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Performance and Economic Analysis of the Utilization of Construction and Demolition Waste as Recycled Concrete Aggregates

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ABSTRACT

Construction and demolition (C&D) wastes are increasing continuously with intensified construction activities worldwide resulting in ecological concerns. Recycling of these waste products into recycled concrete aggregates (RCA) in base and sub-base layers of pavement is one of the solutions for the problem. Thus, the present study is an in-depth investigation of the utilization of the RCA in construction sector containing laboratory tests, microstructural characterization, and economic analysis. The experiment revealed that, for each mix proportion, the maximum dry density decreases and the ideal moisture content increases as the cement percentage is increased. The 7-day average ultimate compressive strength value for natural aggregates (NA) and recycled concrete (RCA) combined with additives met the requirements. The durability index for all the mix proportions was greater than 0.80. Finally, it was found that 17.86% of the material cost was saved with incorporation of RCA (50%)-NA (50%) for the construction of the sub-base layer of the pavement.

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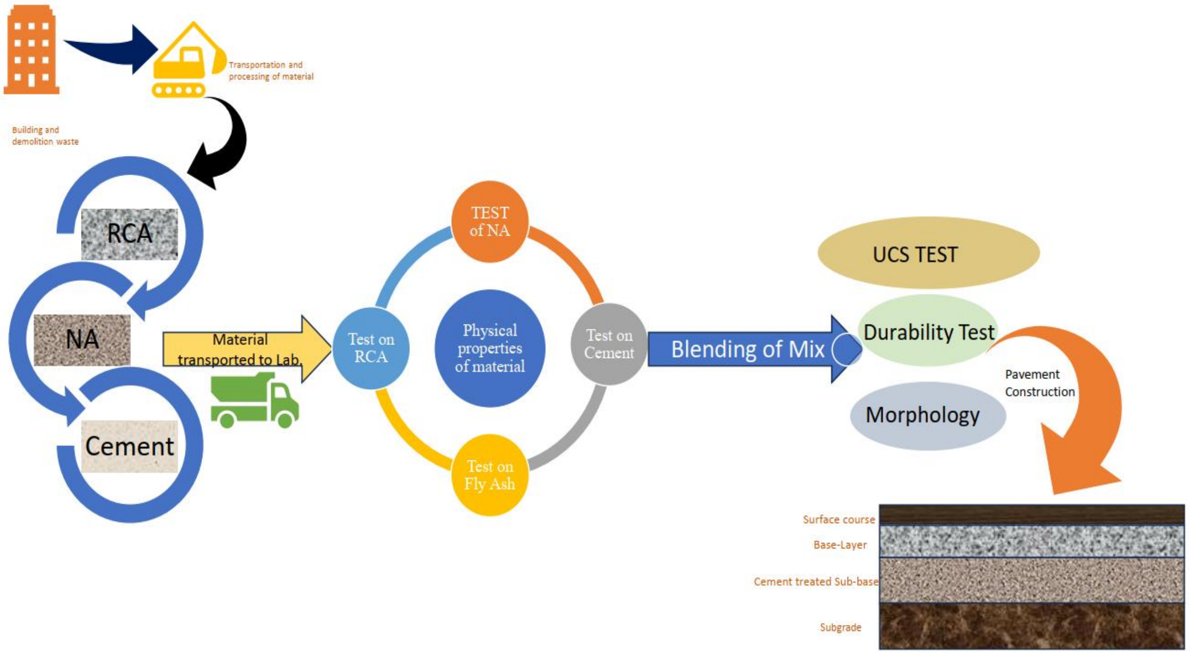
Graphical Abstract



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1. INTRODUCTION

The number of building projects is growing daily. And as a result, it leads to an increase in the production of C&D wastes. The leftovers from maintenance, rehabilitation, and revamping procedures are known as C&D wastes. It consists of steel, plastic, concrete blocks, broken bricks, recycled asphalt, and other building supplies. Additionally, the collection of demolition trash is a result of routine maintenance on the structures. Environmental issues are raised by the improper C&D waste disposal. However, just 1.3 percent of the C&D wastes that are produced overall are recycled. Therefore, C&D waste needs to be properly handled and recycled for its maximum utilization. Based on the volume of construction, C&D wastes come from a variety of sources. They fall into two categories: major and minor contributors. Roads, apartments, bridges, flyovers, malls, etc. are the major contributors, whilst low-rise residential structures are the minor ones. These factors therefore have an adverse influence on the soil's natural composition, threaten flora and animals, affect human health, etc. Figure 1 displays the C&D waste produced in India's main cities (1).

