Influence of Reclaimed Asphalt Pavement Aggregates on Strength and Durability Properties of Concrete Mixes in Rigid Pavements

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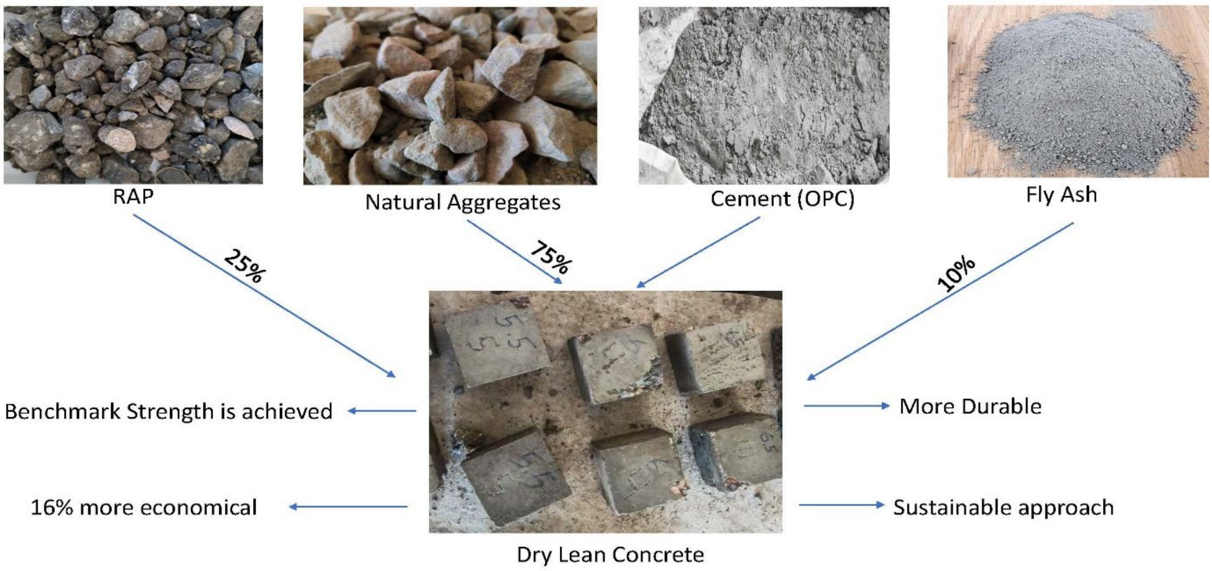

ABSTRACT: The use of Reclaimed Asphalt Pavement (RAP) aggregates in rigid pavements instead of conventional aggregates in Himalayan regions solves the problem associated with shrinking natural resources and dumping of wastes. This study studied the effect of partial replacement of conventional coarse aggregates by RAP in Dry Lean Concrete (DLC) mixes suitable for rigid pavements. A total of 114 specimens (cubical and cylindrical) were cast and tested for mechanical and durability properties as per ASTM and IS code guidelines, partially replaced with CRAP by 25%, 50%, and 75% by weight. The simultaneous effect of fly ash addition by partial replacement of cement by it was also studied. The study concludes that 25% partial replacement by CRAP with 10% fly ash as partial replacement of cement led to the achievement of the strength benchmark as mandated by IRC SP 44 (2014). It was also observed that durability properties such as resistance to acid attack, sulphate attack and carbonation also improved in DLC mixes, including CRAP and fly ash, when compared to control mixes.

الملخص: إِسْتِخْدامُ الخَرَسانَةِ المُعادِ تَدْوِيرُها (RAP) كَمادَّةٍ خامٍ فِي الأَرْضِيّاتِ الصُلْبَةِ بَدَلاً مِن المَوادِّ التَّقْلِيدِيَّةِ فِي مِنْطَقَةِ الهِمَلايا يَحُلُّ المُشْكِلَةَ المُرْتَبِطَةَ بِالنَّقْصِ فِي المَوارِدِ الطَّبِيعِيَّةِ وَتَجَمُّعُ النُفاياتِ. هٰذِهِ الدِراسَةُ تَناوَلَت تَأْثِيرَ الإِسْتِبْدالِ الجُزْئِيِّ لِلرُّكامِ التَّقْلِيدِيِّ الخَشِنِ بِواسِطَةِ RAP فِي خَلْطاتِ الخَرَسانَةِ الجافَّةِ المُنْخَفِضَةِ (DLC) المُناسِبَةِ لِلأَرْضِيّاتِ الصُلْبَةِ. تَمَّ صَبُّ وَاخْتِبارُ ما مَجْمُوعُهُ 114 عَيِّنَةً (مُكَعَّبَةً وَأُسْطُوانِيَّةً) لِلخَصائِصِ المِيكانِيكِيَّةِ وَالمَتانَةِ وِفْقاً لِإِرْشاداتِ رَمْزِ ASTM وَ IS وَأُسْتُبْدِلَت جُزْئِيّاً بِـ CRAP بِنِسْبَةِ 25%، 50%، 75% حَسَبَ الوَزْنِ. كَما تَمَّ دِراسَةُ التَّأْثِيرِ المُتَزامِنُ لِإِضافَةِ الرَمادِ الطائِرِ بِواسِطَةِ إِسْتِبْدالِ جُزْئِيِّ لِلأَسْمَنْتِ. خَلَّصَت الدِراسَةُ إِلَى أَنَّ إِسْتِبْدالَ 25% جُزْئِيّاً بِواسِطَةِ CRAP مَعَ 10% مِن الرَمادِ الطائِرِ كَإِسْتِبْدالِ جُزْئِيِّ لِلأَسْمَنْتِ أَدَّى إِلَى تَحْقِيقِ مَعايِيرِ القُوَّةِ كَما هُوَ مَطْلُوبٌ بِمُوجِبِ مُواصَفَةِ IRC SP 44 (2014). كَما لُوحِظَ أَيْضاً أَنَّ خَصائِصَ المَتانَةِ مِثْلُ المُقاوَمَةِ لِلهُجُومِ الحَمْضِيِّ، هُجُومُ الكِبْرِيتِ وَالكَرْبَنَةِ تَحَسَّنَت أَيْضاً فِي خَلْطاتِ الخَرَسانَةِ الجافَّةِ المُنْخَفِضَةِ بِما فِي ذٰلِكَ CRAP وَالرَمادُ الطائِرُ مُقارَنَةً بِالخَلْطاتِ النَمَوذَجِيَّةِ.

