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RESEARCH PAPER

Behavioural Study of Incorporation of Recycled Concrete Aggregates and Mineral Admixtures in Pavement Quality Concrete

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ABSTRACT: The following is an in-depth study discussing various aspects of a sustainable Pavement Quality Concrete (PQC) mix with inclusion of Recycled Concrete Aggregates (RCA) and mineral admixtures. In addition to investigation of basic mechanical properties; compositional, morphological and interspatial aspects of hardened concretes were analysed to understand the macro and micro level effects of incorporating fine particulate fly ash, rice husk ash or bagasse ash in concrete mix having recycled concrete aggregates using state of the art techniques such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Mercury Intrusion Porosimetry (MIP). The study of PQC mixes prepared with assimilation of RCA and mineral admixtures show that addition of particulate mineral admixtures significantly enhanced the compressive and flexural strength of the mix incorporating RCA to the order of 15% and 25%, respectively. The study concluded that admixing mineral admixtures at 15% dosage refined the pore structure by reducing the average pore size by up to a few microns and also reducing the total pore volume which indicates towards the concrete mix being less permeable. This refinement in pore structure of concrete mix resulted in reduced water absorption and higher density values thus indicating improvement in durability of concrete.

Keywords: Concrete, Mercury Induced Porosimetry, Mineral Admixtures, Recycled Concrete Aggregate.

1. Introduction

In today's scenario, the construction industry plays a major role in helping developing countries to move at a steady pace towards urbanization and industrialization. Developing countries are going through a rapid infrastructural transformation phase wherein more urban areas are being developed. For a developing country like India, wherein the population count is growing profoundly every day from around 1210 million in 2011 (Census of India, 2011) to a projected count of over 1.64 billion by 2050 (UN DESA, 2018) stress on construction is the need of the hour. This has led to rapid growth in new construction activities as well as demolition

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of old structures resulting in generation of construction waste in huge quantities. In order to get an idea of future construction activities for a country like India, according to a study it is estimated that almost 70% of the buildings supposed to exist by 2030 are yet to be constructed (Sankhe et al., 2010).

Such activities demand large quantities of materials from depleting natural sources, forcing us to look beyond conventional sources for alternatives. Countries all over the world have come up with creative techniques for utilization of different recycled construction wastes. Hongkong has introduced a construction waste charge for developers as well as tax concession benefits for recycling centers (CSE, 2014). Singapore legislature brought in tightened rules and regulations with penalties due to which it is able to recycle nearly 98% of its Construction and Demolition (C & D) waste (Nagapan et al., 2012). Malaysia is also one such country which is trying to handle C & D waste with aggressive rules and policies (Wahi et al., 2015). Many countries like USA, UK, Australia, Germany, Portugal, Korea, Hongkong, France, China, Japan, European Union etc. have already established specifications for incorporating recycled materials in fresh construction activities (CCANZ, 2013; Tam and Lu, 2016; Jain et al., 2019; Tam, 2008; Zega and Di Maio, 2011; Lennon, 2005). According to a report by the Technology Information Forecasting and Assessment Council (TIFAC), an approximate 40-60 kg/m^2 of waste is generated from new construction activities while an approximate 300-500 kg/m^2 of construction waste is generated out of demolished buildings (TIFAC, 2001).

Considering the scenario for a rapidly developing country like India, no codal standards or specifications are generally established for using concrete waste for new applications. Such a country produces a large quantity of waste; just to get an idea approximately 150 million tons of annual construction and demolition waste was estimated by BMTPC in 2020 (Centre for Science and Environment, 2020). This waste is generally dumped openly along the roadsides due to weak government laws or their implementations; or is transported to a site outside the city for disposal as landfill. Considering the pace at which developing countries are urbanizing, this waste is bound to increase profoundly which has already started to pose an environmental threat.