Before incorporating C&D waste into building procedures, it should be thoroughly processed via several steps such as breaking, removing, and crushing. There are no garbage, plastic, glass, or wood in these wastes. The unharmed bricks are separated from the others and set out on the tipping floor. Later, a crusher is used to reduce them to sizes between 20 and 40 mm. Then, to create recycled concrete aggregates, concrete fragments are sorted and put into the crusher (RCA). Comment 4 and 6 Concrete (45%), mortar (24%), masonry/crushed bricks (5%), wood/plastic/crushed glass (3%), and metal wires/marbles (1 percent) make up the majority of RCA, which is composed primarily of gravel (22%) (2, 3).

Various countries have developed specifications of implementation and classification of RCA based on their composition. European (CEN) practice includes RCA in European (EN) standards; which comprises of natural aggregates (NA), manufactured aggregates, and recycled aggregates. British standards, UK-BS 8500-2:200628, have two variants namely RCA and recycled aggregate. The International Union of Laboratories and Experts in Construction Materials, Systems and Structures, (RILEM) have of aggregates as Type I, II, and III based on its constituents. There are numerous advantages of using RCA in construction sector. It mitigates shortage of raw material such as coarse aggregate, sand etc. Its availability is closer to the construction site; thus, transportation cost reduces. Sources of NA are conserved and dumping site requirement for C&D waste is reduced.

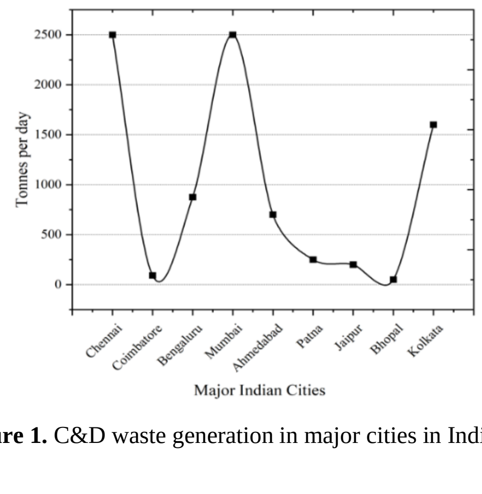

Figure 1. C&D waste generation in major cities in India [1]

Various researchers have investigated on use of RCA in construction sector (4-6). The growth of India's road network after independence has led to NA depletion. Up to 40% of cement can be replaced in part by cementitious materials (by weight of concrete). This study of the literature addresses the use of artificial aggregates and demolished bricks as a partial replacement for cement (7-9). Fly Ash (FA) usage with RCA increased compressive strength, tensile strength and durability. Experiments on chloride ion penetration and drying shrinkage were carried out to investigate into the durability aspect (10-13). The mechanical properties and durability of concretes are greatly influenced by the size of FA particles. The compression resistance gain of the mortars increases as the FA particle size decreases. If there are any significant differences between the investigated properties, an analysis of variance (ANOVA) test was used to evaluate this (14). Researchers also examined C&D materials that had been hydrated with lime (HL) in concentrations ranging from 1% to 5%. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy were used for micro-scale analysis (EDS) (15, 16). Utilizing waste materials in building will aid in reducing the rate of the depletion of natural resources (17). Two distinct waste kinds, FA and connected mortar clay brick, have their geo-polymeric potentials examined. Compared to attached mortar clay brick, the UCS value of FA + Fine Aggregates (C&D) raise by 10% over the course of 28 days (CBS) (18). It is explored if recycling C&D waste as aggregate in pavements with substantial traffic volumes is feasible. The mechanical behaviour of the aggregate material was improved by stabilising the C&D waste with Portland cement or lime, reducing mechanical response variability (19). Researchers looked more closely at using RHA to stabilise RCA. It was discovered that adding RHA increases the compressive strength value for blended mixtures. When added to the blended mixture, the hydrated lime raised the blend's crushed strength value (20, 21). Researchers compared several stabilised concrete mix designs (with and without the incorporation of the cooking oil) The blended mixes, consisting of 100 percent RCA plus 70 percent FA plus