Keywords: Reclaimed Asphalt Pavement, Dry Lean Concrete, Rigid Pavement, Mechanical Strength, Durability, Partial Replacement

الكلمات المفتاحية: الأسفلت المسترجع، الخرسانة الجافة المنخفضة، الأرضيات الصلبة، القوة الميكانيكية، المتانة، الاستبدال الجزئي.

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NOMENCLATURE

RAP	Reclaimed Asphalt Pavement
NA	Natural Aggregates
NCA	Natural Coarse Aggregate
NFA	Natural Fine Aggregate
CRAP	Coarse Reclaimed Asphalt Pavement
FRAP	Fine Reclaimed Asphalt Pavement
DLC	Dry Lean Concrete
PPC	Portland Pozzolana Cement
OPC	Ordinary Portland Cement
SCM	Supplementary Cementitious Materials
QPC	Pavement Quality Concrete
IS	Indian Standard
ASTM	American Society for Testing and Materials (Concrete)
AIV	Aggregate Impact Value
ACV	Aggregate Crushing Value
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
pH	Potential of Hydrogen Ions
H_2SO_4	Sulfuric Acid
Na_2SO_4	Sodium Sulphate
HCl	Hydrochloric Acid
RAP 25	Mix containing 25% CRAP
RAP 50	Mix containing 50% CRAP
RAP 75	Mix containing 75% CRAP
SRAP 25	Mix containing 25% CRAP and 10% fly ash
SRAP 50	Mix containing 50% CRAP and 10% fly ash
SRAP 75	Mix containing 75% CRAP and 10% fly ash

1. INTRODUCTION

Seeing the long–term benefits of rigid pavements, such as longer life, low life cycle and maintenance costs, the Transport Ministry of India has adopted rigid pavements as the default mode of construction (Bhalla, Jaya Shroff 2014). But in places where natural aggregates are scarce, restrictions to quarrying are posed, detrimental implications to flora and fauna are seen, and global release of carbon dioxide for the production of cement is at alarming levels, attention is being shifted towards finding alternate sources of aggregates and binders (Surender Singh et al. 2019). Among alternate sources of aggregates, the use of reclaimed asphalt pavement (RAP) in concrete pavements has attracted the attention of various researchers in the recent past. Reclaimed asphalt pavement aggregates are aggregates coated with bitumen obtained after milling existing flexible pavement (IRC 120 2015). Incorporation of RAP in the construction of concrete pavements has various advantages, such as the conservation of natural aggregates, reduction in transportation costs (owing to on-the-spot utilization), reduction in the burden on landfill facilities, and reduction in carbon footprints. RAP is a waste material generated during the milling and rehabilitation of old flexible pavements. Usually, in Himalayan regions, after every monsoon season, the flexible pavements are resurfaced, and the process produces a large amount of RAP waste, which is a major solid waste concern (Abraham Sarah Mariam et al. 2018). Millions of tons of RAP aggregates are extracted every year and are found either in open ground or in disposal sites. RAP aggregates consist of a layer of asphalt around them which gets stiff due to the oxidation of volatile compounds during service life and stockpiling. As most of the flexible pavements in India have reached their design life and need either resurfacing or re-construction therefore, a huge amount of RAP will be generated. More studies have been conducted to analyze the feasibility of CRAP aggregates in cement concrete and mechanical properties; also, few studies have been on the utilization of fine RAP aggregates too (Abraham Sarah Mariam et al. (2019). The study concluded that engineering properties like compressive Strength and flexural Strength tend to reduce with an increase in RAP content in the concrete mixture (Solanki Pranshoo et al., 2015).

