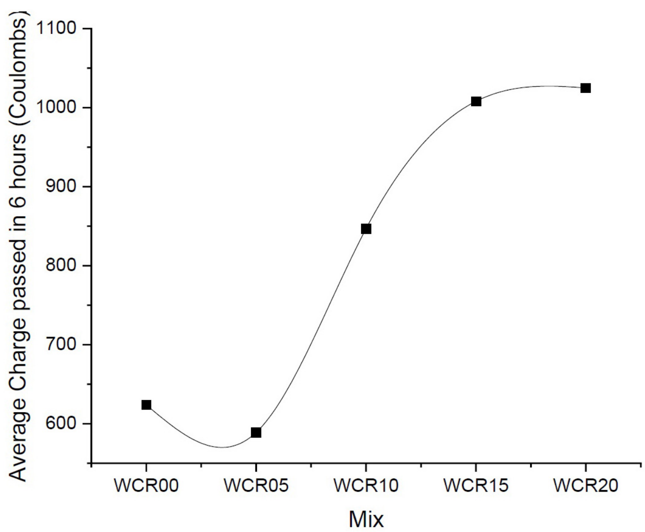

Figure 13: Chloride resistance test – Average charge passed in 6 hours.

Table 5: Penetrability of chloride ion based on charge passed.

CHARGE PASSED (COULOMBS)	CHLORIDE PENETRABILITY
>4000	High permeable concrete
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

It is seen from the results that sand replacement of 5% with WCR gives the best results which is "Very Low". The justification arrived at from the test and the SEM results of various mixes for the above conclusion is that, concrete with 5% FA replacement shows more uniform and denser surface in SEM images. The denser and more uniform a material, the lesser will be the chloride ingression.

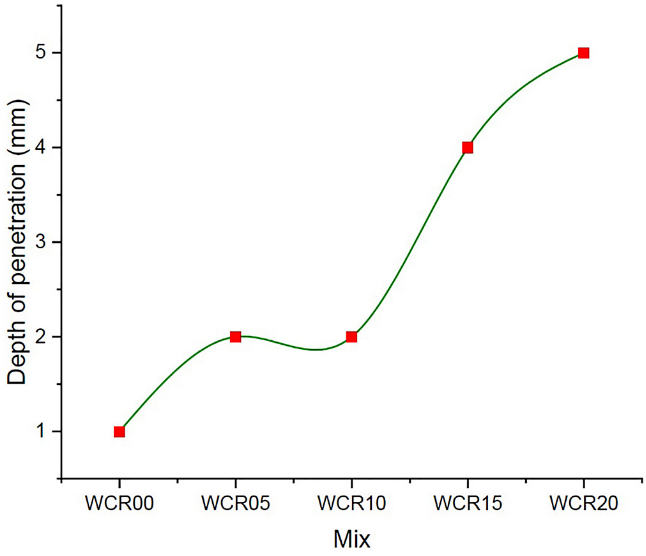

Figure 14: Water permeability – depth of penetration.

3.3.2. Water penetration

The control mix with M-sand as the FA showed the highest depth of water penetration. Concrete with 5%, 10%, and 15% replacement percentages showed lower depths of water penetration compared to control mix. 20% Replacement: The concrete with 20% replacement exhibited the lowest depth of water penetration among all tested specimens. Obtained values of depth of water penetration are depicted in Figure 14.

The reasons for observed results could be the following:

- Increased packing density: WCR sand has a more angular and irregular shape compared to natural sand. This angularity improves the packing density of the concrete mix, leading to a denser microstructure with fewer voids. Consequently, water penetration becomes more difficult, resulting in lower permeability. The fines content of WCR sand seems to be more than that of natural sand. A higher fines content can fill the voids in the concrete matrix, leading to lower permeability.
- The above points may be correlated with the comparison of SEM image of the control mix and mix with 5% replacement.

A previous study conducted by replacing FA with waste marble powder shows reduction of water penetration depth with increase in replacement percentage. But some other studies conducted by SAU *et al.* [54], MHAYA *et al.* [55] and MARDANI-AGHABAGLOU *et al.* [56], show that the water penetration and thereby water permeability increase with increase in percentage replacement of FA and similar to these, in the present study, the property is increasing steeply beyond the 10% replacement and hence WCR sand can be recommended to be a replacement for natural sand and M-sand with regards to water penetration.