Around 25% of total C & D waste in India is contributed by concrete alone which amounts up to around 2.40 to 3.67 million tons per year (TIFAC, 2001). Concrete today is undoubtedly the most widely used construction material (Gagg, 2014). Aggregates in concrete, of all constituents generally contributes towards 60%-70% of the concrete volume (Arredondo-Rea et al., 2019), thus making them one basic amenity for all sorts of concrete constructions. Utilizing this waste as recycled highway materials in pavement construction is therefore an effort to preserve the natural environment by reducing waste and providing a cost-effective material for constructing highways. In fact, the primary objective is to encourage the use of recycled materials in the construction of highways to the maximum economical and practical extent possible with improved or equal performance.

As recycling has become the focus of researchers, a lot of research has been carried out with the inclusion of different recycled/waste materials. However, the majority of the past research concentrates on the mechanical and durability aspects from a macroscopic level; very few studies could be found discussing the microscopic and interstitial properties of pavement quality concrete mix incorporating RCA and mineral admixtures. This study thus concentrates on investigating the effect on concrete mix (PQC mix) at both macro level and microscopic levels owing to the inclusions of RCA as partial substitution for natural coarse aggregates. Thus, determining the suitability of incorporating

RCA for construction of concrete pavements in Indian conditions. The morphological aspects of hardened concrete were analyzed in detail in order to understand the micro level effects of incorporating fly ash, rice husk ash or bagasse ash in concrete mix having RCA. While fly ash and rice husk ash have been in use as mineral admixtures for quite some time, use of bagasse ash is not popular. Also, the literature available for micro analysis of PQC mix using SEM, XRD and Mercury Intrusion Porosimetry (MIP) techniques together is very scanty. This study is thus an effort to discuss the morphological and porosity behaviour of concrete admixed with RCA and mineral admixtures in order to establish a sustainable and durable concrete pavement mix with the incorporation of locally available materials.

2. Literature Review

Re-using waste or recycled materials for new construction applications is not a new concept, in fact it dates back to the Romans who often reused stones from broken roads to construct newer ones. Over the course of time, different materials have been studied by researchers which could be used alongside and or for part replacement of conventional construction materials. Recycled concrete aggregate obtained from processing of demolished concrete waste, has been one such material of interest to researchers globally for quite some time.

Recycled concrete aggregates are aggregates coated with circumferential adhered mortar from old concrete. Researchers such as Rao et al. (2007), Etxeberria et al. (2004), de Oliveira and Vazquez (1996), Kenai et al. (2005), Crentsil et al. (2001) and many more have discussed that recycled concrete aggregates when used without surface treatment in newer concrete applications result in concrete with inferior properties. This has been attributed to weak and porous circumferential mortar surrounding the recycled concrete aggregate particle. Further it has been reported by several researchers such as Xiao et al. (2005), Yong and Teo (2009), Rao et al. (2007), Akbari et al. (2011) and Martínez-Lage et al. (2005) that the inferiority in concrete is reflected both in mechanical and durability properties and was found to be increasing with increase in content of recycled concrete aggregates. Meddah et al. (2020) further discussed that inclusion of recycled concrete aggregates more than 30% as replacement of natural aggregates results in inferior mechanical properties of concrete. Hatungimana et al. (2020) also discussed the effects of incorporating recycled concrete aggregates on the mechanical and durability behavior of concrete. Saravanakumar et al. (2021) discussed that the incorporation of recycled concrete aggregates in addition to slag results in better durability properties and improves the characteristics of concrete in all aspects substantially.