Past Studies

In past studies, RAP has been used as a partial replacement for NCA and NFA. Researchers have studied properties such as strength, durability and pore structure of cement mortar, dry lean concrete (DLC) mix, concrete mix and high-strength concrete mix with and without the use of mineral admixtures. In very early studies, CRAP was used in plain cement concrete as a partial replacement for NCA. Along with this, cement was also replaced partially with supplementary cementitious materials. These studies showed a reduction in strength (both compressive and tensile) significantly. Also, the workability of the mix decreased almost to zero in some of the studies, which is also a matter of concern (Huang B et al. 2006). Further, in 2009, researchers tried to incorporate more fractions of CRAP as a partial replacement to NCA, but these time strength results were found to be comparable as the study was conducted for lower grades of concretes (Singh Surender et 2019). The researchers compared the failure pattern of the control specimen with CRAP included specimen and concluded that the result variation was because of the failure of the mortar interface in CRAP concrete mixes but the crushing of aggregates in control specimens (Okafor Fidelis O. et al. 2010). Although the fine RAP was also tried to be utilized in concrete mixes, a study was conducted to incorporate both CRAP and FRAP, but it also concluded the same results as previous studies. The authors suggested using RAP concrete for low-strength purposes (Solanki Pranshoo et al. 2015). A similar study used both the fractions of RAP (milled from 20-year-old and eight months old pavement), i.e., CRAP and fine RAP was used for making DLC(Singh Surender et al. (2018)). Incorporations of new RAP (CRAP from the new pavement) aggregates were found to have a greater negative effect on the fresh and hardened properties of DLC as compared to old RAP (CRAP from the old pavement) aggregates (Singh Surender et al. 2018). To investigate the suitability of CRAP in high-strength concrete, studies were carried out on the strength and durability properties of high-strength concrete specimens mixed with CRAP. There was a similar trend seen in this study, too, in the context of strength parameters, but durability properties were found to be better in these CRAP-incorporated concrete mixes (Thomas R J et al. 2018). Also, partial replacement of conventional natural aggregates in a proportion of 50% by either fraction of RAP (coarse and fine) was suitable for Roller compacted concrete pavements (for the base course) since these mixes had even higher flexural strength than the recommended target laboratory mean strength of 4.3MPa (Debbarma Solomon et al. 2019*)*. The issues with the utilization of CRAP and FRAP were low workability. Also, a reduction in compressive and tensile strength was seen. When RAP was collected locally, a lot of dust particles were there in the sample. Hence RAP aggregates were washed before usage so that dust could be removed. One of the reasons for the reduction of strength stated by many researchers was an improper gradation of RAP aggregates in comparison to natural aggregates. Hence, heat treatment was given for 3 hours before extracting CRAP and FRAP from the sample of RAP collected so that proper extraction of aggregates could be carried out. In the current study, RAP was collected from a locally deteriorated pavement. The sample was collected and transported to the laboratory. The heat was applied to the RAP so that the bitumen coating around it get loosened and could be easily broken. RAP was then broken with a hammer, yielding both fine and coarse fractions. A portion of RAP that passed through the 20mm sieve but retained on the 4.75mm sieve was used as CRAP, and the remaining balance was FRAP. In this study, CRAP will be utilized as a weight replacement for NCA, as well as the effect of fly ash as a partial replacement for cement was examined. The impact of these two additives on workability (slump test, compaction factor test, and fresh density test), mechanical properties (compressive strength and split tensile strength test), and durability (pH, resistance to acid attack, sulphate attack and carbonation) was assessed as to meet the real-life condition in rigid pavement during its service life. A cost analysis was also performed to get an idea of the overall benefit of using RAP in rigid pavement construction.

2. COLLECTION OF RAP

RAP used in this study was collected from a roadside stockpile on NH-20A, about 1km from the Massal bridge near the Rajiv Gandhi Government Engineering College in Kanga, India. As the material was in the form of lumps and was filthy, it was crushed with a hammer and washed with tap water until all of the dirt was removed.

3. CHARACTERIZATION OF RAW MATERIALS

3.1 Gradation of Aggregates

The results of the grain size distribution of NCA and CRAP carried out are shown in Figure 1. The test was done as per the procedure explained in IS 383 (1970)/ ASTM C 136-06 (2015).

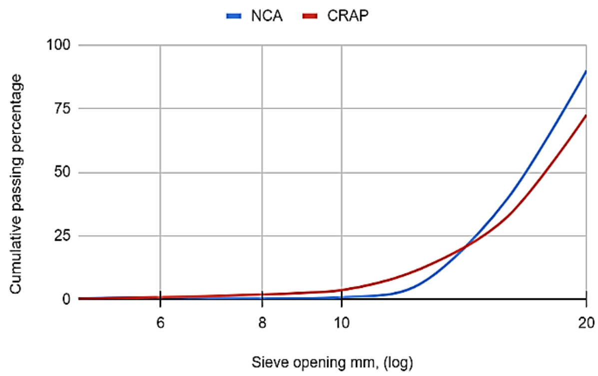

Figure 1. Comparison of the particle size distribution of NCA and CRAP.

3.2 Specific gravity and water absorption

The specific gravity of NCA (2.65) was found to be more than CRAP (1.95). This was due to the presence of oxidized bitumen coating in CRAP. The normally specific gravity of bitumen lies in the range of 1 to 1.1. Hence, a specific gravity of NCA was found to be more than CRAP. The water absorption of CRAP was marginally less compared to NCA, which was calculated as per IS 2386 part 3 (1963)/ASTM C 29(2016). The main reason for this could be the presence of bitumen coating, as it is a well-known water-repellent material. These water absorption values were used during the final corrections of water content in the trial and the modified design mix.

3.3 Aggregate impact value

Bitumen is a ductile material that is bounded around the aggregate. When aggregate was under impact loading, CRAP absorbed more energy before fracture. Hence, the impact resistance of CRAP was found to be more than NCA. In the current study, AIV for NCA was 16%, and CRAP was 9.32% as per the procedure mentioned in IS 2386 part 4 (1963)/ASTM C 33 (2018).

3.4 Aggregate crushing value

A similar trend was seen for ACV for NCA and CRAP. Under gradual loading in compression testing machines (CTM), CRAP showed more resistance. Values of aggregate crushing for NCA and CRAP were 26.8 % and 18%, respectively, which were calculated with reference to IS 2386 part 4 (1963)/ASTM C 535 (2016).