3.3.3. Sulphate resistance – loss of compressive strength & loss of weight

Going through the results of the test, it can be seen that concrete with 5% replacement exhibited the best sulphate resistance, with lowest weight loss and compressive strength loss. The strength loss of the samples with 5% and 10% replacement was very similar, suggesting that up to 10% replacement could be feasible without significantly compromising the sulphate resistance of the concrete. The control mix (0% replacement) exhibited higher weight loss compared to all other mixes, indicating its lower sulphate resistance.

These observations align with previous studies where replacement of FA with other materials also resulted in improved sulphate resistance to a limited percentage of replacement of FA [57, 58].

The WCR sand could potentially fill the voids in the concrete, due to more fine particles, leading to a denser and more compact microstructure, which could further enhance the sulphate resistance. From the SEM images of 5% replacement and on comparison with that of the other mixes, a uniform and dense structure can be seen which validates the above point in the present study. Figure 15 given below shows the performance of various mixes of concrete in sulphate resistance test.

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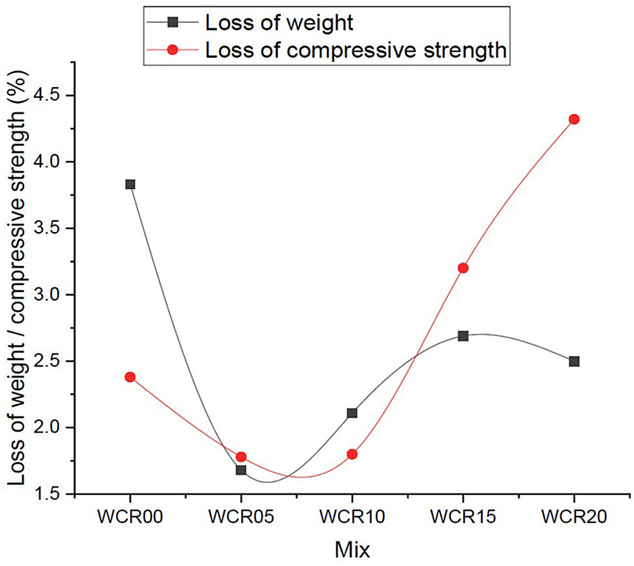

Figure 15: Loss of weight/compressive strength.

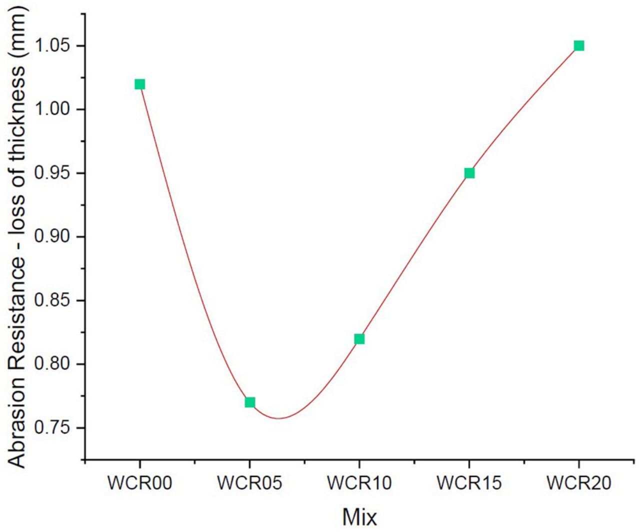

Figure 16: Abrasion resistance.

3.3.4. Abrasion resistance

The values obtained as shown in Figure 16, from the abrasion resistance test aligns with the principle that the abrasion resistance of concrete is influenced by the hardness and durability of the aggregate used. WCR sand, being a type of rock abundantly available in tropical areas, is known for its hardness and durability [59]. Therefore, its inclusion as a replacement for FA could potentially enhance the abrasion resistance of the concrete.

Results of the abrasion value of the various mixes are consistent with previous studies that have investigated the impact of replacing FA in concrete on its abrasion resistance. For instance, a study on the use of recycled-waste-polyethylene (PE) and waste-polyethylene-terephthalate (PET)-based aggregate as replacement of natural fine and coarse aggregate reported that the Cantabro and surface abrasion weight loss showed a similar trend [60].

Notably, the strength loss of the samples with 5% and 10% replacement was very similar, suggesting that up to 10% replacement could be feasible without significantly compromising the abrasion resistance of the concrete. This could be due to the optimal balance between the hardness of the WCR sand and the workability of the concrete at these replacement levels. SEM images of the 5% replaced mix – Figure 17 - with others justifies the point as the surface seems to be more uniform and pore free.

