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Utilization of industrial and agricultural wastes for productions of sustainable roller compacted concrete pavement mixes containing reclaimed asphalt pavement aggregates

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ABSTRACT

Asphalt pavement recycling has become a common practice across the globe and has been successfully employed in construction of new pavements. While several studies considered utilization of reclaimed asphalt pavement (RAP) aggregates for flexible and rigid pavements, very few attempted its possibility for roller compacted concrete pavements (RCCP). Additionally, studies on the possibility of enhancing the proportion of RAP for RCCP are very scanty. The present study is an attempt to increase the potential of RCCP mixes containing 50% RAP (dust contaminated & stiffened asphalt coated: 50RAP via including various industrial and agricultural wastes such as Silica Fume, Fly ash, and Sugarcane ash as partial replacement of conventional cement. It was observed that the inclusion of the stated admixtures had an insignificant effect on the density of the fresh RCCP mixes, however, increased the moisture demand considerably. In fact, the results firmly indicated the potential of silica fume for RAP-RCCP blends, as, it not only enhanced the physical and mechanical properties, but found to improve the durability of RCCP mixes considerably. Also, utilization of silica fume was found to be economical & environmentally friendly amongst all wastes: with reduced initial construction cost & CO_2 emissions by up to 8.4% & 9.7%. As far as the other industrial wastes are concerned, 15% fly ash could also be utilized for producing sustainable RCCP mixes, whereas, higher dosage of fly ash (30%) and sugarcane ash (10 & 15%) may be employed as base layer material of conventional concrete pavements.

1. Introduction

Extracted asphalt pavement materials commonly known as Reclaimed Asphalt Pavement (RAP), is being widely utilized for various pavement application and now becoming a global trend (Su et al., 2009; Aurangzeb et al., 2013; Shi et al., 2018b, a,b,c,d; Mukhopadhyay and Shi, 2019) but in developing countries like India, its effective utilization is meager owing to hesitation amongst the highway engineers due to the unavailability of proper codal provisions (Kumari et al., 2018). In India, a huge amount of RAP is generated annually, which usually makes its way to legal/illegal landfills and as a result, increases the burden on landfill authorities and also, contributes further addition to greenhouse gases (Singh et al., 2018a,f; Debbarma et al., 2019). On the other hand, In India alone, approximately ~825 kg of CO_2 is released per tonne of cement produced (MoEF, 2010) and this constitutes around 5–7% of the global CO_2 emissions (Hasanbeigi et al., 2012; Turner and Collins, 2013; Yang et al., 2015; Maddalena et al., 2018). If both the afore-stated could be prevented, it will definitely contribute towards achieving the concept of sustainability in the highway sector.

Owing to the superiority of concrete pavements over asphalt pavements, the Ministry of Roads, Transport & Highways, Govt. of India aimed to shape concrete pavements towards the desired mode of transportation across the nation (Singh et al., 2017a,c). However, the initial construction costs of concrete pavements are very high as compared to asphalt pavements (Modarres and Hosseini, 2014) and this does not seem to meet the economic viable of sustainability. Taking this into account, implementation of Roller Compacted Concrete Pavements (RCCP) in Indian roads sounds quite viable since RCCP is not only fast to construct, easy to lay and pave, less requirement of heavy machineries (Palmer, 1987; ACI, 2001; Harrington et al., 2010; Courard et al., 2010; Settari et al., 2015; Fakhri et al., 2017; Fakhri and Amoosoltani, 2017; Debbarma et al., 2019a,b) but also its initial construction costs

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are ~10–20% lower than conventional concrete pavements i.e. Portland Cement Concrete (PCC) pavements (Modarres and Hosseini, 2014). Not only that, if properly designed, RCCP mixes can exhibit strength parameters nearly/equivalent to PCC mixes. Further, including RAP in RCCP mixes would not only meet the economic viability of sustainability, but would also provide several environmental benefits such as a reduction in conventionally used non-renewable aggregates and reduction in greenhouse gases.

In the last few decades, increase in virgin aggregate consumption encourages the usage of RAP for construction of new pavements (Monu et al., 2019; Shi et al., 2018a; Singh et al., 2019b; Shi et al., 2019c). RAP has been extensively used for base and sub-base layers application (Taha et al., 1999, 2002; Arulrajah et al., 2013; Brand and Roesler, 2015b; Avirneni et al., 2016), whereas, a limited studies are available for its usage as wearing course material of concrete pavements (Delwar et al., 1997; Huang et al., 2005, 2006; Hossiney et al., 2010; Singh et al., 2017a, b,c; Shi et al., 2017; Mukhopadhyay and Shi, 2017; Shi et al., 2018a,b; Shi et al., 2019a: Singh et al., 2018a,b,c,d,e,f). RAP is the reusable material obtained from milling or demolition of an existing asphalt road and this precious material holds potential for re-utilization in asphalt and concrete roads (Taha et al., 2004; Robinson et al., 2004; Brand and Roesler, 2015a; Shi et al., 2017; Singh et al., 2017; Shi et al., 2018a; Singh et al., 2019a). RAP is welcomed as an addition in asphalt pavements owing to reduction in virgin binder content, however, its utilization in concrete pavements is still of meager (Shi et al., 2018b). This is due to the fact that in developing countries like India, the milling of existing asphalt roads are usually carried out employing uncontrolled milling technique (generally using a backhoe or a bulldozer). In such cases, dust from the underlying layers of pavements intermix with the RAP particles as well as additional dust layer accumulates in the RAP owing to stockpiling in the open for several months and thus adding another contaminant i.e. dust along with the layer of asphalt present in the RAP (Singh et al., 2018b; Debbarma et al., 2019a). These factors contribute to the lower potential of RAP for its effective utilization in concrete pavements owing to inferior strength outputs. Incorporations of coarser fraction of RAP in concrete mixes were found to be promising up to a proportion of 50% only (Settari et al., 2015; Fakhri and Amoosoltani, 2017), whereas, utilization of fine RAP is restricted owing to gap-graded nature of the same (Singh et al., 2017b,d,e). Poor interfacial transition zone (ITZ) between the RAP aggregate and cement mortar is generally held responsible for reducing the concrete strength properties (Brand and Roesler, 2017a,b; Singh et al., 2019b).

Supplementary Cementitious Mineral Admixtures (SCMs) such as Silica Fume (SF), Fly Ash (FA), and Sugarcane Ash (SA) have been reported to be used extensively in concrete pavements as partial replacement of Portland cement (Khan and Siddique, 2011; Cetin et al., 2010; Cordeiro et al., 2009). These materials act as artificial pozzolana which has cementitious properties and contributes in reducing the quantity of Portland cement which is an expensive material. Utilization of industrial by-product coming from Silicon Industry commonly known as Micro Silica or Silica Fume could improve the mechanical and durability properties of conventional concrete mixes significantly (Siddique, 2011). The huge concentration of Silicon Dioxide (SiO_2) (> 80%) and higher specific surface area of SF particles densifies the concrete microstructure, Interfacial Transition Zone (ITZ), formations of extra Calicum Silicate Hydrate (CSH) gels (Khan and Siddique, 2011; Siddique and Chahal, 2011; Harbec et al., 2017; Singh et al., 2017b) and also increases the resistance to abrasion (Cai et al., 2016; Singh et al., 2017b).

FA is the waste by-product coming from coal-based thermal power plants (Alkan et al., 1995; Baykal et al., 2004; Haibin and Zhenling, 2010; Kourti and Cheeseman, 2010) and has been extensively used to replace Portland cement in PCC mixes (Baykal and Döven, 2000; Cetin et al., 2010). FA has a relatively lower concentration of SiO_2 and Aluminum Oxide (Al_2O_3) than SF particles which helps in producing extra CSH gels (Singh et al., 2017b). The use of FA in concrete mixes has been limited to 30% (Zeng et al., 2012), whereas, in RAP inclusive concrete mixes, its utilization is restricted to 20% only (Singh et al., 2017b). Whereas, higher doses of FA often leads to the formation of ettringite (owing to the filler effect of FA particles) and is usually considered harmful for concrete structures (Singh et al., 2018d).

Similar to RAP materials, agricultural waste coming from sugarcane industry commonly known as SA also finds its way to open dumps resulting in disposal issues, air, water, land, and ground pollution (Moisés et al., 2013; Bajwa et al., 2016). India ranks second in the production of sugarcane across the globe, and thereby, leading to an enormous amount of SA waste being produced annually (Pongpat et al., 2017; Pryor et al., 2017). SA if burnt in boilers at temperatures varying 600–800 °C can produce a high amount of SiO_2 and can be used as artificial pozzolana for replacement of Portland cement (Cordeiro et al., 2009; Loh et al., 2013). The maximum pozzolanic activity of SA is usually achieved on using the particles passing 45 μm Indian Standard (IS) sieve size (Bahurudeen and Santhanam, 2015). Literature reported improvement in strength properties of PCC mixes up to 10% replacement of Portland Cement by SA particles (Singh et al., 2000; Bahurudeen et al., 2015). In the case of RAP inclusive PCC mixes, it has been observed to be beneficial up to 5% only beyond which resulted in a detrimental effect on PCC properties owing to the hygroscopic nature of SA particles (Singh et al., 2017b).