With time and further research various methods / processes / techniques known as beneficiation methods were proposed to help in removal of adhered mortar from recycled concrete aggregates. A few of the beneficiation techniques include acid soaking technique by Tam et al. (2007), thermal-mechanical beneficiation technique by Shima et al. (2005), chemical-mechanical beneficiation technique by Abbas et al. (2007) and microwave assisted beneficiation technique by Akbarnezhad et al. (2011). In addition to the above techniques for removal of adhered mortar, certain methods have also been proposed to improve the performance of recycled concrete aggregates without removing adhered mortar. These studies include treatment of recycled concrete aggregates by oil and silane type surface improvement agents by Tsujino et al. (2007), treatment of recycled concrete aggregates by soaking in pozzolanic slurry by Shaban et al. (2019), treatment of recycled concrete aggregates using calcium carbonate bio-deposition by Grabiec et al. (2012). Kehan et al. (2021)

also discussed various ways of improving the quality of recycled concrete aggregates either by coating them by polymer emulsions or using pozzolanic solutions which tends to fill in the voids with in recycled concrete aggregates thereby lowering its porosity.

Mineral admixtures owing to their pozzolanic properties help in improving the properties of concrete upon their incorporation as evident from the literature. Various researchers have reported improvements in concrete properties with the inclusion of different mineral admixtures in their studies. Some of the studies included use of blast furnace slag with recycled concrete aggregates by Berndt (2009), use of fly ash with recycled concrete aggregates by Kou and Poon (2002), use of high fine fly ash with recycled concrete aggregates by Tangchirapat et al. (2010), use of ground bagasse ash with recycled concrete aggregates by Somna et al. (2012), use of silica fume with recycled concrete aggregates by Wagih et al. (2013), use of ground granulated blast furnace slag with recycled concrete aggregates by Maier and Durham (2012), use of silica fume and ground granulated blast furnace slag with recycled concrete aggregates by Cakir (2014) and many more. Padhi et al (2018) also concluded improvement in properties of concrete containing recycled concrete aggregates with inclusions of rice husk ash with a recommendation of using 100% recycled concrete aggregates with 10-15% rice husk ash for practical applications. Javed et al. (2021) reported an increase in compressive strength of concrete with 100% recycled concrete aggregates with inclusion of bagasse ash up to the order of 20%.

3. Experimental Part

The experimental program for the study included investigations pertaining to properties and behaviour of pavement quality concrete consisting of recycled concrete aggregates and different mineral admixtures both at macro and micro level. The morphological aspects of hardened concrete were analyzed in detail in order to understand the micro level effects of incorporating fly ash, rice husk ash or bagasse ash in concrete mix having recycled concrete aggregates. Among the morphological studies, small hardened concrete specimens were investigated using Scanning Electron Microscopy (SEM) technique for understanding visible morphological variations and powdered concrete specimens were studied using X-Ray Diffraction (XRD) technique for ascertaining the variations in compound compositions. Porosity behaviour and pore structure was studied using Mercury Intrusion Porosimetry (MIP) on hardened concrete specimens. In addition, mechanical and durability properties of concrete mixes were also investigated to correlate the macro level variations in concrete with variations at micro level.

Conventional PQC mixes with and without recycled concrete aggregates and mineral admixtures were prepared as referral mixes for understanding the inclusion effects of recycled concrete aggregates and mineral admixtures. Inclusion of recycled concrete aggregates was carried out by substituting coarse aggregates at a replacement level of 30%. The three mineral admixtures were included at levels of 5%, 10% and 15% as addition to cement.

3.1. Materials Used in Study

3.1.1. Cement

The binder, i.e. cement used for the study was investigated for its physical properties in accordance with IS: 8112 (1989). Table 1 summarizes the properties of Ordinary Portland Cement (OPC), 43 grade used in study.

3.1.2. Aggregates

Coarse Aggregates: Natural and recycled concrete aggregates were used as coarse aggregates in the study both in sizes of 20 mm and 10 mm. Recycled concrete aggregates were obtained from demolished concrete waste locally procured while crushed granite was used as natural coarse aggregate.

Recycled concrete aggregates obtained from concrete waste after screening, mechanical and manual crushing had adhered mortar which is responsible for inferior properties in comparison to their natural counterparts. Recycled concrete aggregates were processed for surface treatment by soaking them in 0.1 Molar H_2SO_4 solution for a duration of 24 hours and thereafter abrading the dried aggregates in order to remove the adhered mortar. As per studies carried out by Tam et al. (2007) soaking recycled concrete aggregates in H_2SO_4 makes the adhered mortar brittle which helps in better removal of mortar. Figures 1a and 1b show demolished concrete waste and recycled concrete aggregates obtained after processing.