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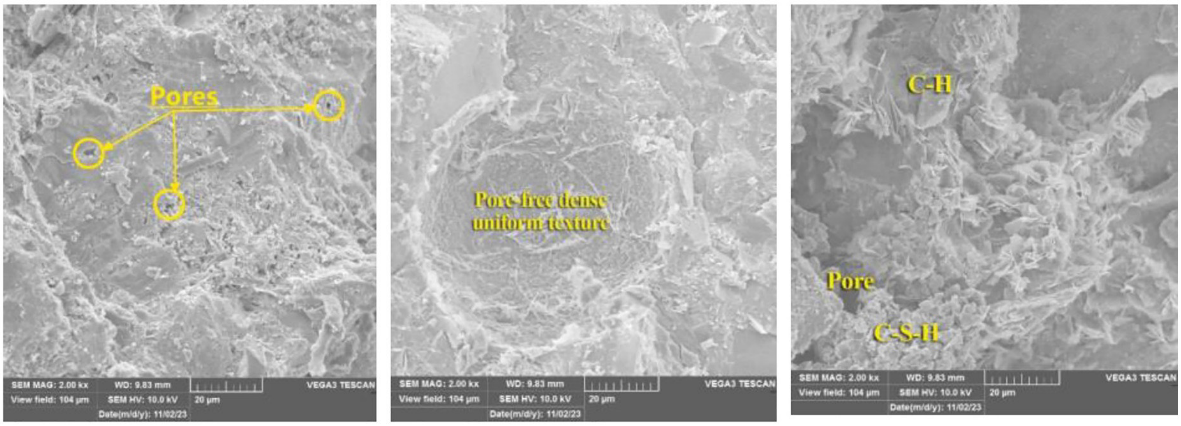

Control Mix 5% fine aggregate replaced 10% fine aggregate replaced

2k Magnification

Figure 17: SEM images of different mixes.

3.4. Microstructure properties

SEM analysis of control specimen and WCR replaced concretes for 5% & 10% were conducted and the results are shown in Figure 17. WCR replacement percentages of 15 and 20 were not conducted as majority of the mechanical and durability properties were not promising when compared with that of 5% and 10% and also with control mix. It is seen from the SEM images that, the sample with WCR replacement of 5% is more denser and control mix have more inter molecular pores while concrete with10% replacements seems to be less dense.

4. CONCLUSIONS

The results of the study showed that the use of WCR sand as a replacement for FA had a significant effect on the mechanical and durability properties of the HSC. Though the compressive strength, tensile strength and flexural strength decreased with an increase in the replacement percentage, the reduction is less than 1% for the 5% replacement and a similar reduction for 10% replacement compared with the control mix. Hence, the concrete made with a replacement rate of 5 to 10% exhibited the best combination of mechanical, durability and microstructural properties. The abrasion resistance, sulphate resistance and chloride resistance improved with a replacement of 5 to 10%. Beyond 10%, there was a significant decrease in most of the durability properties of the concrete.

From the study, the following conclusions can be made:

- This study concludes that it is feasible to replace the FA in HSC with WCR sand is recommendable.
- Up to a maximum of 10% replacement level maintains the compressive strength and improves many of the durability properties when compared to the control sample.
- With respect to workability, 5% replacement with WCR improves it by around 3% compared with that of control mix.
- With regards to durability, WCR added concrete exhibits reduced chloride penetrability, reasonable water penetration, enhanced sulphate resistance and superior abrasion resistance.
- Many of the results are in alignment with the results from similar studies of FA replacement.
- The findings of the study are correlated with the results from scanning electron microscopy images of the various materials and different concrete mixes.
- From the test results and the discussions it can be concluded that WCR sand is a good alternative for natural sand like river sand and M-sand up to a maximum of 10% of replacement without affecting the strength and durability properties of concrete.
- With reference to the cost aspect of concrete, as a waste material is utilized a reduction in cost can also be expected.

These findings backs up the feasibility and benefits of utilizing WCR in concrete, contributing to apply sustainable methods and materials in construction industry as natural sand mining and quarrying can be reduced by at least 5% and up to a maximum of 10%. Also, this study supports the usage of locally available wastes for high performance construction materials.