Table 1. Detailed properties of NCA and CRAP.

Properties of Aggregate	NCA	CRAP	Code
Specific Gravity	2.65	1.95	IS 2386 part 3 1963
Water Absorption	0.83%	0.23%	IS 2386 part 3 1963
Elongation Index	18.55%	14%	IS 2386 part 1 1963
Flakiness Index	16.79%	18%	IS 2386 part 1 1963
Impact Value	16%	9.30%	IS 2386 part 4 1963
Abrasion Value	19.40%	14%	IS 2386 part 4 1969
Crushing Value	26.80%	18%	IS 2386 part 4 1963

3.5 Los Angeles abrasion value

Similar to AIV and ACV, abrasion value was also reported better in the case of CRAP in comparison to NCA. Bitumen coating and dust particles were responsible for this increased resistance of CRAP in abrasion. The Los Angeles abrasion value was 19.4% for NCA and 14% for CRAP, as calculated with reference to IS 2386 part 4 (1963)/ ASTM C 535 (2016).

3.6 Silt content

The workability of lean mixes was comparatively less in comparison to control mixes when CRAP was utilized as a replacement for NCA (Okafor Fidelis O. et al. 2010). One of the reasons was the presence of dust particles, as RAP was collected from the site. The silt content in NFA and FRAP shows that there is more quantity of silt content in FRAP. These fine dust particles absorb water and reduce the amount of water that is responsible for the flowing properties of concrete. Also, smaller particles have a larger surface area, and hence more cement paste is required to make the mix more workable. Silt content for NFA and FRAP was 1.33% and 3.5%, respectively, although both values were within the permissible range as per IS code.

3.7 Shape test

The flakiness and elongation index was calculated in this test. MDD of DLC incorporating RAP was lower due to the presence of elongated and flaked particles (Thomas R J et al. 2018). This test provides information about the interlocking ability of aggregates which is a parameter that affects the maximum density of concrete. CRAP was better in terms of elongation in comparison to NCA.

4. CASTING OF CONCRETE

Mix design for the casting of specimens was performed according to the standard procedure as per IS 10262 (2019), and design mix proportioning was adopted in the determination of optimum moisture content for maximum dry density.

4.1 Trial mixes and calculation of Optimum Moisture Content (OMC)

As the name indicates, DLC is dry lean concrete; the specimens were cast to achieve Maximum Dry Density (MDD) with water content taken as OMC. To determine OMC, trial mixes were done with various percentages of water. These percentages of water were in the range of 5% to 6.5% of the total weight of the dry volume as per the procedure mentioned in IRC SP 49 (2014). Three specimens were cast for each percentage of water used for casting. In total, 12 cubes were cast in 1st trial. The specimens of standard sizes (150*150*150mm^3) were used for casting as per IS 516 (2004)/ACI 318 (2022). A tamping rod was used for compaction while casting. The specimens made were kept undisturbed for 24 hours after casting, and these cubes were kept under damp jute bags during this period. After that, they were de-moulded, and the weight of each cube was measured. The average weight of the specimen was measured, which was then divided by the volume of the specimen to determine the bulk density. The relation between bulk density and dry density is given by the equation (1)

$$\gamma_d = \frac{\gamma_b}{1+w} \tag{1}$$

were, γ_d is dry density to be determined, γ_b is bulk density, and w is moisture content.

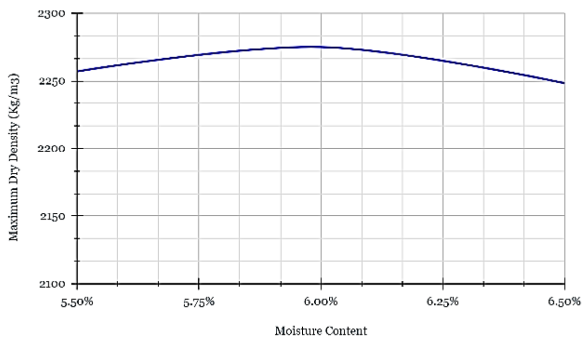

Figure 2. The graph between dry density and moisture content

Figure 2 indicates that a moisture content of 6% is required.
So, based on this OMC, three major categories of specimens were cast.

- Control mix
- Mixes containing 25%, 50% and 75% of RAP as a replacement for NCA
- Mixes containing both RAP and 10% fly ash as a replacement for cement

Table 2. shows all details of mixed proportions with reference to the above-said points.

Table 2. Mix proportions for dry lean concrete.

Mix Type	Cement	Fly ash	FA	NCA	CRAP
Control Mix	191.1	0	611.5	1597.4	0
RAP 25	191.1	0	611.5	1198.05	399.35
RAP 50	191.1	0	611.5	798.7	798.7
RAP 75	191.1	0	611.5	399.35	1198.05
SRAP 25	171.99	19.11	611.5	1198.05	399.35
SRAP 50	171.99	19.11	611.5	798.7	798.7
SRAP 75	171.99	19.11	611.5	399.35	1198.05

* Units for Cement, fly ash, FA, NCA and CRAP are (Kg/m^3).

The characteristics of concrete were examined in both the fresh and hardened stages after casting mixes mentioned in Table 2.

5. RESULTS AND DISCUSSION

5.1 Workability of Concrete

Table 3 Initial slump, compaction factor and fresh density of concrete with and without fly ash.