30 percent L (by weight of aggregates) and 100 percent RCA plus 95 percent GGBS plus 5 percent L with cooking oil, respectively, were found to have strength of 2 MPa in just two days and 28 MPa after 56 days (22). According to the examined literature, researchers stabilised processed C&D wastes such RCA, bricks, mortar, broken concrete, etc. with the help of additives like FA, lime, RHA, and ground-granulated blast furnace slag (GGBFS). They did not, however, combine FA-L mixes with C&D wastes (for partial replacement of the cement). Additionally, just 1.3 percent of all C&D wastes are recycled on a marginal basis. Furthermore, only a few numbers of studies have used SEM, X-Ray diffraction (XRD), EDS, etc. to characterise the blends' microstructures. Therefore, further study is needed in the area of C&D waste use in the construction sector, specifically in terms of performance evaluation and economic analysis. This research has replaced the granulated sub-base of flexible pavement with a cementitious sub-base mix. Using recycled aggregate in place of natural aggregate can save natural resources and become cost-effective. (Comment 1& 2)

2. MATERIAL AND METHODS

For the present investigation, materials to be studied are selected and procured initially. Then, different types of tests are performed on these procured materials. After that, these materials are graded and blended as per required percentage. Further, laboratory tests are repeated on the blended mixture. Then, microstructural characterization of the blend is performed using SEM. Lastly, cost comparison of blend with original material is performed to check economic viability of the study.

2. 1. Selection of Materials Crushed concrete, crushed bricks, demolition scrap, and scraped-off pavement are just a few examples of the various elements that are included in C&D wastes. C&D wastes have been treated & recycled prior to being used into the building of the pavement foundation or sub-base. Table 1 lists material used in the present research with their procurement sites. Stone, gravel, sand, silt, and clay are produced as a result of rock erosion and weathering in NAs. For the investigation, an ordinary Portland cement (OPC) of Grade 53 cement was employed, which met the IS: 12269: 1987 standard's specifications. To keep it safe from moisture, the cement was stored in an airtight container. FA is a kind of industrial waste that is created when coal is burned. Iron, silicon, and aluminium oxides make up the majority of fine particles. HL is a dry, white, crystalline powder that is produced when calcium oxide is treated with water. When HL and FA are combined, early strength is improved. Therefore, HL was utilized as an addition to enhance the pozzolanic capabilities of FA or the blended mix's ability to reach early age compressive strength. The materials used in this work are listed in Table 1 along with the locations where they were purchased. Table 2 lists the chemical make-up of Fly Ash "Class F" and Hydrated lime.

TABLE 1. Types of Materials and their procurement sites

Sr. No.	Material	Procurement site
1	RCS	Surat Green Precast Pvt. Ltd.
2	NA	From Stone Quary Site at Chikhli
3	OPC 53	Aditya Birla Company
4	FA (Class F)	From Hazira Industrial area
5	HL	Purchased from local market

TABLE 2. Chemical composition of Fly Ash "Class F" and Hydrated lime

Chemical Analysis	"Class F" Fly Ash (%)	Specifications as per ASTMC618 (%)	Hydrated Lime (%)	Specifications as per ASTM C977-18 (%)	Recycled Material	Test method
Al_2O_3	25.70	-	-	-	13.77	IS 1727 (2013)
Fe_2O_3	5.3	-	-	-	7.86	
SiO_2+Al_2O_3+Fe_2O_3	85.9	70	-	-	76.44	
CaO	5.6	-	72	CaO + MgO = 90%	10.65	
MgO	2.1	5	4		1.98	
TiO_2	1.3	-	-	-	-	-
K_2O	0.6	-	-	-	-	-
Na_2O	0.4	1.5	-	-	-	-
SO_3	1.4	5	-	-	-	-
Loss on Ignition	1.9	6	24	-	7.28	IS 1727 (2013)