All the coarse aggregates used in study were investigated for their physical and mechanical properties to check their suitability in accordance with IS: 2386 Part I to VI (1997). Properties discussed in Table 2 show variation in parameters for natural and recycled aggregates, however, the recorded parameters were found to be under acceptable limits for recycled concrete aggregates after surface treatment.

Gradation: Aggregates used in the study were also checked for their gradation as per IS: 383 (1999) and MoRTH (2013). The combined gradation of coarse natural and recycled concrete aggregates are given in Table 3.

Table 1. Cement Properties

	Specific gravity	Fineness percent (%)	Soundness (mm)	Initial setting time (min)	Final wetting time (min)	Consistency (%)
Obtained values	3.15	1.5	2	63	161	28

(a) (b)

Fig. 1. a and b) Recycled concrete aggregates processed from demolished concrete waste

Table 2. Aggregate properties

Type of aggregate	Specific gravity	Water absorption (%)	Aggregate impact value (%)	Crushing value (%)
Acceptable limits	2.5-3.0	0.1-2%	30%	30%
Natural aggregate	2.677	0.274	13.88	17.775
Untreated RCA	2.417	3.18	22.23	19.42
Treated RCA	2.660	1.88	15.67	17.91

Table 3. Combined gradation of coarse aggregates

IS sieve (mm)	Upper limit	Lower limit	Combined gradation for conventional aggregates	Combined gradation for recycled aggregates
40	100	100	100	100
20	100	95	94.41	92
10	55	25	37.47	37
4.75	10	0	1.85	0

Figure 2 represents the graphical plots for combined gradation of coarse natural as well as recycled concrete aggregates. Efforts were made to achieve gradation of recycled aggregates similar to those of natural ones. The gradation of recycled concrete aggregates closely follows the gradation of natural aggregates plot, while for both aggregate types the gradation fits perfectly between the specified limits.

Fine Aggregates: Riverbed sand procured from a local river was used as fine aggregate in this study. The fine aggregates used were found to be belonging to Zone II grade with a fineness modulus of 2.76.

3.1.3. Water

In order to prepare concrete mix and for moist curing of concrete specimens, potable water conforming to IS: 456 (2001) was used.

3.1.4. Mineral Admixture

In order to promote the use of locally available materials efforts were made to incorporate mineral admixtures procured locally or from nearby sources. Fly ash, rice husk ash and bagasse ash were included as mineral admixtures in this study. All the mineral admixtures were assimilated as part additions to binder in concrete mixes. The physical properties and composition of these mineral admixtures are discussed below.

Class F Fly ash procured from the nearest thermal power plant having a specific gravity of 2.24 was used in the study. Rice husk ash used in study was obtained by incinerating locally procured rice husk. Similarly, Bagasse ash was obtained from a local jaggery-manufacturing unit. The specific gravity of Rice husk ash and bagasse ash were reported as 1.81 and 2.38 respectively. Further, Table 4 gives the chemical compositions of all three mineral admixtures determined in laboratory.

3.2. Concrete Mixtures

The concrete mixes under study were designed in accordance with specifications discussed in (Indian Road Congress) IRC 15 (2011) citing the incorporations from IRC 44 (2017) to be intended for concrete pavements. In order to determine mechanical and microscopic properties, investigations on pavement quality concrete mix incorporating recycled concrete aggregates and mineral admixtures were carried out in this study.

In the previous part of study recycled concrete aggregates were incorporated at different levels ranging from 10% to 50% where it was established that mixes with RCA content up to 30% had test values within the specified limits, thus suggesting their potential use for pavement quality concrete (Jindal et al., 2017). Therefore, in this part of study recycled concrete aggregates were included at an optimized level of 30%.