Mix Type	Slump (mm)	Compaction factor	Density (kg/m^3)
Control Mix	0	0.7	2352
RAP 25	5	0.75	2312
RAP 50	8	0.8	2287
RAP 75	15	0.86	2276
SRAP 25	0	0.72	2290
SRAP 50	5	0.75	2301
SRAP 75	10	0.8	2287

5.1.1 Slump cone test

Workability was measured by using a slump cone per IS 1199 (1959), and a true slump was achieved. DLC, in general, is zero-slump concrete. The inclusion of CRAP in DLC raises the slump value. The slump value for RAP 75 mix concrete was found to be the highest, i.e., 15mm, among all the concrete mixes tested. Despite this fact, almost every mix saw an increase in slump value. This increase in slump value was due to the absence of water-absorbing dust in CRAP aggregates. However, another reason for the overall increase in slump value when compared to NCA concrete (control specimen) was due to the presence of asphalt coating, which is usually hydrophobic and gives a smooth texture to CRAP in comparison to NCA. In addition, the incorporation of fly ash into concrete did not result in a significant change in workability in both NCA and CRAP-incorporated concrete.

5.1.2 Compaction Factor

For DLC, which is generally used in rigid pavement construction, workability is usually extremely low; it is critical to assess workability in terms of compaction factor. As for low slump concretes, the compaction factor test is used to calculate workability. However, proper compaction is a major concern while placing concrete. Hence, the compaction factor for the mixes was determined. Before casting concrete specimens, a compaction factor test was performed on fresh concrete to determine its workability in terms of compaction factors for various mixes. From 3, it was observed that the value of the compaction factor was the greatest for the mix type RAP 75. Although the fact values of the compaction factor increased slightly with each CRAP replacement, the reason for this could be the gradation of CRAP. The gradation of CRAP revealed that it was less coarse than NCA. As a result, better packing was observed with the addition of CRAP to NCA. However, the addition of fly ash reduced the compaction factor.

5.1.3 Fresh Density of Concrete

The density of the concrete in its fresh form was measured according to ASTMC 138 (2016). A cylindrical container measuring 20cm in height and 25cm in diameter was used to determine the fresh density of concrete prepared with the various mix proportions as per Table 2., to calculate density. Since CRAP has lower specific gravity than NCA (Table 1), a trend of decreased fresh density was observed in various mixes. The maximum fresh density of the concrete prepared control specimen was 2352.7kg/m^3.

5.2 Mechanical properties

Hardened density and strength parameters such as compressive and splitting tensile strength are among the mechanical properties which are evaluated in the current study. The hardened density was calculated by dividing the specimen's mass at the required age by its volume (by measuring the length, width and depth of the specimen). Separate specimens are not required, and the specimens used for strength testing before being placed in the CTM could be used to measure mass and dimensions. Three specimens per mix and age of curing were used for the compressive strength test.

5.2.1 Compressive Strength

Cubes were cast in moulds 150*150*150mm^3 in size, and the moulds were oiled before the concrete was poured. Thereafter, the cubes were left for 24 hours. After 24 hours, the cubes were de-moulded and cured for 7 and 28 days, respectively. After the 7th and 28th day, the cubes were removed from the curing tank, gently wiped and tested to determine their compressive Strength per IS 516 (2004)/ASTM C 39 (2021). According to IRC SP 49 (2014), the compressive strength of each consecutive group of 5 cubes must be greater than 7MPa after seven days, and the compressive strength of each cube must be greater than 5.5MPa after seven days. The compressive strength of samples was found to decrease as CRAP content was increased. After seven days of curing, samples had an average compressive strength of 5.1MPa for a 25% CRAP addition, which is slightly lower than the benchmark of 7MPa. On the 7th-day compressive strength test, the overall percentage reduction in compressive strength for 25, 50 and 75% CRAP added specimens was approximately 11%, 27% and 40% less, respectively, when compared to the control mix. However, by incorporation of supplementary cementitious material, i.e., fly ash for mix SRAP 25, the strength reached nearly to 6.2MPa on the 7th day and reached the benchmark strength of 10MPa as per IRC SP 49 (2014), but samples with higher proportions of CRAP failed to meet the strength criteria. The main cause could be poor bonding between the cement paste and the CRAP, as bitumen film prevented proper bonding between the CRAP and the cement mortar. This is evident from Figure 3. Furthermore, concrete mixes containing CRAP failed only at the interfaces of cement mortar and aggregates, which resulted in lower compressive strength.

Figure 3. Compression strength testing of concrete

Table 4. Compressive and split tensile strength on the 7th and 28th day of curing

Mix Type	CS 7*	CS 28*	STS 7**	STS 28**
Control Mix	6.8	10.8	0.75	1.12
RAP 25	5.9	9.6	0.62	0.92
RAP 50	4.9	7.8	0.52	0.77
RAP 75	4.0	6.4	0.41	0.61
SRAP 25	6.2	10	0.64	0.96
SRAP 50	5.1	8.2	0.55	0.82
SRAP 75	4.4	7	0.47	0.71

*Compressive strength at 7th and 28th day of curing
**Split tensile strength at 7th and 28th day of curing

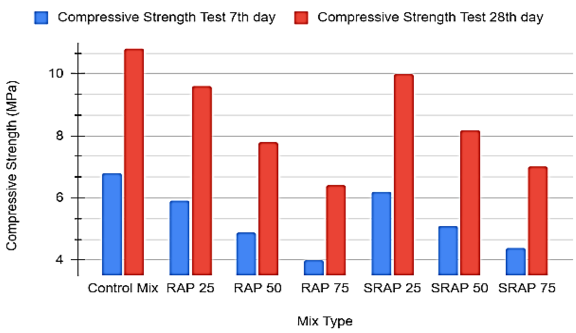

Figure 4. Compressive Strength of DLC on the 7th and 28th day of curing.