5. BIBLIOGRAPHY

[1] ALI, T., BULLER, A.S., ABRO, F.U.R., *et al*., "Investigation on mechanical and durability properties of concrete mixed with silica fume as cementitious material and coal bottom ash as fine aggregate replacement material", *Buildings*, v. 12, n. 1, pp. 44, 2022. doi: http://dx.doi.org/10.3390/buildings12010044.

[2] THUNGA, K., DAS, V., "An experimental investigation on concrete with replacement of treated sea sand as fine aggregate", *Materials Today: Proceedings*, v. 27, n. P2, pp. 1017–1023, 2020. doi: http://dx.doi.org/10.1016/j.matpr.2020.01.356.

[3] RUDŽIONIS, Ž., ADHIKARY, S.K., MANHANGA, F.C., *et al*., "Natural zeolite powder in cementitious composites and its application as heavy metal absorbents", *Journal of Building Engineering*, v. 43, pp. 103085, 2021. doi: http://dx.doi.org/10.1016/j.jobe.2021.103085.

[4] SHEN, W., LIU, Y., CAO, L., *et al*., "Mix design and microstructure of ultra-high strength concrete with manufactured sand", *Construction & Building Materials*, v. 143, pp. 312–321, 2017. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.03.092.

[5] NILIMAA, J., "Smart materials and technologies for sustainable concrete construction", *Developments in the Built Environment*, v. 15, pp. 100177, Oct. 2023. doi: http://dx.doi.org/10.1016/j.dibe.2023.100177.

[6] SANNAG, M.J., "High strength concrete containing natural pozzolan and silica fume", *Cement and Concrete Composites*, v. 27, n. 6, pp. 399–406, Dec. 2000. doi: http://dx.doi.org/10.1016/S0958-9465(00)00037-8.

[7] SANDANAYAKE, M., BOURAS, Y., HAIGH, R., *et al*., "Current sustainable trends of using waste materials in concrete - a decade review", *Sustainability (Basel)*, v. 12, n. 22, pp. 9622, 2020. doi: http://dx.doi.org/10.3390/su12229622.

[8] MITIKIE, B.B., WALDTSADIK, D.T., "Partial replacement of cement by waste paper pulp ash and its effect on concrete properties", *Advances in Civil Engineering*, v. 2022, pp. 8880196, 2022. doi: http://dx.doi.org/10.1155/2022/8880196.

[9] ABDUL-WAHAB, S.A., AL-DHAMRI, H., RAM, G., *et al*., "An overview of alternative raw materials used in cement and clinker manufacturing", *International Journal of Sustainable Engineering*, v. 14, n. 4, pp. 743–760, 2021. doi: http://dx.doi.org/10.1080/19397038.2020.1822949.

[10] FARAHANI, H., BAYAZIDI, S., "Modelling the assessment of socio-economic and environmental impacts of sand mining on local communities: a case study of villages Tatao River Bank in North-western part of Iran", *Resources Policy*, v. 55, pp. 87–95, 2018. doi: http://dx.doi.org/10.1016/j.resourpol.2017.11.001.

[11] BENDIXEN, M., IVERSEN, L.L., BEST, J., *et al*., "Sand, gravel, and UN Sustainable Development Goals: conflicts, synergies, and pathways forward", *One Earth*, v. 4, n. 8, pp. 1095–1111, 2021. doi: http://dx.doi.org/10.1016/j.oneear.2021.07.008.

[12] DINH, H.L., LIU, J., DOMINIC, E.L., "A sustainable solution to excessive river sand mining by utilizing by-products in concrete manufacturing: a state-of-the-art review", *Cleaner Materials*, v. 6, pp. 100140, 2022. doi: http://dx.doi.org/10.1016/j.clema.2022.100140.

[13] PANDEY, S., KUMAR, G., KUMARI, N., *et al*., "Assessment of causes and impacts of sand mining on river ecosystem", In: Madhav, S., Singh, V. B., Kumar, M., *et al.* (eds), *Hydrogeochemistry of aquatic ecosystems*, Hoboken, John Wiley & Sons, pp. 357–379, 2023. doi: http://dx.doi.org/10.1002/9781119870562.ch16.

[14] PADMALAL, D., MAYA, K., "Impacts of river sand mining", In: Padmalal, D., Maya, K. (eds.), *Sand mining: environmental science and engineering.* Springer, Dordrecht, pp. 31–56, 2014. doi: http://dx.doi.org/10.1007/978-94-017-9144-1_4.