Taking in cognizance of the above, utilization of contaminated RAP aggregates along with other industrial and agricultural wastes seems to fulfill the concept of sustainability providing with the following benefits:

a) Conservation of natural resources i.e. aggregates, cement, and bitumen. (Singh et al., 2017c; Shi et al., 2018a)
b) Transportation cost of virgin aggregates from quarrying sites to batching sites would be negligible due to on spot availability of RAP aggregates. (Singh et al., 2017c; Monu et al., 2019)
c) Elimination of landfill/disposal problems of RAP and Sugarcane ash. (Singh et al., 2018a)
d) Requiring minimal production and transportation efficiencies, making silica fume environmentally conscientious (Khan and Siddique, 2011)
e) Improving the durability of concrete roads (Siddique, 2011)
f) Net reduction in energy use and greenhouse gases emissions (Shi et al., 2018a)
g) Improving road aesthetics (Singh, 2018)

1.1. Research significance

Many studies are available on the use of RAP for sustainable concrete pavements, however, in these studies, the considered RAP was either laboratory fabricated (Huang et al., 2005)/washed RAP (Brand, 2015)/laboratory processed RAP (effective sieving or processing such as Abrasion&Attrition (AB&AT) (Singh et al., 2017a)) or result of controlled milling technique (i.e. unpolluted RAP). Very fewer studies are available wherein considered RAP was obtained via uncontrolled milling technique (contains a significant amount of dust) and directly used without any processing for cement concrete mixes. Whereas, no study (in authors knowledge) is available on the utilization of such RAP for RCCP pavements. Furthermore, no studies related to the enhancement of RAP-RCCP blends using commercially and locally available Supplementary Cementitious Mineral Admixtures (SCMs) such as Silica Fume, Fly Ash, and Sugarcane Ash has been carried out till date. Therefore, the present investigation is first of its kind, wherein an attempt has been made to enhance the properties of RCCP mixes containing 50% dust contaminated RAP aggregates with the help of above-mentioned SCMs based on a number of laboratory tests. It is expected that the findings from the current study will create awareness amongst the academicians and highway engineers in deciding the optimum dosage and suitability of the stated SCMs for the preparation of RAP-RCCP mixes in worst

Fig. 1. Materials used in the present study.

scenario available (unprocessed materials). It is also believed that the findings from the present study would help in solving the hesitancy of using RAP and SCMs for construction of RCC pavements and encourages the government agencies and policymakers towards the framework of a codal provision for effective utilization of SCM inclusive RAP-RCCP mixes, taking into account the economic and environmental benefits that could be attained by incorporating such wastes.

2. Materials and mix design

Portland cement 43 grade confirming to IS:8112 (BIS, 2013) was used throughout the current investigation. Sugarcane Ash (SA) and Fly Ash (FA) being waste materials are commonly dumped in open environment but these materials contains reactive silica and can be used to replace Portland cement up to some extent, owing to its secondary pozzolanic reaction. Whereas, Silica Fume (SF) owing to its higher reactive silica content (> 85%) has been reported to significantly improve the performance of concrete structures (Khan and Siddique, 2011). SA (Fig. 1) was obtained from Uttam Sugar Mill, situated in Roorkee City, Uttarakhand, India and was received in an unprocessed state. The received SA was dried in oven for 24 h and then sieved through a 75 μm sieve so as to increase its pozzolanic activity (Singh et al., 2017b). After that, the processed SA was used as part replacement of Portland cement in proportions of 10% & 15%. Similarly, SF and Class-F FA (Fig. 1) confirming to ASTM C1240 (ASTM, 2015) and C618 (ASTM, 2019) specifications were obtained locally and were utilized in proportions of 5% & 10% and 15% & 30%, respectively. ASTM C1240 (ASTM, 2015) and ASTM C618 (ASTM, 2019) recommends a minimum of 85% & 50% silicon dioxide content (SiO_2), moisture content not exceeding 3%, and loss of ignition not exceeding 6%. From Table 1, it can be noted that all the values are within the permissible limits as specified in ASTM C1240 (ASTM, 2015) and ASTM C618 (ASTM, 2019). The chemical composition of the considered SCMs determined by X-Ray Fluorescence (XRF) Spectrometry is tabulated in Table 1.

Table 1
Chemical composition of Portland cement, silica fume, fly ash and sugarcane ash.

Component	Amount (%)			
	Portland Cement	Silica Fume	Fly Ash	Sugarcane Ash
SiO_2	36.28	90.76	53.08	65.98
Al_2O_3	5.63	0.96	22.69	2.26
Fe_2O_3	2.51	2.53	5.11	1.49
MgO	2.25	3.13	0.73	2.18
CaO	49.84	0.63	0.96	2.65
Na_2O	0.83	1.05	0.76	0.80
K_2O	0.62	3.14	1.35	1.79
MnO	0.03	0.06	0.04	0.04
TiO_2	0.34	0.11	1.49	0.20
P_2O_5	0.28	0.15	0.32	0.73
LOI (%)	1.24	2.3	3.86	4.67
Moisture (%)	0.1	0.25	0.31	0.35
Specific Gravity	3.15	2.20	2.35	2.14
Fineness (cm^2/g)	3363	20,000	3287	2956

Virgin crushed sandstone with nominal maximum size aggregate of 19 mm and natural sand obtained from the river Ganges, Uttarakhand, India was used throughout the present investigation. RAP was collected from a nearby town (Manglaur, Uttarakhand, India) and fractionated using 4.75 mm sieve to separate coarser & finer particles. The stated RAP (Fig. 1) was procured via uncontrolled reclamation technique, due to which, dust contaminants from underlying layers intermixed with RAP aggregates, and thus adding on another barrier for potential utilization of RAP aggregates for RCCP mixes (Debbarma et al., 2019a), however, this contaminated dust turned the fine RAP to relatively well-graded in nature and hence indicating its effective utilization (Singh et al., 2018b; Debbarma et al., 2019a). The physical properties of natural and RAP aggregates are presented in Table 2, whereas, the grain size distribution of the considered virgin and RAP aggregates are presented in Fig. 2. In the previous part of the present study (Debbarma et al., 2019a), virgin aggregates were part replaced by RAP (in different fractions), based upon which, RAP replacement level of 50% (combination of 50% coarse RAP & 50% fine RAP: 50RAP) was recommended by the authors for the production of sustainable RCCP mixes (Debbarma et al., 2019a). Therefore, in the present investigation, the stated SCMs were incorporated in the optimum RAP mix, i.e. 50RAP mix, in an attempt to increase the suitability of RAP-RCCP blends based on a number of laboratory experiments. The mix proportions worked out in accordance with IRC: SP: 68–2005 (IRC, 2005) guidelines are tabulated in Table 3.

3. Testing program

The mix design of roller compacted concrete pavement (RCCP) is based on the water content corresponding to its highest compactness, and therefore, ASTM D1557 (ASTM, 2012a) method was followed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) values of the mixes considered. A minimum compressive and flexural strength of 27.6 MPa and 3.67 MPa is required if RCCP is to be used as the surface layer of pavements (ACI, 2001). IS:516 (BIS, 1959) standards was adopted to determine the compressive and flexural strength of the RCCP mixes at 7, 28 & 91 days of curing ages, whereas, IS:5816 (BIS, 1999) standards was adopted in determining the split tensile strength at 7 & 28 days of normal curing. Furthermore, the abrasion resistance is an important parameter that needs to be evaluated if a pavement layer is to function as surface layer and therefore ASTM C1747 (ASTM (American Society for Testing and Materials), 2013a) standards was adopted to determine the resistance to abrasion in terms of loss in mass at 28 & 91 days of normal curing ages.

The porosity is considered to be the most important physical property affecting almost all the durability properties of cement concrete mixes. Higher the concentration of voids more would be the porosity and higher would be the water absorption capacity of the concrete mixes which would eventually allow the ingress of acidic ions from nearby environments resulting in durability issues. In lieu of the above, the porosity and water absorption at 28 & 91 days of curing ages were determined in accordance with ASTM C642 (ASTM (American Society for Testing and Materials), 2011). Singh et al., 2018e found that the bitumen layer around the RAP melted under the application of heat

Table 2
Aggregate properties.

Properties	Natural coarse	Natural fine	RAP coarse	RAP fine	Testing Methods
Specific Gravity	2.63	2.59	2.41	2.35	IS: 2386-III (BIS, 1963a,b)
Water absorption (%)	0.65	0.60	0.70	2.03	IS: 2386-III (BIS, 1963a,b)
Density (kg/m^3)	1745.3	1744.2	1613.7	1663.1	IS: 2386-III (BIS, 1963a,b)
Voids (%)	17.9	8.7	8.5	10.5	IS: 2386-III (BIS, 1963a,b)
Impact Value	19.07	–	10.03	–	IS: 2386-IV (BIS, 1963a,b)
Agglomerated particles (%)	–	–	14.95	–	(Singh et al., 2018f)
Asphalt content (%)	–	–	1.9	4.5	ASTM D2172 ASTM (American Society for Testing and Materials), 2017

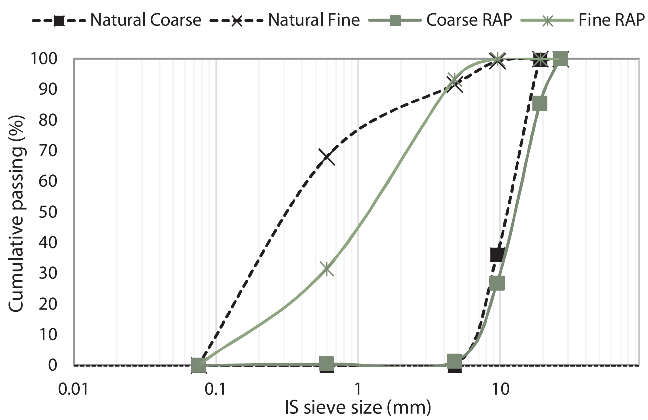

Fig. 2. Grain size distribution of aggregates.

during the oven drying period, resulting in imprecise results. Therefore, the stipulated testing conditions of 110 ± 5 °C and 2 h as per ASTM C642 (ASTM (American Society for Testing and Materials), 2011) was changed to 48 ± 2 °C and 8 days to minimize the melting of bitumen.