2. 2. Tests on Materials The Los Angeles abrasion test is used to determine how much wear is caused by the abrasive action between the aggregates and the steel balls used as abrasive charges. The specific gravity of coarse aggregates is regarded to be a better indicator of the strength and quality of materials used in construction while the water absorption test gives information on the coarse aggregates' capacity to hold water or, to put it another way, their strength. For coarse aggregates, the Ministry of Road Transport and Highways (MoRTH) 5th revision has established an acceptable limit for the combined flakiness and elongation index. According to MoRTH, the sub-base and base layers of the pavement might suffer negative effects from the presence of flaky and elongated pebbles. To assess the durability and resilience of the coarse aggregates under heavy traffic loads, an aggregate impact test was conducted. Only aggregates that pass 12.5 mm and are retained on a 10 mm Indian Standard (IS) screen are subjected to this test.

3. RESULT AND DISCUSSION

3. 1. Gradation and Blending of Aggregates For better evaluation of the laboratory tests, the current study effort has integrated a varied percentage of the relevant materials, including RCA, FA, and HL. Cement was mixed in the following proportions: 3%, 4%, 5%, and 6% (by weight of aggregates) with RCA in the following proportions: 25%, 50%, 75%, and 100% by partially substituting NA. In addition to using RCA, it's crucial to minimize cement usage by partially substituting it with affordable pozzolanic materials like FA and HL blends in the proportions of 10%, 15%, and 20% (by weight of cement), respectively, when creating blended mixes.

3. 2. Tests on Blended Mix Executing the tests required for evaluating the physical properties of the NA and RCA was the first step in the relevant research endeavour (according to the standards as indicated in respective IS codes and MoRTH: 5th Revision). Regarding the strength and durability properties of the blended mixes, the recommended tests as explained in detail in the following sections, meeting the requirements of IS Code and IRC: SP:89 specifications, conducted in the lab.

3. 2. 1. Modified Proctor Test On the mix proportions specified in IS:2720 (Part-8): 1983, a modified Proctor test was conducted in the lab. The test was conducted using a sample that weighed 30 kg and passed through a 37.5 mm IS Sieve. With a 4.9 kg rammer, each layer received 55 hits. Figures 2 and 3 displays the OMC-MDD plot for the RCA (100 percent).

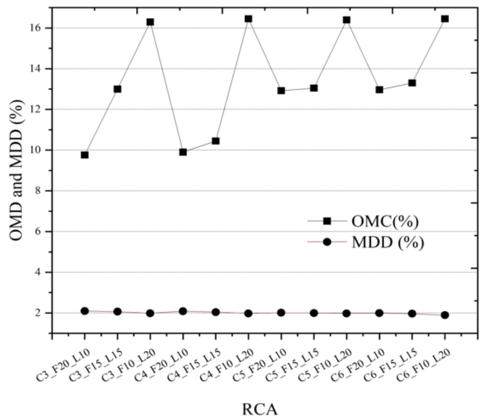

Figure 2. OMC-MDD plot for RCA (100%)