[15] BARMAN, B., KUMAR, B., SARMA, A.K., "Impact of sand mining on alluvial channel flow characteristics", *Ecological Engineering*, v. 135, pp. 36–44, 2019. doi: http://dx.doi.org/10.1016/j.ecoleng.2019.05.013.

[16] KARTHIK, S., RAO, P.R.M., AWOYERA, P.O., "Strength properties of bamboo and steel reinforced concrete containing manufactured sand and mineral admixtures", *Journal of King Saud University-Engineering Sciences*, v. 29, n. 4, pp. 400–406, 2017. doi: http://dx.doi.org/10.1016/j.jksues.2016.12.003.

(cc) BY

[17] GANESH, P., MURTHY, A.R., "Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material", *Construction & Building Materials*, v. 197, pp. 667–680, 2019. doi: http://dx.doi.org/10.1016/j.conbuildmat.2018.11.240.

[18] KAVYA, A., VENKATESHWARA, R.A., "Experimental investigation on mechanical properties of concrete with M-sand", *Materials Today: Proceedings*, v. 33, n. Part 1, pp. 663–667, 2020. doi: http://dx.doi.org/10.1016/j.matpr.2020.05.774.

[19] BHOOPATHY, V., SUBRAMANIAN, S.S., "The way forward to sustain environmental quality through sustainable sand mining and the use of manufactured sand as an alternative to natural sand", *Environmental Science and Pollution Research International*, v. 29, n. 21, pp. 30793–30801, 2022. doi: http://dx.doi.org/10.1007/s11356-022-19633-w. PubMed PMID: 35322368.

[20] HO, H.L., HUANG, R., LIN, W.T., *et al*., "Pore-structures and durability of concrete containing pre-coated fine recycled mixed aggregates using pozzolan and polyvinyl alcohol materials", *Construction & Building Materials*, v. 160, pp. 278–292, 2018. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.11.063.

[21] NEDELJKOVIC, M., JOHANNA, H.M.V., SAVIJA, B., *et al*., "Use of fine recycled concrete aggregates in concrete: a critical review", *Journal of Building Engineering*, v. 38, n. 1, pp. 102196, Jan. 2021. doi: http://dx.doi.org/10.1016/j.jobe.2021.102196.

[22] SHARMA, H., SHARMA, S.K., ASHISH, D.K., *et al*., "Effect of various bio-deposition treatment techniques on recycled aggregate and recycled aggregate concrete", *Journal of Building Engineering*, v. 66, pp. 105868, 2023. doi: http://dx.doi.org/10.1016/j.jobe.2023.105868.

[23] MOBILI, A., GIOSUE, C., CORINALDESI, V., *et al*., "Bricks and concrete wastes as corase and fine aggregates in sustainable mortars", *Advances in Materials Science and Engineering*, v. 2018, pp. 1–11, Sep. 2018. doi: http://dx.doi.org/10.1155/2018/8676708.

[24] DONGBIN, L., HUANG, K., WANG, W., "Influence of pre -treatment methods on compressive performance improvement and failure mechanism analysis of recycled aggregate concrete", *Materials (Basel)*, v. 16, n. 10, pp. 3807, 2023. doi: http://dx.doi.org/10.3390/ma16103807.

[25] TALUKDAR, S., ISLAM, S.T., BANTHIA, N., "Development of a lightweight low-carbon footprint concrete containing recycled waste materials", *Advances in Civil Engineering*, v. 2011, pp. 594270, 2011. doi: http://dx.doi.org/10.1155/2011/594270.

[26] SIDDIQUA, A., HAHLADAKIS, J.N., AL-ATTIYA, W.A.K.A., "An overview of the environmental pollution and health effects associated with waste landfilling and open dumping", *Environmental Science and Pollution Research International*, v. 29, n. 39, pp. 58514–58536, 2022. doi: http://dx.doi.org/10.1007/s11356-022-21578-z. PubMed PMID: 35778661.

[27] SADH, P.K., DUHAN, S., DUHAN, J.S., "Agro-industrial wastes and their utilization using solid state fermentation: a review", *Bioresources and Bioprocessing*, v. 5, n. 1, pp. 1, 2018. doi: http://dx.doi.org/10.1186/s40643-017-0187-z.