The performance of concrete structures lying in the vicinity of aggressive environments such as in chloride and sulphate-rich ions mostly depends upon the permeability of the pore systems. Structure with a higher concentration of capillary pores will allow easy ingress of aggressive ions and thus would have lower serviceability owing to which ASTM D1585 (ASTM American Society for Testing and Materials, 2013) procedure was followed to determine the initial and coefficient rate of water absorption by capillarity at 28 & 91 days of curing ages. The initial & coefficient rate of absorption were evaluated using Eqs. (1 & 2).

$$I = \frac{\Delta \mathrm{m}}{\mathrm{A\,x\,d}} \tag{1}$$

$$K = \frac{\mathrm{Q}}{\mathrm{A\,x}\,t^{0.5}} \tag{2}$$

Where, Δm is the change in mass, d is the density of water, K is the coefficient rate of water absorption, Q is the water absorbed in 24 h, A is the area of the exposed surface and t is the time.

Concrete durability is of equal importance to that of the strength properties which determines the degree of harshness of the environmental condition to which the concrete is exposed over its entire life. Most of the concrete structures situated in aggressive environments such as marine environments are considered to be vulnerable to deterioration since sea water contains high concentration of chlorides and sulphates. This harmful ions can penetrate deep into the concrete matrix, react with the insoluble calcium hydroxide ($Ca(OH)_2$), and cause leaching of the concrete resulting in further deterioration of the concrete. In the present study, the durability was assessed in terms of loss in mass after exposure to acid attack and conforms to ASTM C267 (ASTM (American Society for Testing and Materials), 2012b) guidelines. In order to simulate the actual field condition in the laboratory, RCCP specimens cured till 28 days were immersed in Hydrochloric Acid (HCl) and Sulphuric Acid (H_2SO_4) solution tanks with concentration level of 1.5% each. The specimens remained exposed to the acidic solution tanks for 63 days after which the loss in mass due to acid attack was calculated using Eq. (3).

$$\text{Mass Loss (\%)} = \frac{\mathrm{SSD_1} - \mathrm{SSD_2}}{\mathrm{SSD_1}} \mathrm{x}\,100 \tag{3}$$

Where, SSD_1 is the saturated surface dried weight of the hardened RCCP specimen at 28 days, and SSD_2 is the saturated surface dried weight of RCCP specimen after exposure to acidic solutions till 63 days.

4. Results and discussion

4.1. Influence of SCMs on OMC & MDD

Fig. 3 depicts the effect of stated Supplementary Cementitious Mineral Admixtures (SCMs) on the Optimum Moisture Content (OMC) & Maximum Dry Density (MDD) values of the roller compacted concrete pavement (RCCP) mix containing 50% coarse & fine RAP (50RAP). It was observed that the replacement of virgin aggregates by 50% of Reclaimed Asphalt Pavement (RAP) aggregates increased the OMC of the RCCP mixes by about 12%. This is in contradictory to the study conducted by Modarres and Hosseini (Modarres and Hosseini, 2014) reporting lesser water demand in RAP inclusive concrete mixes wherein

Table 3
Mix proportions of considered RCCP mixes.

Mix. ID	Cement	Natural Coarse	Natural Fine	RAP coarse	RAP fine	Silica Fume	Fly Ash	Sugarcane Ash	Water
Control	350	962.5	787.5	–	–	–	–	–	130
50RAP	350	481.3	393.8	481.3	393.8	–	–	–	145
5SF	332.5	481.3	393.8	481.3	393.8	17.5	–	–	172
10SF	315	481.3	393.8	481.3	393.8	35	–	–	185
15FA	297.5	481.3	393.8	481.3	393.8	–	52.5	–	159
30FA	245	481.3	393.8	481.3	393.8	–	105	–	164
10SA	315	481.3	393.8	481.3	393.8	–	–	35	193
15SA	297.5	481.3	393.8	481.3	393.8	–	–	52.5	206
15FA + 10SA	262.5	481.3	393.8	481.3	393.8	–	52.5	35	205
15FA + 15SA	245	481.3	393.8	481.3	393.8	–	52.5	52.5	205

Note: All calculations in kg/m^3.

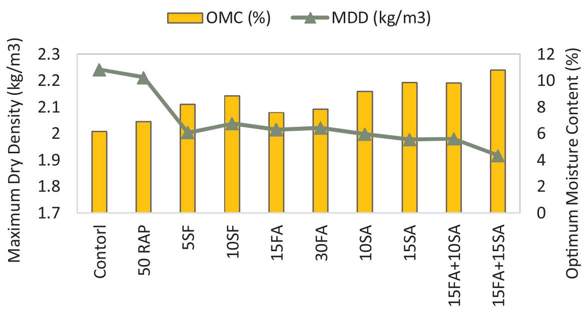

Fig. 3. Fresh properties of stated RCCP mixes.

lower water demand was observed for RAP inclusive concrete mixes than the conventional control mix. In the present study, the water absorption value of RAP aggregates was higher than the virgin aggregates and this was primarily owing to accumulation of dust contaminant layer around the RAP aggregates which in turn demanded more mixing water and subsequently, increased the optimum moisture content of the 50RAP mix considerably compared to the control mix (Debbarma et al., 2019a). The presence of agglomerated particles may also be held responsible to some extent for higher water demand (Singh et al., 2018f). This along with the presence of a significant amount of water soaking dust contaminants in the fine RAP may also attributed for higher water demand in the RCCP mixes. Inclusions of selected SCMs were further noted to increase the OMC in comparison to the optimum (50RAP) mix. For instances, the OMC increased by 19 & 28%, 10 & 14%, 33 & 43%, and ~57% when Portland cement was partly replaced by 5 & 10% Silica Fume (SF), 15 & 30% Fly Ash (FA), 10 & 15% Sugarcane Ash (SA), and combination of FA & SA particles, respectively. This increase in the water demand is due to the higher specific surface area of SF particles, whereas, the water soaking nature of SA particles may be held responsible in SA mixes (Singh et al., 2019b). On the other hand, the spherical structure of FA particles may be held responsible for lesser water demand as compared to the other considered SCMs (Singh et al., 2018d).

Despite significant increase in OMC values of the SCM inclusive 50RAP mixes, the percentage reduction in the MDD values was noted to be on a lower side. For instances, replacing Portland cement by SF, FA, SA & blended FA&SA, reduced the MDD value by about 8%, 9%, 11%, and 13% respectively. This reduction may be due to the lower specific gravities of SCMs than Portland cement. The lower specific surface area of the SCMs (except SF) may also be held responsible for reduction in the MDD values. This indicates that the inclusion of SCMs would have an insignificant effect on the fresh densities of the 50RAP mix even though the water demand is increased.

4.2. Influence of SCMs on compressive strength

Incorporation of 50% of RAP aggregates was noted to reduce the compressive strength of the RCCP mix by ~21% when cured till 28 days (Fig. 4a). The reason behind this reduction may be attributed to the asphalt film around the RAP which restricted the formation of a bond between the RAP and cement mortar (Singh et al., 2017b; Singh et al., 2018d; Singh et al., 2019b). Inclusions of the considered SCMs were noted to further reduce the compressive strength of the 50RAP mix and the same is being presented in Fig. 4. As can be seen in Fig. 4a, at 28 days, reduction of 6%, 15%, 12%, and 19% with respect to. the 50RAP mix was noted on part replacing PC by 15% FA, 30% FA, 10% SA, and 15% SA particles, respectively. This reduction in the compressive strength may be attributed to the fact that the Interfacial Transition Zone (ITZ) between the RAP aggregate and cement mortar did not improve due to the presence of asphalt film around the RAP, despite of inclusion of the stated SCMs (Huang et al., 2006; Singh et al., 2019b). But on the other hand, in agreement to the available literature (Brand and Roesler, 2017a,b; Singh et al., 2017b,d; Singh et al., 2019b), inclusions of SF particles as part replacement of PC was noted to enhance the compressive strength of the 50RAP mix (Fig. 4a). For instances, at 7 days, the improvement in compressive strength with respect to. 50RAP mix was noted to be 5% & 7% upon inclusions of 5% & 10% SF particles. Similarly, at later days of curing i.e. 28 and 91 days, the enhancement in compressive strength was noted to be 5% & 8% and 4% & 8%, respectively, for the same stated SF mixes. This enhancement in strength may be attributed to the higher specific surface area and higher amorphous silica content of the SF particles which may have resulted in a better cementitious matrix and improved the ITZ of the SF mixes (Singh et al., 2017b,d). Field Emission Scanning Electron Microscopic (Fe-SEM) images (Fig. 5) revealed a closely packed ITZ in the SF mixes as compared to the 50RAP mix, whereas, a relatively poor ITZ was noted in the 30FA mix. The X-Ray Diffractometer (XRD) pattern of SF mixes also revealed the formation of calcium silicate hydrates (CSH) gels as shown in Fig. 6. The highest Quartz (SiO_2) peaks, with intensity counts of about 1600 for the 50RAP mix containing 5% SF were observed at Bragg's angle (2θ) of 26.6°, whereas, in the case of FA and SA mixes, Ettringite (E) and Portlandite (P) were observed at about 2θ angle of 8.9° and 29.5°. This finding further provides evidence to the fact that silica fume particles may have produced additional CSH gel hydrates and resulted in a better compressive strength as compared to FA and SA mixes.