5.2.2 Splitting Tensile Strength Test

Tensile Strength was determined for the 7th and 28th day using cylindrical specimens (150mm diameter and 300mm depth) by IS 5816 (1999)/ASTM C 496 (2017). Specimens were initially surface dried before being placed in the compressive testing machine depicted in Figure 5. The loading rate was kept constant at 2kN/minute. Following the failure load readings, the tensile strength is calculated by using equation (2)

$$T = \frac{2P}{\pi l d} \tag{2}$$

Where T is the tensile strength of concrete, P is the load applied, l is the length of the specimen, and d is the diameter of the specimen. Since load is transferred to the subgrade by slab action in the case of rigid pavements, tensile strength becomes an important factor in the design of rigid pavements. Hence, a split tensile strength test was carried out, and it was found that the 28th-day split tensile strength reduced by 29%, 43%, and 57%, respectively, for 25%, 50%, and 75% CRAP added specimens as compared to the control specimen. Furthermore, unlike compressive strength, there was a slight improvement in split tensile strength even when fly ash was used as a 10% replacement for cement. The reason for the decrease in tensile Strength of CRAP-incorporated concrete is similar to the reason for the decrease in compressive strength. However, the tensile strength of SRAP 25 was 0.16MPa lower than that of the control specimen.

Figure 5. Split tensile strength testing of concrete.

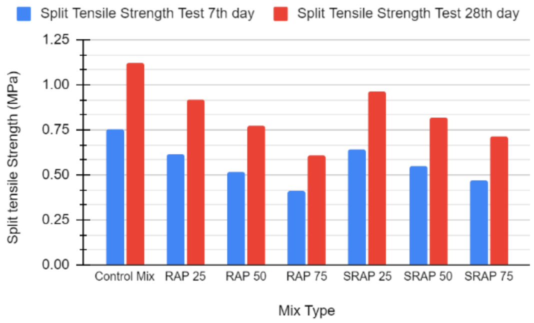

Figure 6. Split tensile Strength of DLC on the 7th and 28th day of curing.

5.3 Carbonation

Concrete is naturally alkaline. Steel bars are inserted in rigid pavements. When the pH falls below 9, CO_2 from the atmosphere seeps into the concrete. Steel may corrode, and the rebar's strength could be compromised. It also has an impact on the overall strength of the pavement. The solution of the phenolphthalein indicator turns pink when it comes in contact with an alkaline concrete surface with a pH value less than 9; then, that concrete is said to be non-carbonized. Figure 7 shows a carbonated and uncarbonated specimen of a freshly split concrete cylinder sprayed with the indicator (phenolphthalein) to check the depth of carbonation in the concrete specimen.

Figure 7. Carbonation depth comparison

Table 5. Carbonation test results.

Specimen Description	100% NAC Carbonation depth (mm)	50% CRAP Carbonation depth (mm)
Specimen age: 28 days	0	0
Specimen age: 56 days	7	8
Specimen age: 75 days	21	25
Approximately 1-year-old specimen	30	-

By spraying phenolphthalein on freshly split cylinders, it was observed that no carbonation occurred in any of the specimens at the expected age of 28 days. As carbonation is a time-consuming process, it occurs as atmospheric carbon dioxide penetrates into the specimens after it has been exposed to open air for a long period. After 45 days of healing, the samples were split in half and sprayed with an indicator. It was observed that carbonation depth was 21mm and 25mm in samples cast with 100% NCA and 50% CRAP, respectively. A concrete cylinder cast with NCA from the laboratory, which was about one year old, was also tested. It was found to be carbonated to a depth of 30mm. In lean concrete, CSH gel reacts with carbon dioxide and forms lime precipitates, which are smaller in size, so more pores will be there in the system. So, RAP DLC will perform better in compression than NCA DLC.

5.4 Alkalinity

The pH of concrete signifies its deterioration level, and for concrete used in rigid pavement, it should not be less than 9.0 and for durable concrete, it should lie between 12.0 to 13.0. Concrete with a pH greater than 9.0 can withstand salting in winter and other variable climatic conditions. The pH of the powdered concrete mixture passing through a 300-micron IS sieve was measured using a pH meter. The pH of concrete was also determined for various combinations mentioned in Table 2. Figure 9 represents the pH value of various concrete mixes. With the incorporation of CRAP, pH decreased up to 4.72% as compared to the control mix. A slight decrease in pH is noted for all mixes.

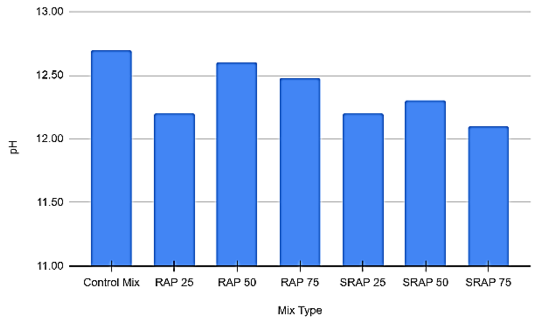

Figure 8. Variation of pH in different concrete mixes.