Three different mineral admixtures were used in different proportions (5%, 10%, 15%) along with recycled concrete aggregates as part substitution of coarse aggregates (30% substitution level) in the study. Accordingly, a total of 11 concrete mixes were prepared and investigated for desired properties as presented in Table 5. Amongst 11 concrete mix, one concrete mix designated as NAC was prepared as a base mix (no recycled concrete aggregates and no mineral admixtures) and one concrete mix designated as RAC was prepared with inclusions of recycled concrete aggregates only (no mineral admixtures). A total of 9 concrete mixes containing substituted RCA and mineral admixture are defined by code RAC-Z-n, where the part RAC represents recycled aggregate concrete, Z stands for individual mineral admixture type (F for fly ash, RA for rice husk ash and BA for bagasse ash) and finally ‘n’ defines the incorporation level of mineral admixture (1 for 5%, 2 for 10% and 3 for 15%). Thus RAC-F-3 represent PQC mix incorporating RCA and 15% fly ash, RAC-RA-1 represent PQC mix incorporating RCA and 5% rice husk ash and RAC-BA-2 represent mix RCA and 10% bagasse ash.

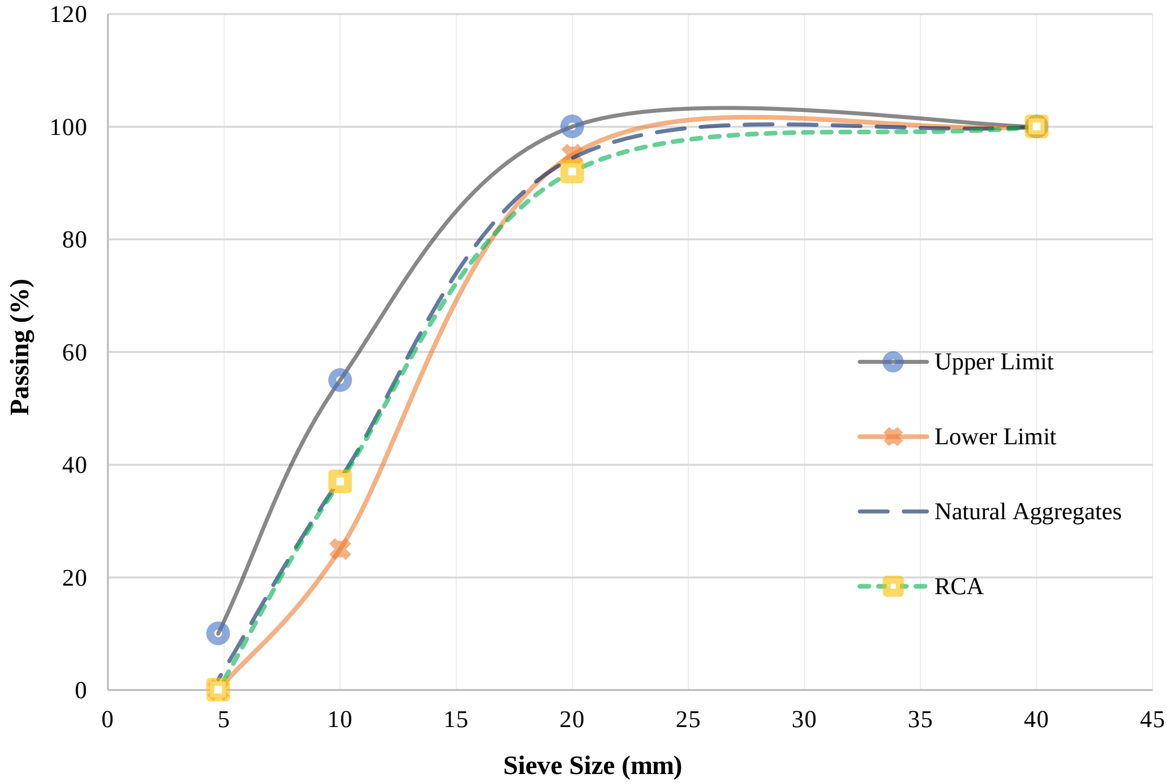

Fig. 1. (a & b): Recycled concrete aggregates processed from demolished concrete waste