[28] EL-SAADONY, M.T., SAAD, A.M., EL-WAFAI, N.A., *et al*., "Hazardous wastes and management strategies of landfill leachates: a comprehensive review", *Environmental Technology & Innovation*, v. 31, pp. 103150, 2023. doi: http://dx.doi.org/10.1016/j.eti.2023.103150.

[29] NIMITA JEBARANJITHAM, J., SELVAN CHRISTYRAJ, J.D., PRASANNAN, A., *et al*., "Current scenario of solid waste management techniques and challenges in Covid-19 - a review", *Heliyon*, v. 8, n. 7, pp. e09855, 2022. doi: http://dx.doi.org/10.1016/j.heliyon.2022.e09855. PubMed PMID: 35800245.

[30] AL-JABRI, K.S., HISADA, M., AL-ORAIMI, S.K., *et al*., "Copper slag as sand replacement for high performance concrete", *Cement and Concrete Composites*, v. 31, n. 7, pp. 483–488, 2009. doi: http://dx.doi.org/10.1016/j.cemconcomp.2009.04.007.

[31] AL-JABRI, K.S., AL-SAIDY, A.H., TAHA, R., "Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete", *Construction & Building Materials*, v. 25, n. 2, pp. 933–938, 2011. doi: http://dx.doi.org/10.1016/j.conbuildmat.2010.06.090.

[32] KIRTHIKA, S.K., SINGH, S.K., CHOURASIA, A., "Alternative fine aggregates in production of sustainable concrete: a review", *Journal of Cleaner Production*, v. 268, pp. 122089, 2020. doi: http://dx.doi.org/10.1016/j.jclepro.2020.122089.

[33] MUNDRA, S., SINDHI, P.R., CHANDWANI, V., *et al*., "Crushed rock sand-An economical and ecological alternative to natural sand to optimize concrete mix", *Perspectives in Science*, v. 8, pp. 345–347, 2016. doi: http://dx.doi.org/10.1016/j.pisc.2016.04.070.

[34] NANTHAGOPALAN, P., SANTHANAM, M., "Fresh and hardened properties of self-compacting concrete produced with manufactured sand", *Cement and Concrete Composites*, v. 33, n. 3, pp. 353–358, 2011. doi: http://dx.doi.org/10.1016/j.cemconcomp.2010.11.005.

[35] INDIAN STANDARD, *IS 12269: 2013, Indian Standard, Ordinary Portland cement 53 grade - specification*, New Delhi, Bureau of Indian Standards, 2013.

[36] INDIAN STANDARD, *IS 383: 1970: Specification for coarse and fine aggregates from natural sources for concrete*, New Delhi, Bureau of Indian Standards, 1970.

[37] INDIAN STANDARD, *IS 10262: 2019: Concrete Mix Proportioning - Guidelines*, New Delhi, Bureau of Indian Standards, 2019.

[38] INDIAN STANDARD, *IS 516: 1959, Method of tests for strength of concrete*, New Delhi, Bureau of Indian Standards, 1959.

[39] INDIAN STANDARD, *IS 5816: 1999, Splitting tensile strength of concrete - method of test*, New Delhi, Bureau of Indian Standards, 1999.

[40] INDIAN STANDARD, *IS 1199: 1959 Part 5, Method of sampling and analysis of concrete*, New Delhi, Bureau of Indian Standards, 1959.

[41] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *ASTM C1202-19-2019: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, West Conshohocken, ASTM International, 2003.

[42] INDIAN STANDARD, *IS 1237-2012: Cement concrete flooring tiles - specifications*, New Delhi, Bureau of Indian Standards, 2012.

[43] INDIAN STANDARD, *IS 1199: 1959: Method of sampling and analysis of concrete*, New Delhi, Bureau of Indian Standards, 1959.

[44] ASHISH, D.K., "Concrete made with waste marble powder and supplementary cementitious material for sustainable development", *Journal of Cleaner Production*, 2018. doi: http://dx.doi.org/10.1016/j.jclepro.2018.11.245.

[45] GARCIA-TRONCOSO, N., ACOSTA-CALDERON, S., FLORES-RADA, J., *et al*., "Effects of recycled rubber particles incorporated as partial sand replacement on fresh and hardened properties of cement-based concrete: mechanical, microstructural and life cycle analyses", *Materials (Basel)*, v. 16, n. 1, pp. 63, 2023. doi: http://dx.doi.org/10.3390/ma16010063.