On the other hand, the combination of FA and SA mixes is not recommended since the percentage reduction in the compressive strength is considerably higher than those of the individual SCMs mixes. For instances, the combination of 15% FA and 10% SA was found to exhibit 43% lower compressive strength than the 50RAP mix, whereas, further increase in the SA proportion (15%) increased the reduction rate to 50%. This indicates the unsuitability of blended FA&SA for preparations of RAP-RCCP mixes, if strength improvement is required. But, 15% FA mix achieved the minimum compressive strength benchmark of 27.6 MPa (ACI, 2001) despite not being able to improve the compressive strength of the optimum RAP mix, i.e. 50RAP mix in the present study. On the other hand, SF mixes achieved the stipulated benchmark and enhanced the compressive strength of the 50RAP mix as well, however, its usage may not be recommended for projects wherein economy is a major concern. The results from the present study indicates that up to 10% silica fume and 15% of fly ash could be utilized when RCCP is to be used as a surface layer intending to serve heavy-duty low volume traffic.

4.3. Influence of SCMs on modulus of rupture

Fig. 4b illustrates the effect of SCMs on the modulus of rupture of the RCCP mixes containing 50% RAP aggregates. Like compressive strength results, the inclusion of SCMs was noted to reduce the modulus of rupture of the 50RAP mix considerably (except SF mixes). For instances, the reduction in the modulus of rupture was found to be around 8%, 9%, and 16% when Portland cement was partly replaced by 30% FA, 10% SA, and 15% SA particles, respectively. This reduction in strength upon inclusions of the stated particles may be accounted to the insufficient quantity of activated silica available to react with Portlandite (Singh et al., 2018d). Generally, enhancement in strength of concrete mixes is primarily due to the densification of the ITZ as a result of higher concentration of amorphous silica or higher specific surface area of stated SCMs, however, for RAP concrete mixes, this does not hold valid. The failure mode in RAP inclusive concrete mixes is always an asphalt-cohesion failure (Huang et al., 2005; Mukhopadhyay and Shi, 2019), and therefore, the stated SCMs could not improve the modulus of rupture of the 50RAP-RCCP mixes. Enhancement in the modulus of rupture was observed in the case of SF mixes only, although the percentage increase is very less. For instances, at 28 days, the enhancement in the modulus of rupture of 5SF & 10SF mix was noted to be ~1% & 5% with respect to. 50RAP mix. The same reason i.e. the higher

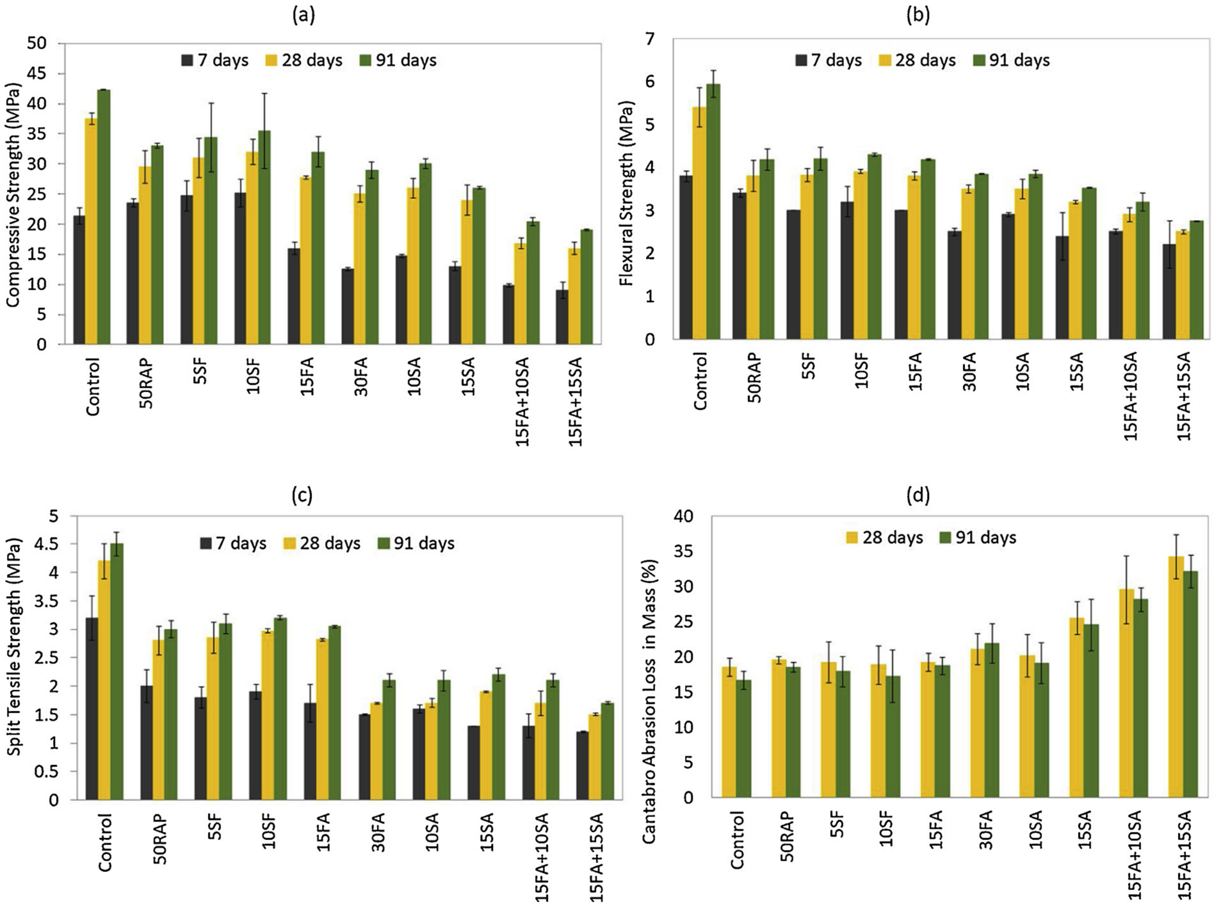

Fig. 4. (a) Compressive Strength, (b) Flexural Strength, (c) Split Tensile Strength, and (d) Cantabro Abrasion Loss.

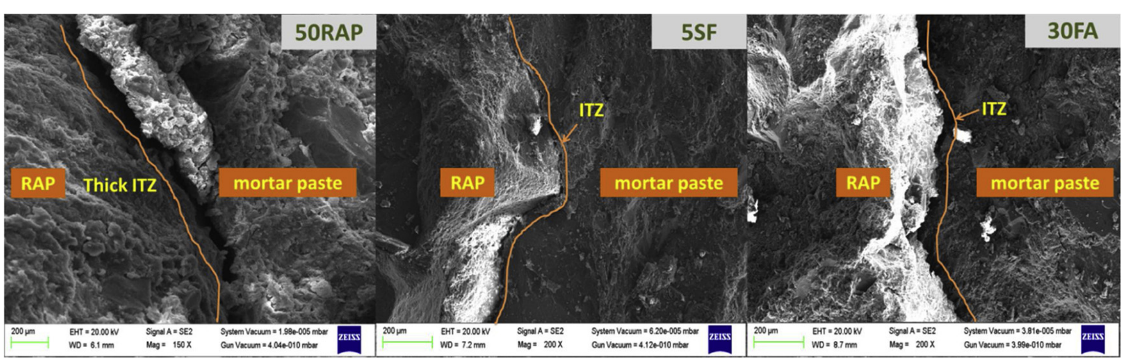

Fig. 5. Fe-SEM images showing ITZ of stated RAP-RCCP mixes.

concentration of amorphous silica and higher specific surface area of SF particles may be held responsible for the enhancement in the modulus of rupture of the SF mixes (Brand and Roesler, 2017a,b; Singh et al., 2017b,d). Comparing the considered SCMs, the highest reduction in the modulus of rupture was observed in the combined mixes i.e. FA&SA mixes, followed by individual SA and FA mixes, respectively (Fig. 7). For instances, the reduction with respect to 50RAP mix was found to be 34%, 16%, and 8% for the above stated mixes at 28 days of age. These finding indicates that fly ash and sugarcane ash particles are not beneficial for RAP-RCCP mixes, if the modulus of rupture improvement is desired. On the other hand, SF mixes achieved the minimum stipulated strength benchmark of 3.67 MPa as per ACI (ACI, 2001) guidelines and may be recommended for surface layers of RCC pavements. It may also be encouraged to utilize fly ash (up to 15%) for the preparation of RAP-RCCP mixes since it could meet the stipulated flexural strength benchmark. Contrarily, higher doses of fly ash (30%) and sugarcane ash may also be used in pavement systems serving higher traffic speeds, however, as a base course for conventional concrete pavements or as the lower lift in a two-lift paving operation.