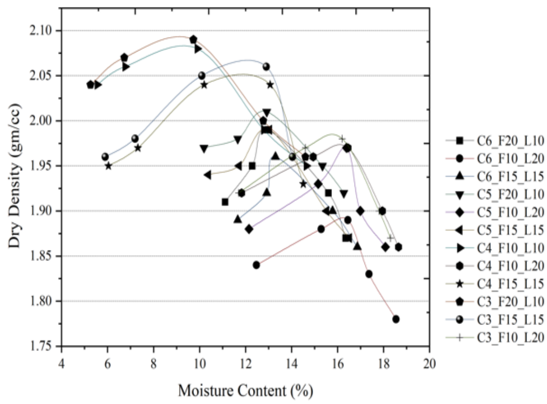

Figure 3. Variation in OMC-MDD with changes % of binder

The findings indicate that, for each mix proportion, the maximum dry density (MDD) decreases and the ideal moisture content (OMC) rises as cement percentage, notwithstanding the trend observed following the integration of the combinations of the used additives, i.e. For FA and HL combined, the lime content increased to 30% of the cement weight (partially replaced), which led to an upward trend in the OMC. For MDD, an increase in the lime content would have led to an upward trend. The water-absorbent property of RCA is another factor contributing to the rising trend of OMC. OMC rises in tandem with an increase in RCA %. The RCA's MDD (100%) turned out to be lower than the NA's (100 percent). This is the reason why the MDD has decreased: attached cement mortar over the surface of the RCA created a porous, considerably weaker fractured layer. The RCA was crushed into considerably finer fractions than NA during the compaction process, which led to a fall in dry density and an increase in water content. This was the other factor.

3. 2. 2. UCS Test The pozzolanic action of the FA and Lime with cement is the primary factor contributing to the development of strength in FA-L blended mixtures. The production of calcium silicate hydrate (CSH) gel and calcium aluminosilicate hydrate (CASH) gel occurred as a result complementing the lime's greater calcium content. The of the silica and alumina rich FA possibly mix-proportions produce an unconstrained compressive strength as a result of the binding gels' pozzolanic reaction. Since FA was present, which slows down the hydration process of pozzolanic materials, greater strength at 7 days could not be reached. However, the UCS value significantly rises if the mixture is cured for a lengthy period of time, such as 28 days. Moreover, the required unconfined compressive strength (UCS) of the sub-base layer, according to the IRC:SP:89, is 1.5 to 3 MPa (comments 3 and 4).

The usage of RCA in the sub-base layer of the pavement was the subject of the most recent study. Therefore, the computed average UCS values of the mixed fraction with RCA content are the major emphasis. It was found that the 50/50 blend of RCA and NA, along with 6 percent C, 10 percent FA, and 20 percent L, produced a 7-day average UCS value (3.57 MPa) that met the requirements of IRC 37:2018. For successful application in the sub-base layer of the pavement, all other mix proportions of 50% RCA and 50% NA readily obtained the average UCS values at 7 days and 28 days, respectively. However, for cement contents of 5% and 6%, the obtained UCS values for the mix-proportion were less than NA (100%) (by weight of aggregates).

3. 2. 3. Durability Test Two like sets (Set 01 and Set 02) of UCS specimen have been made for the observed OMC. Both sets had been dried out in a humidity chamber with a fixed moisture level. For aggregates coarser than 20 mm, Method 2 cannot be used. Figure 4 shows the Change in UCS with binder % and curing period and Figure 5 shows the Durability Index plot for the RCA (75%)-NA (25%) combination.

To assess the effects of HL and FA when utilized in the stabilization of RCA under various curing conditions, the Durability test was carried out. The main purpose of the test was to determine if blends were durable or resistant to the effects of water on strength under various curing circumstances. This particular aspect was calculated using the Durability Index. This indicator displays the resistance to the strength's impact from water. If the result is less than 0.80, it should be assumed that the stabilizer content is low and that the value for the stabilizer should be adjusted.

3. 2. 4. Beam Load Test To determine the degree of stiffness of the sub-base layer of the flexible pavement, an elastic modulus test was conducted. Three beam specimens measuring 700 × 150 × 150mm have been cast out for the combined RCA-NA percentage of 50%. Table 3 lists the E-value calculations for the RCA (50%)-NA (50%) pair. Figure 6 depicts a beam load test specimen and specimen testing.