5.5 Resistance to sulphate and acid attack

In addition to strength factors, a structure's lifetime, regardless of its matrix, is determined by its durability qualities, such as how it responds to an aggressive environment. Sulphate, which can be found in soil and groundwater, is one of the chemical components responsible for aggressive environments. The sulphates in solution form can enter through the pores of the concrete and can react with hydration products. The resistance of concrete specimens against sulphate attack was analyzed. The cubical specimens of 150*150*150mm^3 size were immersed in a 5% sodium sulphate solution which is a rich source of sulphate ions, and H_2SO_4 is a source in which sulphate ions are in an acidic environment. The cubes were immersed for 90 days (inclusive of 28 days of submerged curing). Before immersing in the sodium sulphate and H_2SO_4 solution, the mass of the specimens was noted. The effect of these solutions on cubes was evaluated in terms of change in mass and loss in compressive strength in comparison to specimens cured in water.

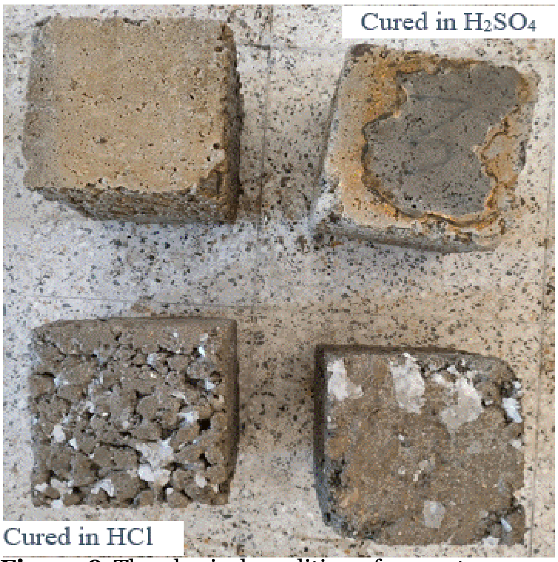

Figure 9. The physical condition of concrete specimens after the attack of H_2SO_4 and HCl.

The acid resistance of the concrete sample was investigated as per ASTMC 237 (2012). The Cubical specimens of 150*150*150mm³ mm size were immersed in an HCl solution of pH 1. The cubes were immersed for 90 days. Observations were made similar to the attack of Na_2SO_4 and H_2SO_4.

After being cured in Na_2SO_4 and H_2SO_4, concrete specimens were expected to lose weight slightly; Figure 10 shows the weight loss of several concrete samples after being exposed to a 5% Na_2SO_4 and H_2SO_4 Solution. In CRAP-incorporated concrete specimens, the loss in mass of concrete was very little compared to the control specimen when exposed to a concentrated 5% Na_2SO_4 solution. For the largest percentage of CRAP-added specimens, after 90 days of curing in Na_2SO_4, the maximum loss in the material was 0.7% of the original weight. As a result, it was observed that the weight loss of concrete was comparable when CRAP was used. Figure 10 depicts weight loss after exposure to Na_2SO_4 solution.

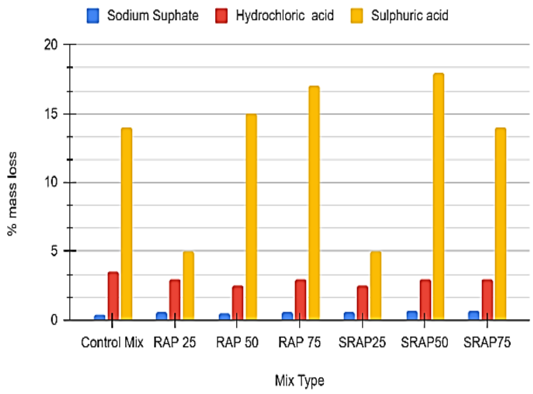

Figure 10. Percentage mass loss in mixes after 90 days of sulphate and acid attack

Concrete specimens that have been cured in H_2SO_4 show drastic weight loss; Table 6 shows the weight loss of various concrete samples after being exposed to a pH 1 H_2SO_4 solution. Also, from Figure 9 texture of deteriorated concrete specimens are clearly visible. The concrete weight loss, when exposed to concentrated H_2SO_4 solution, was found to be 18% for mix with 50% RAP incorporated specimens. After 90 days of H_2SO_4 curing, it was noticed that the weight loss of concrete increases with the addition of CRAP. This could be due to the formation of permeable voids, which increases water absorption. Figure 10 depicts weight loss after being exposed to a pH 1 H_2SO_4 solution.

After being cured in HCl, concrete specimens lose a significant amount of weight; Table 6 shows the weight loss of concrete samples after being exposed to a pH 1 HCl solution. The greatest material loss after 90 days of HCl curing was 3% of the original weight for the large percentage of CRAP-added specimens. As a result, it was observed that the weight loss of concrete was comparable when CRAP was used. Figure 10 illustrates weight loss after being exposed to a pH 1 HCl solution.

5.5.1 Compressive Strength Reduction in concrete cubes exposed to Sulphate Attack and acidic attack

A reduction in compressive strength was noted when concrete specimens were being cured in Na_2SO_4, H_2SO_4 and HCl, which is presented in Figure 11. Samples were tested in CTM after 90 days of curing in the above-mentioned solutions as per IS 516 2004. There was not a significant reduction in compressive Strength for CRAP-added specimens when cured in Na_2SO_4. The percentage fall in strength for 25, 50, and 75% CRAP added specimens was found to be 2%, 5%, and 13% respectively when compared to those with 100% NCA concrete.