4.4. *Influence of SCMs on splitting tensile strength*

Fig. 4c illustrates the influence of SCMs on the splitting tensile strength of the RCCP mixes containing 50% RAP aggregates. Similar to compressive and modulus of rupture results, poor ITZ owing to the presence of asphalt layer around the RAP aggregates is held responsible for strength reduction of ~34% in the mix containing 50% RAP. Furthermore, inclusions of stated SCMs (except SF particles) were found to be unfavorable in terms of strength enhancement requisition in the 50RAP mix. For instances, at 28 days of curing age, the splitting tensile

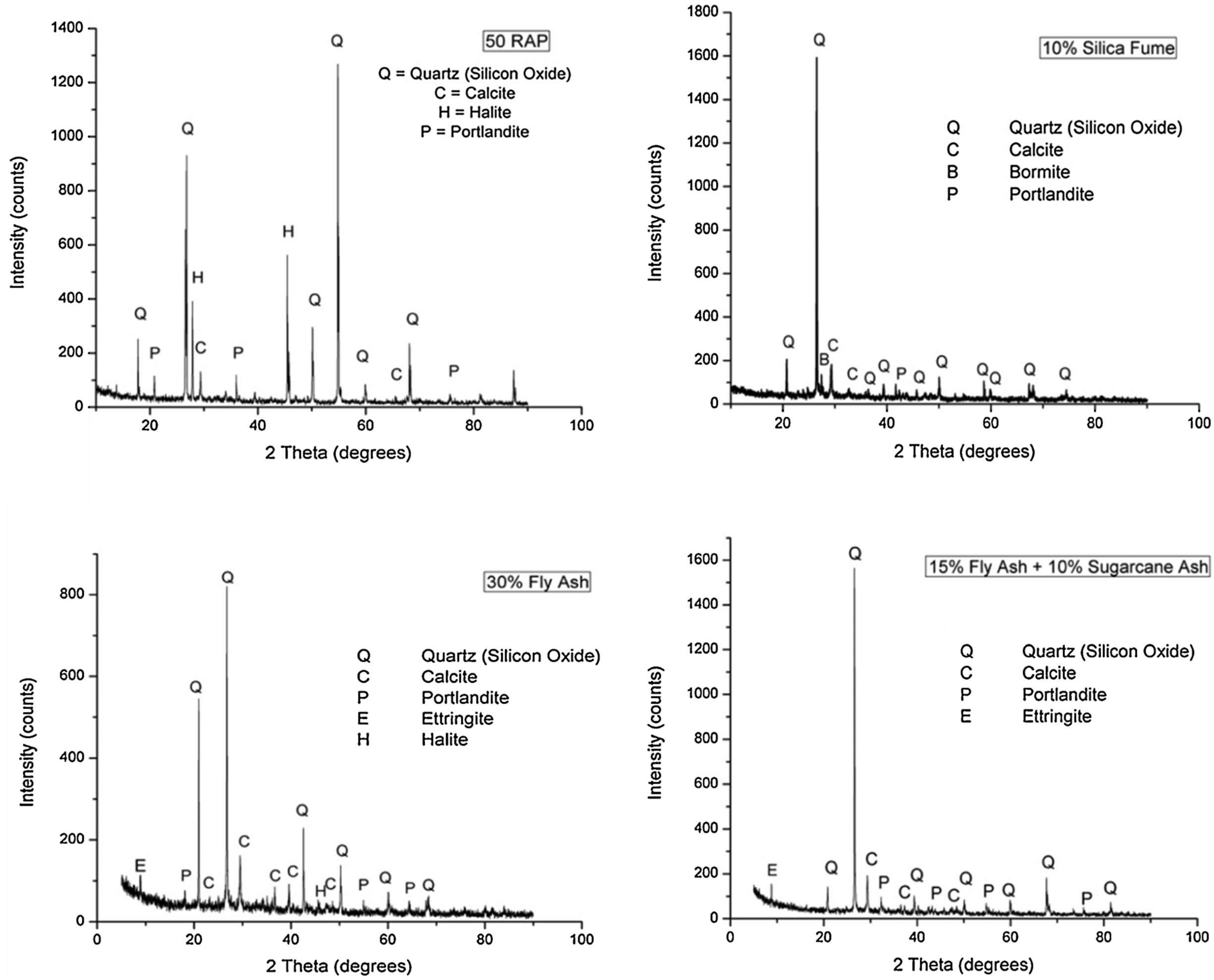

Fig. 6. XRD patterns of stated RAP-RCCP mixes.

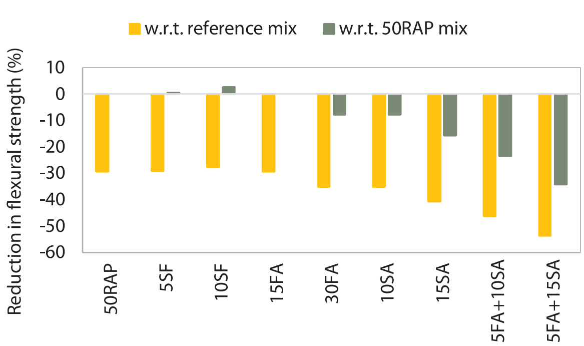

Fig. 7. Percentage reduction in the Modulus of Rupture.

strength of 30% FA, 10% SA, 15% SA, 15% FA + 10% SA, and 15% FA + 15% SA mixes were observed to be 38%, 39%, 32%, 39%, and 46% lower than the 50RAP mix. Whereas, 15% FA and SF mixes were noted to exhibit an enhancement of ~6% in the splitting tensile strength of the 50RAP mix. This again indicates the suitability of silica fume and 15% of fly ash particles as part replacement of Portland cement for production of RAP-RCCP mixes.

4.5. Influence of SCMs on cantabro abrasion resistance

Abrasion resistance is an important parameter to depict the suitability of a concrete pavement when it is to be used as a surface/wearing course (Abou Sleiman et al., 2019). As can be seen in Fig. 4d, it can be observed that least abrasion loss in mass was noted for the mix containing 100% virgin aggregates, with a loss in mass of 18.5% & 16.6% at 28 & 91 days, respectively. Part replacing 50% virgin aggregates by RAP increased the abrasion mass loss by about 5% & 11% at the same curing ages. As far as SCMs are concerned, it was observed that, only the SF mixes could enhance the abrasion resistance of the stated mix. For instances, at 28 & 91 days, inclusions of 5% SF and 10% SF lowered the abrasion mass loss by 2% & 3% and 4% & 7%, with respect to the 50RAP mix, respectively. This may be attributed to the fact that abrasion resistance depends on the compressive strength of the concrete mixes, and in the present case, SF particles showed increased compressive strength of the 50RAP mix. Interestingly, FA & SA mixes were also noted to provide adequate abrasion resistance since the associated difference in the abrasion mass loss is only ~8%, however, recommended to a limit up to 15% FA and 10% in the case of SA, since, higher doses of the stated particles may compensate with the strength related properties. These findings indicate the potential of silica fume as replacement of Portland cement when RCCP mixes containing 50% RAP aggregates is to be used as a surface/wearing course. However, from an economical point of view, silica fume may always not seem feasible and, in such cases, use of fly ash (15%) and sugarcane ash (10%) may be recommended but as base layers of RCC pavements.

4.6. Influence of SCMs on total permeable voids

Fig. 8a represents the effect of the stated SCMs on the concentration of total permeable voids in the RCCP mixes containing 50% RAP

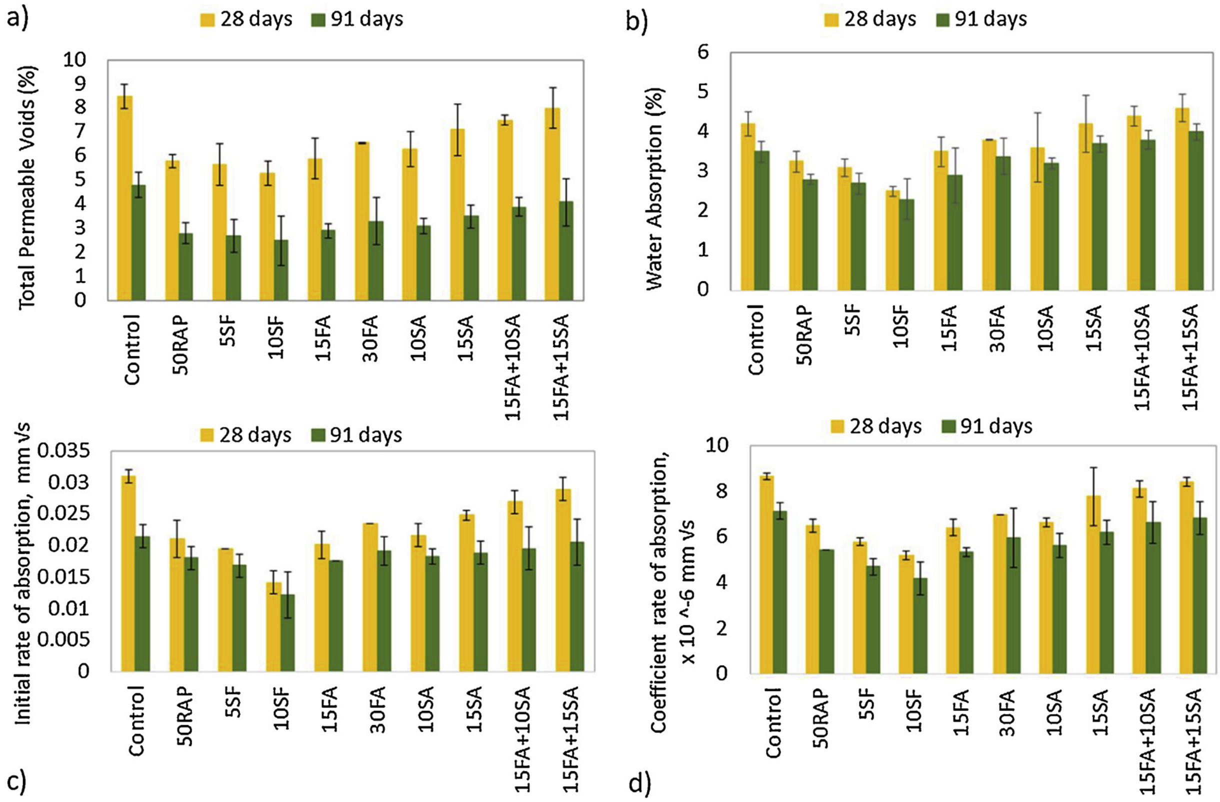

Fig. 8. (a) Porosity, (b) water absorption, (c) initial rate of absorption, and (d) coefficient rate of absorption.