The explanation for the discrepancy in the E-value is that the UCS specimen had a higher surface area under load, but in a beam load test, the area under stress is lower, hence a smaller weight would have a greater influence on the specimen. As the E-value completely depends on the load value, it represents the specimen's stiffness. As a result, this can be one of the causes of the lower number seen during the Beam Load test. However, the ECTSB found in the Beam Load test is within the parameters specified in IRC:37:2018.

3. 3. SEM The SEM technique can be employed to gather data on the specimen's crystallinity, microstructural composition, and surface topography.

TABLE 3. Calculation of E-value for RCA (50%)-NA (50%)

Sample No.		1	2	3
Failure Load (P) kN		9.88	9.92	9.94
Corresponding Disp. (d) mm		6.221	6.29	6.31
	700	700	700	700
Dimension of Beam	150	150	150	150
	150	150	150	150
Effective Length of Beam (L) mm		600	600	600
Moment of Inertia (mm^4)		42187500.00	42187500.00	42187500.00
a=L/3 (mm)		200	200	200
E value (MPa)		2556.60	2566.95	2572.13
Average E-value (MPa)			2565.23	
Modulus of Rupture (MPa)		2.049	2.057	2.061

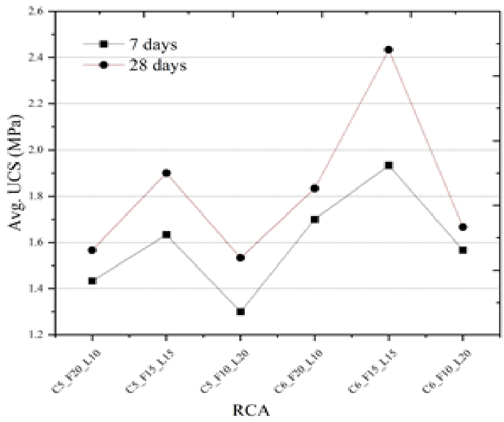

Figure 4. Change in UCS with binder % and curing period

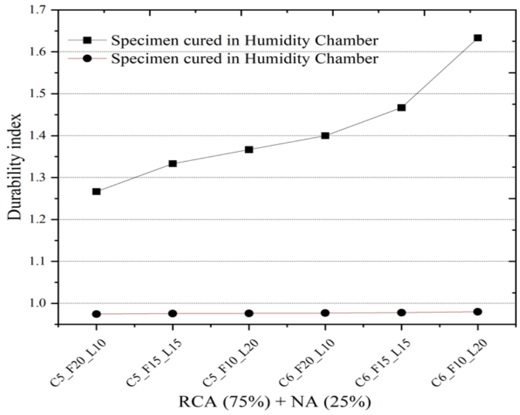

Figure 5. Durability Index plot for RCA (75%)-NA (25%)

Magnification in SEM reaches up to 400X to 30000X resolution. The resolution of a microscope is its capacity to effectively discern two nearby spots. The pores, ettringite gel formation, and microcracks on the aggregate surface have all been investigated using SEM. With a resolution of 1000X, the SEM image shown in Figure 7 for microscopically characterized analysis. The major elements in this specific SEM picture, including the pores, Ettringite gel formation, Calcium Hydroxide, CASH, hydrated cement, and microcracks on the aggregate surface, have all been examined. Tricalcium Silicate, Dicalcium Silicate, and Tricalcium Aluminate are the primary components of cement (C3A). Gypsum and C3A react over the first 24 hours of the hydration process, resulting in the formation of Calcium-Alumino Sulfate ettringite gel. The hydrated lime and fly ash's pozzolanic interaction with the cement is what increases strength. Fly ash, which is rich in silica and alumina, might possibly complement the lime's greater calcium content, resulting in the creation of gels called CSH and CASH. The mix-proportions produce an unconstrained compressive strength as a result of the binding gels' pozzolanic reaction. Since Fly Ash delayed the hydration process of pozzolanic materials, greater strength at 7 days could not be attained because of its presence. However, the UCS value significantly rises if the mixture is cured for a lengthy period of time, such as 28 days. The cementitious materials that were used to fill the tiny holes on the surface of the RCA prevented the electrons from being backscattered, giving the pores a darker appearance.