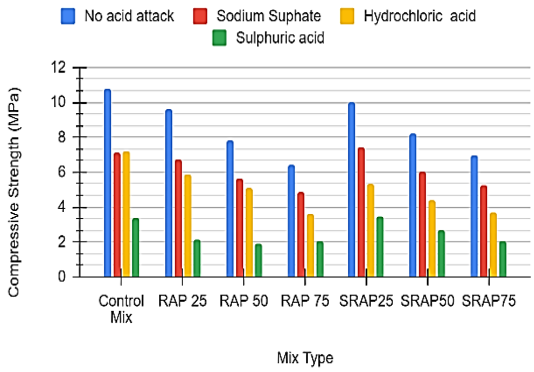

Figure 11. Compressive strength of cubes subjected to acid and sulphate attack

Further, when specimens were tested after curing under an H_2SO_4 solution of pH 1, there was a drastic fall in the compressive strength of CRAP-added specimens. The percentage fall in strength for 25, 50, and 75% CRAP added specimens was found to be 78, 76%, and 69%, respectively, when compared to control specimens. The reason for the reduction in compressive strength beyond 25% CRAP incorporation might be the formation of permeable voids in concrete due to differences in gradation which allowed more sulphate ions to penetrate inside and lead to a loss in the mass of specimens.

Table 6. Loss of compressive Strength in various concrete mixes.

Mix Type	% loss of mass in concrete			Loss in compressive strength			
	NS*	HCl	H_2SO_4	Control Mix	NS*	HCl	H_2SO_4
Control Mix	0.4	3.5	14.0	10.8	10.6	7.2	3.4
RAP 25	0.6	3.0	5.0	9.6	9.4	5.9	2.2
RAP 50	0.5	2.5	15.0	7.8	7.4	5.1	1.9
RAP 75	0.6	3.0	17.0	6.4	5.6	3.6	2.0
SRAP25	0.6	2.5	5.0	10.0	10.0	5.3	3.4
SRAP50	0.7	3.0	18.0	8.2	8.2	4.4	2.7
SRAP75	0.7	3.0	14.0	7.0	6.8	3.7	2.0

Units for compressive strength are kN/m^2
*NS stands for Na_2SO_4

For specimens cured in an HCl solution of pH 1. There was a reduction in compressive Strength of CRAP-added specimens with replacement greater than 25%. The percentage fall in strength was found to be 39%, 35%, and 44% for specimens incorporated with 25%, 50%, and 75% CRAP, respectively, when compared to those with 100% NCA concrete. Also, the incorporation of fly ash did not impact acid attack resistance significantly.

6. COST ESTIMATE

In addition to the environmental benefits of using recycled aggregates, it is also important to quantify cost benefits. In conclusion, Table 7 (placed at the end) depicts the cost distribution of various concrete mix components per cubic meter. The rates are taken from the Government of India's Central Public Works Department (CPWD schedule of rates 2016). It should be noted that the material cost and processing of CRAP and fly ash should be included (which is an additional cost, taken as 2% of the overall cost in the current study), but transportation or labour costs are not included. The cost of optimal mixes is considered based on their strength performance, i.e., SRAP 25. It is observed that SRAP 25 provided a reduction of 16% in comparison to the control mix. This cost-saving of 16%, when calculated over a large pavement length, may be substantially large.

7. CONCLUSION

In this study, CRAP was utilized as a partial replacement for NCA, along with a slight incorporation of fly ash. RAP was collected from a stockpile near NH 20-A. The collected RAP was washed and dried to make it free from dirt to ensure proper binding with the cement paste. The basic tests were performed for cement, NFA, NCA and CRAP to determine their feasibility, and the results were compared with the guidelines of Indian Standard Codes. OMC was determined, and the corresponding maximum dry density was calculated. Based on tests carried out on specimens cast with OMC, the following conclusions were arrived at:

- With the incorporation of CRAP, workability increased; this implies that concrete containing CRAP will not set rapidly hence increasing travel time for concrete to reach the site.
- With the incorporation of CRAP, density tends to decrease due to the lower specific gravity of CRAP. A decrease in the density of concrete decreases the compressive and tensile strength of concrete.
- With the increase in the CRAP content, the mechanical properties, viz. compressive and split tensile strength, tend to decrease gradually; 75% replacement of NCA by CRAP shows a maximum reduction in strength as compared to lower percentages of CRAP addition. In the present study, when 25% CRAP has used, the reduction in the mechanical property, i.e., compressive strength, was found to be less than 11% after 28 days of curing. However, if fly ash is utilized as a partial replacement for cement, the compressive strength after 28 days achieves the benchmark strength for the construction of DLC as per IRC SP 49:2014.
- With the incorporation of CRAP, loss in the weight of concrete and compressive strength

also tends to decrease significantly. Similarly, the alkalinity of concrete also increased, which signifies concrete can withstand salting in winter and other variable climatic conditions better.

- From the present study, it can be concluded that 25% of CRAP replacement with 10% usage of fly ash as a partial replacement of cement can be used for the construction of DLC in rigid pavement without affecting the mechanical and durability properties of hardened concrete greatly.
- Cost analysis shows that there is a reduction in cost of about 16% with a minor reduction in strength and durability parameters for optimal mix. Hence, additional cement or SCM may be used as performance improvers, so that overall strength and durability requirements may be achieved without affecting overall economy significantly.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this article.

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