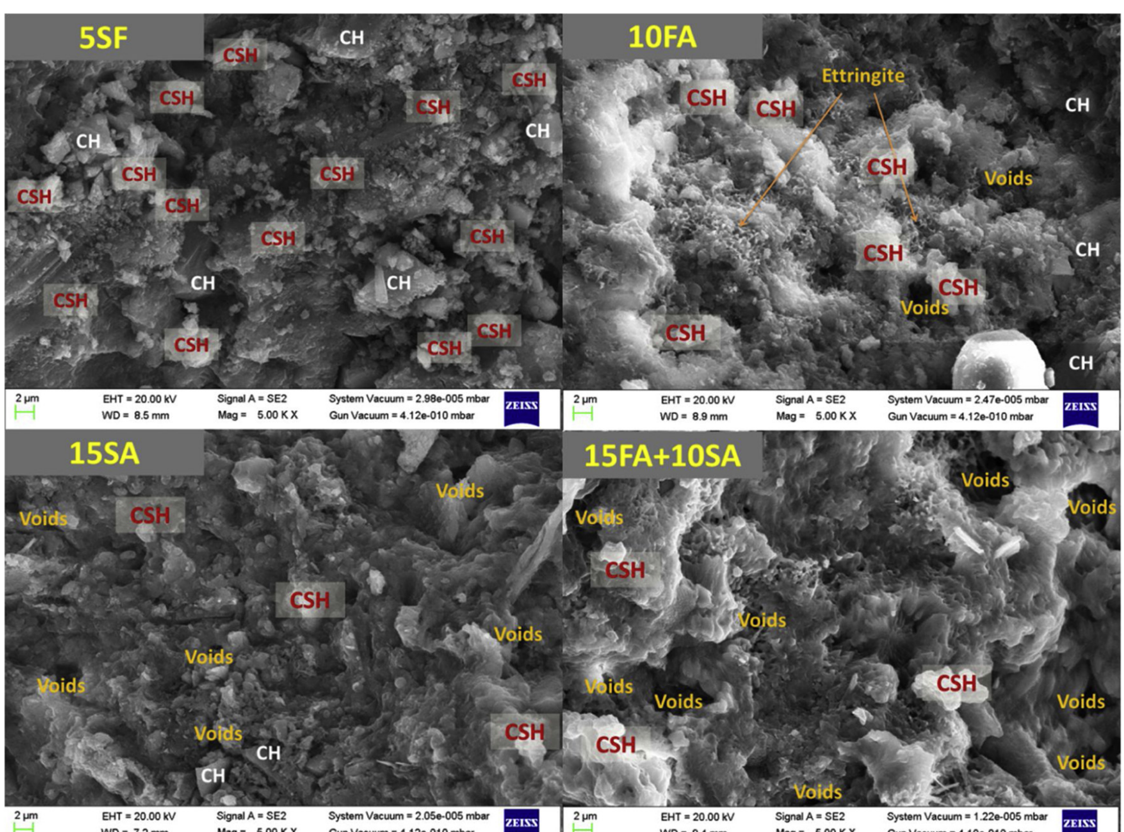

Fig. 9. Microstructure of stated RCCP mixes obtained using Fe-SEM.

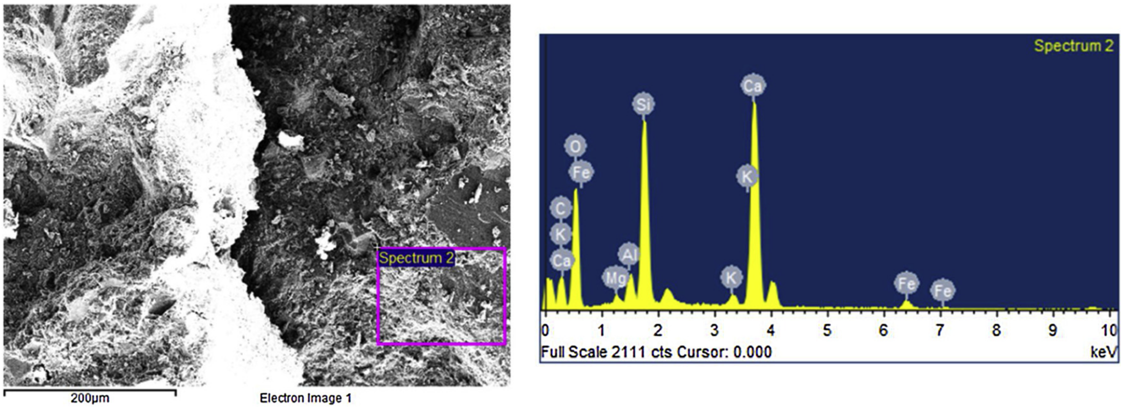

Fig. 10. EDX pattern of 50RAP mix containing 10% Fly Ash.

aggregates. It was observed that replacing 50% virgin aggregates by RAP decreased the total concentration of total permeable void drastically, irrespective of any curing days. For instances, at 28 and 91 days, the 50RAP mix had 32% and 42% lower permeable voids in comparison to the control mix. This decrease in the concentration of permeable voids is primarily due to the asphalt coating around the RAP which melted during the boiling period, thus, filling up the empty voids in the matrix (Debbarma et al., 2019a). Unexpectedly, the inclusion of SCMs (except SF mixes) was observed to increase the concentration of total permeable voids of the 50RAP mix significantly. For instances, at 28 and 91 days, FA and SA mixes showed ~13% & 18% and ~22% & 25% higher permeable voids with respect to. the 50RAP mix. This unusual behavior may be due to the flowability of asphalt at higher temperatures (Singh et al., 2018e). A huge quantity of well-crystallized Portlandite crystals and a less quantity of whisker-like Ettringite crystal (as revealed by Fe-SEM images) can be seen in the hydrates of FA mixes (Fig. 9) and this was positively identified by Energy Dispersive X-Ray (EDX) pattern (Fig. 10). Only the SF mixes were found to reduce the porosity values of the 50RAP mix at both ages. For instances, approximately 9% and 11% lower porosity were noted upon inclusions of SF particles, at 28 days and 91 days. Formation of extra CSH gel may be held responsible for filling up the empty spaces remained after hydration and subsequently leading to lower porosities (Singh et al., 2018a) in the case of SF mixes. EDX analysis shows that the granular hydrates were most likely CSH (Fig. 11).

4.7. Influence of SCMs on water absorption

The trend in the water absorption values are also in line with the results of permeable voids and are depicted in Fig. 8b. Filling of the empty spaces by the extra CSH gel should have lowered the total permeable voids and reduced the water absorption values of the 50RAP mix. But in the present case, inclusions of SCMs were found to increase the water absorption of the 50RAP mix. For instances, at 28 days, 15FA, 30FA, 10SA, and 15SA mixes had 8%, 17%, 11%, and 29% higher water absorption than the 50RAP mix. This increase in the SA mixes may be due to the hygroscopic nature of SA particles, whereas, higher permeable voids in the FA mixes may have led to increased water absorption capacities (Fig. 8a). Additionally, the increase in the water absorption of the stated mixes may also be due to the water-soaking dust contaminants in the fine RAP, and in the current study, the fine RAP had a high water absorption value than the natural fine. As expected, reduced porosity values in the SF mixes resulted in lower water absorption capacities in comparison to the 50RAP mix. On the other hand, a significant increase of about 45% in the water absorption values was observed for the blended FA&SA mixes at both curing ages.

4.8. Influence of SCMs on initial and coefficient of water absorption

Expectedly, the inclusion of 50% RAP aggregates lowered the initial rate of water absorption by capillarity irrespective of any curing ages and is being depicted in Fig. 8c & d. This reduction is again attributed to the flowing of asphalt during the boiling test (Singh et al., 2018e). In line with the available literature (Singh et al. 2017b), the inclusion of SF particles was noted to be profound in reducing the initial rate of absorption at any curing ages. The formation of extra CSH gel, filler effect of SF particles reduced the initial rate of water absorption by > 35%, irrespective of any curing ages. Whereas, part replacement of PC by SA (10% & 15%) particles increased the rate of water absorption by about 4% & 13% respectively with respect to the 50RAP mix. This may again be attributed to the water soaking nature of SA particles which tends to absorb more water and subsequently increase

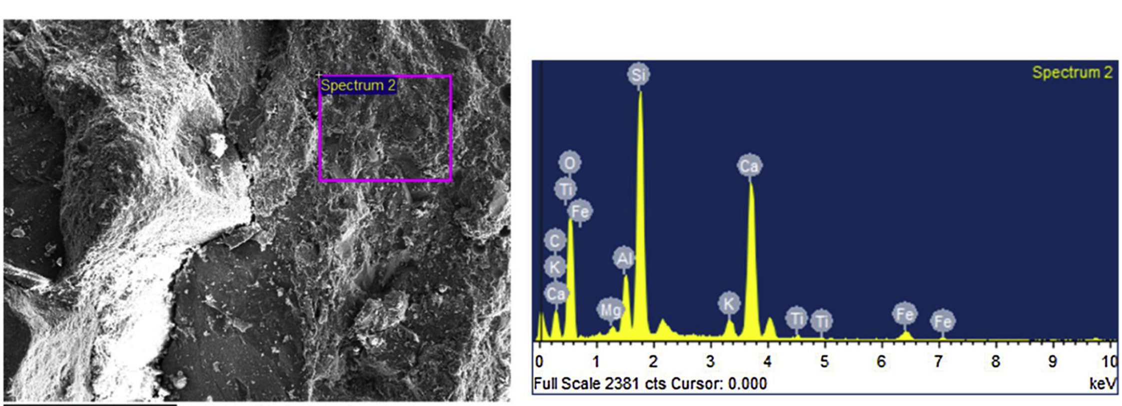

Fig. 11. EDX pattern of 50RAP mix containing 5% silica fume.