The development of UCS strength was aided by the significant HL presence with FA. There would have been less microcracks and unreacted Fly ash present. The structure under examination was made visible using a 3000X resolution magnification of the SEM pictures. The spike-like ettringite particles were seen when the SEM picture was again enlarged at a resolution of 10,000X.

Figure 6. Testing of specimen

The initial stage of the hydration process is when this ettringite gel developed. And it continues to react to create CSH and CASH, which causes the strength to develop (Figure 7) (23-25).

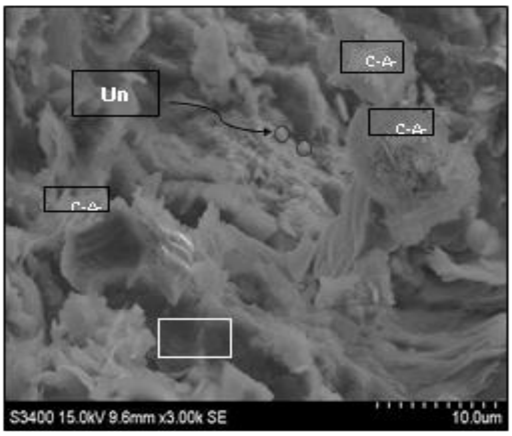

Figure 7. SEM image showing of RCA (50%)-NA (50%) sample Micro cracks, Unreacted Fly Ash, and C-A-S-H

3. 6. Cost Comparison Cost comparison for the present study is performed as per current market price of various materials and binders. The cost of various materials per m3 is calculated for a conventional mix with RCA (50%) and NA (50%) applied. It was determined that if the RCA (50%)-NA (50%) were used in the building of the sub-base layer of the pavement, 17.86% of the material cost (per m^3) would be saved.

4. CONCLUSION

In the present study, an investigation of utilization of RCA in construction sector has been performed using laboratory tests, microstructural characterization, and economic analysis. Following are important findings of the study-

- For each mix proportion, the maximum dry density drops as the cement % rises, but the ideal moisture content rises. The maximum dry density of the RCA (100%) was lesser than the NA (100%).
- The 7 days average ultimate compressive strength value for 50% RCA and 50% NA blended with additives satisfied the specifications.
- All mix proportions had durability indices that were higher than 0.80. The E-value for the mix ratio of RCA (50%)-NA (50%) was calculated to be 2565.23 MPa. SEM study has been done on the aggregate surface's pores, ettringite gel formation, calcium hydroxide, calcium aluminosilicate hydrate, hydrated cement, and microcracks.
- Economic analysis found that employing RCA (50%)-NA (50%) for the construction of the pavement's sub-base layer reduced material costs by 17.86%.

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Persian Abstract

چکیده

زباله های ساخت و ساز و تخریب با تشدید فعالیت های ساخت و ساز در سراسر جهان به طور مداوم در حال افزایش است که منجر به نگرانی های زیست محیطی می شود. بازیافت این ضایعات به سنگدانه های بتن بازیافتی (RCA) در لایه های پایه و زیر پایه روسازی یکی از راه حل های این مشکل است. بنابراین، مطالعه حاضر یک بررسی عمیق از استفاده از RCA در بخش ساخت‌وساز است که شامل تست‌های آزمایشگاهی، خصوصیات ریزساختاری و تحلیل اقتصادی است. آزمایش نشان داد که برای هر نسبت مخلوط، حداکثر چگالی خشک کاهش می‌یابد و با افزایش درصد سیمان، رطوبت ایده‌آل افزایش می‌یابد. میانگین مقاومت فشاری نهایی 7 روزه برای سنگدانه های طبیعی (NA) و بتن بازیافتی (RCA) همراه با مواد افزودنی الزامات را برآورده می کند. شاخص دوام برای تمام نسبت های مخلوط بیشتر از 0.80 بود. در نهایت، مشخص شد که 17.86٪ از هزینه مواد با ادغام (50٪) NA - (50٪) RCA برای ساخت لایه زیرین روسازی صرفه جویی گردید.