[46] OLOFINNADE, O.M., OGARA, J.I., OYAWOYE, I.T., *et al*., "Mechanical properties of high strength eco-concrete containing crushed waste clay brick aggregates as replacement for sand", *IOP Conference Series. Materials Science and Engineering*, v. 640, n. 1, pp. 012046, 2019. doi: http://dx.doi.org/10.1088/1757-899X/640/1/012046.

[47] ZHU, L., ZHU, Z., "Reuse of clay brick waste in mortar and concrete", *Advances in Materials Science and Engineering*, v. 2020, pp. 6326178, 2020. doi: http://dx.doi.org/10.1155/2020/6326178.

[48] ABISHA, Y., NALANTH, N., "Pineapple fibre as an additive to self-compacting concrete", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20220315, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2022-0315.

[49] SHANG, S.P., ZONG, L., "Evaluation of relationship between water absorption and durability of concrete materials", *Advances in Materials Science and Engineering*, v. 2014, pp. 650373, 2014.

[50] VANDHIYAN, R., VIJAY, T.J., MANOJ KUMAR, M., "Effect of fine aggregate properties on cement mortar strength", *Materials Today: Proceedings*, v. 37, pp. 2019–2026, 2021. doi: http://dx.doi.org/10.1016/j.matpr.2020.07.498.

[51] JEYANTHI, J., KARTHIKEYAN, U., MOHAN RAJ, M., *et al*., "Study of concrete with partial replacement of waste foundry sand for fine aggregate and granite waste for coarse aggregate", *Materials Today: Proceedings*, 2023. In press. doi: http://dx.doi.org/10.1016/j.matpr.2023.06.412.

[52] ASHISH, D.K., "Feasibility of waste marble powder in concrete as partial substitution of cement and sand amalgam for sustainable growth", *Journal of Building Engineering*, v. 15, pp. 236–242, 2018. doi: http://dx.doi.org/10.1016/j.jobe.2017.11.024.

[53] PATTUSAMY, L., RAJENDRAN, M., SHANMUGAMOORTHY, S., *et al*., "Confinement effectiveness of 2900psi concrete using the extract of Euphorbia tortilis cactus as a natural additive", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20220233, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2022-0233.

[54] SAU, D., SHIULY, A., HAZRA, T., "Utilization of plastic waste as replacement of natural aggregates in sustainable concrete: effects on mechanical and durability properties", *International Journal of Environmental*

Science and Technology, pp. 1–36, 2023. doi: http://dx.doi.org/10.1007/s13762-023-04946-1. PubMed PMID: 37360565.

[55] MHAYA, A.M., ALGAIFI, H.A., SHAHIDAN, S., *et al*., "Systematic evaluation of permeability of concrete incorporating coconut shell as replacement of fine aggregate", *Materials (Basel)*, v. 15, n. 22, pp. 7944, 2022. doi: http://dx.doi.org/10.3390/ma15227944. PubMed PMID: 36431430.

[56] MARDANI-AGHABAGLOU, A., TUYAN, M., RAMYAR, K., "Mechanical and durability performance of concrete incorporating fine recycled concrete and glass aggregates", *Materials and Structures*, v. 48, n. 8, pp. 2629–2640, 2015. doi: http://dx.doi.org/10.1617/s11527-014-0342-3.

[57] WILSON, J., "Partial replacement of fine aggregate by used foundry sand in concrete", *International Journal of Scientific and Engineering Research*, v. 10, n. 3, pp. 165–169, 2019.

[58] RAJAGOPALAN, S.R., KANG, S.T., "Evaluation of sulphate resistance of cement mortars with the replacement of fine stone powder", *Journal of Material Cycles and Waste Management*, v. 23, n. 5, pp. 1995–2004, 2021. doi: http://dx.doi.org/10.1007/s10163-021-01272-x.

[59] MANJUMMEKUDY, E.M., GOVIND, A.K., VARGHESE, S., "Comparative study on the effect of concrete using eco sand, weathered crystalline rock sand and GBS as fine aggregate replacement", *International Journal of Engineering Research & Technology (Ahmedabad)*, v. 03, n. 10, pp. 1030–1035, 2014.

[60] SAU, D., SHIULY, A., HAZRA, T., "Utilization of plastic waste as replacement of natural aggregates in sustainable concrete: effects on mechanical and durability properties", *International Journal of Environmental Science and Technology*, pp. 1–36, 2023. doi: http://dx.doi.org/10.1007/s13762-023-04946-1. PubMed PMID: 37360565.