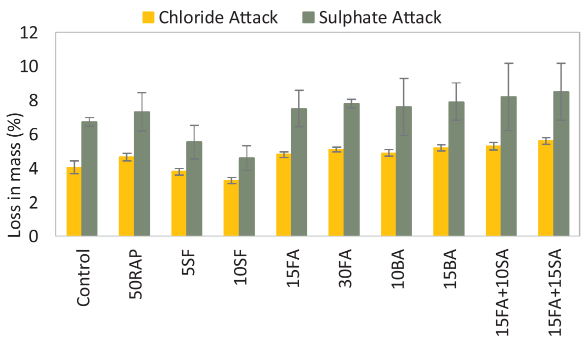

Fig. 12. Effect of SCMs after exposure to acid attack.

the initial rate of water absorption by capillarity (Singh et al., 2018e). Similarly, the coefficient of water absorption was also noted to be improved by ~24% in the SF mixes, whereas, an increase of about 25% was noted in the SA mixes. These findings indicate that inclusions of SF particles as part replacement of Portland cement would not only enhance the mechanical performance of RCCP mixes containing 50% RAP aggregates, but would also restrict the capillary suction of water from subbase/subgrade.

4.9. Influence of SCMs on mass loss due to acid attack

Fig. 12 depicts the mass loss of the stated of SCM inclusive RAP-RCCP mixes after exposure to acidic environments of chloride and sulphate ions. It was observed that the inclusions of stated SCMs (except SF mixes) increased the mass loss of the 50RAP mix substantially, in both the solutions. For instances, 15FA & 30FA mix when kept in chloride and sulphate solutions, the mass loss increased by about 3% & 10% and 2% & 5% respectively. Similarly, in the case of SA mixes, the increase was noted to be 5% & 12% and 2% & 8% in the same solutions. This increase may be attributed to the higher interconnectivity between the pores which led to easy transportation of these acidic ions deep within the matrix, reacted with calcium hydroxide to form calcium chloride and calcium sulphate salts resulting in leaching of the specimens (Singh et al., 2018c). A visual representation is also shown in Fig. 13. Also, the presence of water soaking dust contaminants in the RAP aggregates and the hygroscopic nature of SA particles may have allowed more easy ingress of these ions deep into the structure and subsequently causing further deterioration. Only the SF mixes were noted to restrict the ingress of these harmful ions into the matrix by ~30% in chloride solution and ~37% in sulphate solution with respect to. 50RAP mix. Formation of additional CSH gel owing to the reaction between the amorphous silica of SF particles and the unreacted portlandite may have filled the remaining empty pores, reduced the porosity, and hence subsequently, restricted the ingress of chloride and sulphate ions to some extent. This finding again indicates the potential of SF particles when RCCP is to be laid in the areas of aggressive ions of chlorides & sulphate ions. As far as the combination of FA and SA particles are concerned, its utilization is strictly not recommended due to its significant mass loss of about 5–9%, when kept in both the solutions.

4.10. Sustainability assessment

Table 4 illustrates the economic impact in terms of Construction Cost for the production of 1 m^3 of SCMs inclusive RCCP mixes containing 50% RAP aggregates. Only the initial construction-related costs have been considered in the present investigation. This includes the cost of materials, processing, labor, transportation, and machineries as imposed by the Central Public Works Department (CPWD, 2016), Govt. of India for the construction of 1 m^3 of RCCP. The cost incurred in RAP is being neglected due to the fact that RAP can be obtained on-site, however, its processing charges have been assumed as 1% (Singh et al., 2018d). The processing of sugarcane ash has been assumed to be 5% (Singh et al., 2018a). As expected, the inclusion of SCMs as part replacement of Portland cement was noted to significantly reduce the initial construction costs of RCC pavements in comparison to the control mix. For instances, FA mixes were found to provide the highest cost savings (~22%), followed by SA mixes (~14%) and SF mixes (~9%). RCCP is designed based on the 28 days' flexural strength and from the results of the present study, only 5 & 10% SF and 15% FA mixes achieved the stipulated flexural strength benchmark i.e. 3.67 MPa, and its corresponding cost savings noted to be 8.4%, 2.5%, and 18.1% respectively. This indicates that silica fume (up to 10%) and fly ash (15%) could be used as replacement of Portland cement for the construction of RAP-RCCP mixes intending to serve as a surface layer. As far as other SCMs are concerned, despite significant cost savings it could not be recommended for surface layers, however, 30% fly ash and SA mixes could still be suggested for pavement systems serving high traffic speeds but as a base layer material for conventional concrete pavements only.

Utilization of SCMs in concrete mixes would not only help in reducing the burden on landfills but could also help in reducing the CO_2 emissions (Singh et al., 2018a). Table 5 illustrates the environmental

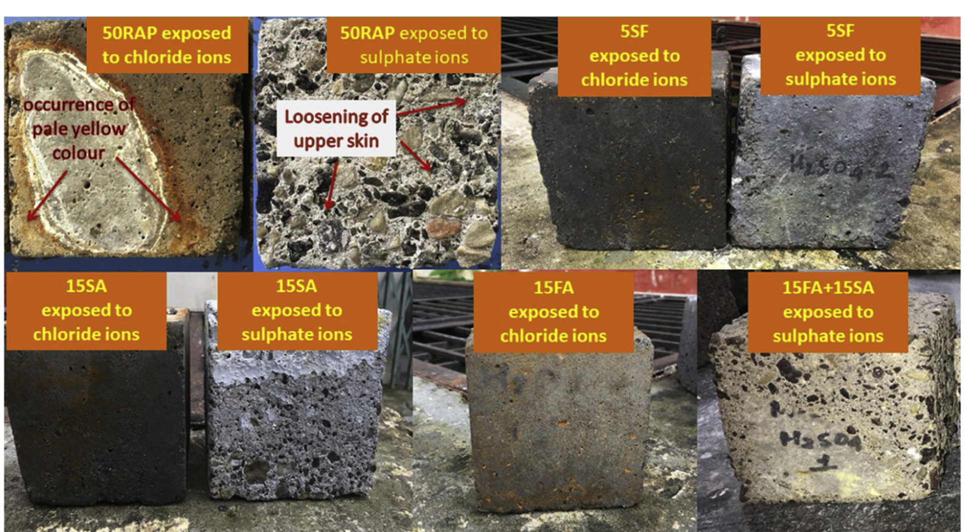

Fig. 13. Test specimens after being exposed to chloride & sulphate ions.

Table 4
Economic analysis of the considered RCCP mixes.

Description	Unit	CPWD Rates ₹(INR)	Costs incurred ₹(INR)									
			Control	50RAP	5SF	10SF	15FA	30FA	10SA	15SA	15FA + 10SA	15FA + 15SA
Material												
Portland Cement	tonne	5700	1995	1995	1895.3	1795.5	1695.8	1396.5	1795.5	1695.8	1496.3	1396
Silica Fume	kg	32	–	–	560	1120	–	–	–	–	–	–
Fly Ash (free of cost from any thermal plant)					–	–	–	–	–	–	–	–
Sugarcane Ash	m^3	–	–	–	–	–	–	–	–	–	–	–
Natural Coarse Aggregate	m^3	1300	1251.3	625.7	625.7	625.7	625.7	625.7	625.7	625.7	625.7	625.7
Natural Fine Aggregate	m^3	1300	945	472.6	472.6	472.6	472.6	472.6	472.6	472.6	472.6	472.6
RAP coarse	m^3	–	–	–	–	–	–	–	–	–	–	–
RAP fine	m^3	–	–	–	–	–	–	–	–	–	–	–
Carriage of NCA	m^3	103.7	99.9	49.9	49.9	49.9	49.9	49.9	49.9	49.9	49.9	49.9
Carriage of NFA	m^3	103.7	81.7	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8	40.8
Carriage of Portland cement	tonne	92.2	32.3	32.3	30.7	29.1	27.4	22.6	29.1	27.4	24.2	22.3
Carriage, loading and unloading of Fly Ash	m^3	8	–	–	–	–	0.42	0.84	–	–	0.42	0.42
Labor (Mixing and laying)												
Skilled laborer	day	368	368	368	368	368	368	368	368	368	368	368
Wage laborer (water supplies)	day	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9
Mate	m^3	16.28	16.28	16.28	16.28	16.28	16.28	16.28	16.28	16.28	16.28	16.28
Labor (for compaction by vibrator)												
Mason	m^3	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7
Wage laborer	m^3	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7
Machinery												
Production cost of concrete by batch mix plant (per m^3)			400	400	400	400	400	400	400	400	400	400
Vibratory roller (8–10 tonne)	hour	2535	2535	2535	2535	2535	2535	2535	2535	2535	2535	2535
TOTAL			**7893.7**	**6703.9**	**7162.5**	**7621.2**	**6400.2**	**6096.6**	**6501.2**	**6399.8**	**6197.5**	**6096.2**
Add 1% water charges (m^3)			78.9	67.0	71.6	76.2	64.0	60.9	65.0	63.9	61.9	60.9
Add 1% processing (RAP) (m^3)			–	67.0	71.6	76.2	64.0	60.9	65.0	63.9	61.9	60.9
Add 5% processing (SA)(m^3)			–	–	–				65.0	63.9	61.9	60.9
TOTAL			**7971.6**	**6838.0**	**7305.8**	**7773.6**	**6528.2**	**6218.5**	**6696.2**	**6591.8**	**6383.4**	**6279.1**
Add 15% Contractor's profit and overheads			1195.7	1025.7	1095.8	1166.0	979.2	932.7	1004.4	988.7	957.5	941.8
Final Total Cost, ₹(INR)			**9167.4**	**7863.7**	**8401.7**	**8939.7**	**7507.5**	**7151.3**	**7700.7**	**7580.6**	**7341.0**	**7220.9**
Reduction in Total cost (%)				**−14.2**	**−8.4**	**−2.5**	**−18.1**	**−22.0**	**−12.7**	**−14.1**	**−16.8**	**−18.2**

Note: ₹(INR) = Indian Rupees; CPWD = Central Public Works Department, Govt. of India.

Table 5
Influence of RAP and SCMs on CO_2 emissions.

Materials	CO_2 kg/kg (MoEF, 2010)	CO_2 emissions (kg/m^3)									
		Control	50RAP	5SF	10SF	15FA	30FA	10SA	15SA	15FA + 10SA	15FA + 15SA
Cement	0.8250	288.8	288.8	274.3	259.9	245.4	202.1	259.9	245.4	216.6	202.1
Silica Fume	0.0140	–	–	1.6	3.3	–	–	–	–	–	–
Fly Ash	0.0190	–	–	–	–	1.00	2.00	–	–	1.00	1.00
Sugarcane Ash	0.0007	–	–	–	–	–	–	0.02	0.03	0.02	0.03
Natural Coarse	0.0075	7.22	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61
Natural Fine	0.0026	2.05	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
RAP coarse	–	–	–	–	–	–	–	–	–	–	–
RAP fine	–	–	–	–	–	–	–	–	–	–	–
Production of fresh concrete	0.0077	17.12	17.24	17.45	17.56	17.35	17.39	17.61	17.72	17.71	17.87
CO_2 emission in kg/m^3 (A)		315.1	310.6	298.0	285.3	268.4	226.1	282.1	267.8	239.9	225.7

Materials	CO_2 emissions during transportation kg/kg (MoEF 2010; Yang et al., 2015)	Distance (km)	CO_2 emissions during transportation (kg/m^3)									
			Control	50RAP	5SF	10SF	15FA	30FA	10SA	15SA	15FA + 10SA	15FA + 15SA
Cement	5.18×10^{-5}	12.7	0.230	0.230	0.219	0.207	0.196	0.161	0.207	0.196	0.173	0.161
Silica Fume	5.18×10^{-5}	82.9	–	–	0.075	0.150	–	–	–	–	–	
Fly Ash	5.18×10^{-5}	176	–	–	–	–	0.479	0.957	–	–	0.479	0.479
Sugarcane Ash	5.18×10^{-5}	3	–	–	–	–	–	–	0.005	0.008	0.005	0.008
Natural Coarse	6.3×10^{-5}	18.4	1.12	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Natural Fine	6.3×10^{-5}	18.4	0.91	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
RAP Coarse	5.18×10^{-5}	–	–	–	–	–	–	–	–	–	–	–
RAP Fine	5.18×10^{-5}	–	–	–	–	–	–	–	–	–	–	–
CO_2 emission (kg/m^3) (B)			2.26	1.24	1.31	1.37	1.69	2.13	1.23	1.22	1.67	1.66
Total CO_2 emission in (kg/m^3) (A + B)			317.4	311.9	299.3	286.7	270.1	228.3	283.4	269.0	241.6	227.3
Reduction in CO_2 emission (%)				**−1.7**	**−5.7**	**−9.7**	**−14.9**	**−28.1**	**−10.7**	**−15.2**	**−23.9**	**−28.4**

impact in terms of CO_2 emission for the production of 1 m^3 of SCMs inclusive RCCP mixes containing 50% RAP aggregates. Only the CO_2 emissions during the initial construction phase of 1 m^3 RCCP mix has been considered in the present study. This includes the CO_2 emissions during material production, CO_2 emissions by vehicle during material transportation, and emissions in production of fresh concrete. The CO_2 emissions in kg/kg for the production of raw materials i.e. cement, aggregates, silica fume, fly ash, and sugarcane ash has been obtained as per Ministry of Environment, Forest and Climate Change, Govt. of India (MoEF 2010). The CO_2 emissions in kg/kg by vehicles during the transportation of raw materials i.e. cementitious materials and aggregates to the construction site has been assumed to be 5.18×10^{-5} and 6.3×10^{-5} of CO_2 per kg/kg (MoEF 2010; Yang et al., 2015). As can be seen From Table 5, a reduction in CO_2 emissions of about 6% and 10% could be achieved on utilizing silica fume in proportions of 5% and 10% for preparation of RCC pavements, whereas, about 15%, 28%, 11%, and 15% reduction in CO_2 emissions were noted in 15FA, 30FA, 10SA, and 15BA mixes respectively. These findings not only depicts the benefits of the considered SCMs in terms of economy but will also help in reducing the carbon footprints, keeping in mind the strength related parameters are not much compromised. Therefore, in cases of RAP having a stiffened asphalt coating and a significant amount of dust contaminants, the utilization of silica fume (up to 10%) as partial replacement of Portland cement may be recommended for the construction of a sustainable RCC pavement. Nevertheless, 15% of fly ash may also be recommended since the associated strength parameters and sustainability factors are also achieved.

5. Special discussion and recommendation

The results from the present study indicate that Silica Fume (SF) outperforms the other considered supplementary cementitious mineral admixtures (SCMs) i.e. Fly ash (FA) and Sugarcane Ash (SA). But the other SCMs should not be overlooked just because they do not have the highest strength parameters. ACI (2001) recommends a minimum flexural strength of 3.67 MPa at 28 days, if Roller Compacted Concrete Pavements (RCCP) is to act as a surface layer. Table 6 illustrates the rating of the considered mixes for its effective utilization in various pavement applications. Only the SF mixes i.e. 5 & 10% SF and 15% FA mix qualified the minimum criteria to act as a surface layer. The same mixes could also be suggested for pavements serving heavy duty low-volume roads. In-fact, these mixes were found to be the most favorable for laying of RAP-RCCP in acidic environments. On the other hand, the other mixes could still be used as base layer of conventional concrete pavements, lower lift of a two-lift paving application, under overlays, parking lots, shipping yards and ports, streets, and highway shoulders.

Utilizing these waste materials in RCCP would not only lower the cost of the project but this could also lead to environmental benefits such as elimination of RAP, fly ash, sugarcane ash disposal issues and also contributing towards reduction in the carbon footprint as well. It is believed that the results from the present study would eliminate the hesitation of utilizing such wastes in pavement applications and also create awareness amongst academicians and highway engineers towards the potential utilization of such wastes. It is also believed that the results from the present study would encourage more recycling of wastes for road construction and also encourage the government authorities for framing policies and guidelines into the utilization of various wastes in various pavement applications.

6. Conclusions

Inclusions of waste originating from roads for the preparation of pavements layers is a good idea and the same has been tried in the present investigation. As expected, the utilization of Reclaimed Asphalt Pavement (RAP) (50% coarse & fine RAP) was found to have a negative effect on the properties of Roller Compacted Concrete Pavement (RCCP) mixes. An attempt was made to enhance it by using a few industrial & agricultural and industrial wastes such as Silica Fume (SF), Fly ash (FA), and Sugarcane Ash (SA), respectively, however, they did not have much positive effect on the fresh properties, rather degraded a few considerably. The Maximum Dry Density (MDD) was further declined and Optimum Moisture Content (OMC) was increased, As far as the effect on the strength properties was concerned, except SF, the inclusion of the considered wastes degraded the strength properties like compressive strength, modulus of rupture, and split tensile strength of the 50RAP mix. Similarly, except SF, the considered wastes could not provide any beneficial effects on the durability properties of the 50RAP mix, rather it increased the total permeable voids, water absorption, initial and coefficient rate of water absorption, respectively. This indicates that Silica Fume holds great potential to be used as a replacement of Portland cement for the preparation of RCCP mixes containing 50% RAP aggregates. Even the abrasion resistance which is an important parameter for depicting the suitability of RAP inclusive RCCP mixes to function as a surface layer of pavements yielded positive results in the case of SF mixes. Therefore based upon the properties considered, the inclusion of silica fume may be recommended for the productions of RAP inclusive RCCP mixes. As far as the other industrial/agricultural wastes are concerned, 15% Fly ash could also be utilized for producing sustainable RCCP mixes, however, bagasse ash shall only be employed as base layer material of conventional concrete pavements.

Recycling and reusing wastes originating from roads, industries, and agriculture would not only yield economic benefits but would also be environmentally friendly. Based on the above-mentioned

Table 6
Rating factor of the considered mixes as per minimum standards for road construction.

Mix ID		Achieved Flexural Strength (MPa) @ 28 days	Rating Scale: 1 to 5 (Not Favorable to Most Favorable). n.a. = not applicable					
			Surface Layer	Base Layer of conventional concrete pavements	High Traffic	Aggressive environments	Cost-effectiveness	Reduction in CO_2 emissions
Control	ACI (2001) stipulated 28 days' Flexural Strength = 3.67 MPa	5.4	5	n.a.	5	5	n.a.	n.a.
50RAP		3.8	3	n.a.	3	3	4	3
5SF		3.8	3	n.a.	3	3	3	3
10SF		3.9	4	n.a.	4	4	3	3
15FA		3.8	3	n.a.	3	3	5	4
30FA		3.5	1	5	1	2	5	5
10SA		3.5	1	5	1	2	4	4
15SA		3.2	1	5	1	2	4	4
15FA + 10SA		2.9	1	4	1	1	5	5
15FA + 15SA		2.5	1	4	1	1	5	5

recommendation, utilizing silica fume and RAP aggregates could reduce the initial construction cost of 1 m^3 of RCCP mix by up to 8.4% and also lower the CO_2 emission by up to 9.7% in comparison to the conventional RCCP mix. This again indicates that utilization of the considered wastes will not only provide a boom in the economy of the project but would also serve environmental benefits such as eliminating waste disposal issues, improving road aesthetics, conserving natural resources for future demand, and reducing the carbon footprints.

Declaration of Competing Interest

None.

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