Table 4. Chemical composition of mineral admixtures

Mineral admixture	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Fly ash	58.78	9.31	26.92	1.77	0.68
Rice husk ash	62.75	24.18	2.4	2.76	5.12
Bagasse ash	65.27	2.1	3.11	11.16	1.27

Table 5. Proportions of concrete mixes

Mix	Cement (Kg/m^3)	Water (lit)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	Recycled aggregate (Kg)	Mineral admixture (Kg)
NAC	400	173	660.22	1180	0	0
RAC	400	173	660.22	826	354	0
RAC-F-1	400	173	660.22	826	354	20
RAC-F-2	400	173	660.22	826	354	40
RAC-F-3	400	173	660.22	826	354	60
RAC-RA-1	400	173	660.22	826	354	20
RAC-RA-2	400	173	660.22	826	354	40
RAC-RA-3	400	173	660.22	826	354	60
RAC-BA-1	400	173	660.22	826	354	20
RAC-BA-2	400	173	660.22	826	354	40
RAC-BA-3	400	173	660.22	826	354	60

4. Study on Hardened Concrete

Behaviour of hardened concrete was studied using destructive testing techniques for the different concrete mixes under study. Representative specimens were investigated for their strength parameters in accordance with IS: 516 (1959) and IS: 5816 (1999). In addition to mechanical properties, efforts were carried out to determine density and water absorption values. Strength parameters recorded at 3, 7 and 28 days of moist curing at room temperature in accordance with IS 456 (2001) and IRC 84 (1983) and density and water absorption parameters observed at 28 days are summarized in Table 6.

Table 6. Strength, density and water absorption values for concrete mixes under study

Mix	Compressive strength (MPa)			Flexural strength (MPa)			Split tensile strength (MPa)			Hardened density (gm/cc)	Water absorption (%)
	3 days	7 days	28 days	3 days	7 days	28 days	3 days	7 days	28 days	28 days	28 days
NAC	18.16	27.17	39.57	2.19	3.68	6.09	1.83	2.12	3.53	2.51	2.117
RAC	16.24	23.77	35.59	2.25	3.41	4.92	2.12	2.54	2.96	2.50	2.3114
RAC-F-1	19.34	25.54	37.06	2.47	3.92	5.40	1.98	2.82	3.10	2.52	2.295
RAC-F-2	20.38	25.99	38.10	2.45	3.43	5.16	1.98	2.40	2.96	2.50	2.204
RAC-F-3	18.46	27.46	41.34	2.41	3.88	6.27	2.12	2.54	3.81	2.49	2.15
RAC-RA-1	17.13	23.77	37.06	2.23	3.62	5.28	1.69	2.40	3.24	2.48	2.31
RAC-RA-2	16.83	23.03	39.13	2.37	3.31	5.52	1.69	2.33	3.53	2.45	2.295
RAC-RA-3	17.42	23.77	40.46	2.39	3.56	6.31	1.98	2.54	3.67	2.45	2.25
RAC-BA-1	17.87	25.10	37.06	2.33	4.24	5.12	1.69	1.98	2.82	2.50	2.35
RAC-BA-2	17.28	24.07	38.54	3.29	4.18	5.87	1.69	2.40	2.96	2.49	2.295
RAC-BA-3	18.31	24.36	40.60	2.35	3.90	6.05	1.83	2.54	3.67	2.49	2.21

4.1. Compressive, Flexural and Splitting Tensile Strength

Hardened concrete specimens representative of different mixes were tested destructively for their compressive, flexural and splitting tensile strength. Efforts were made to establish relationships between the compressive, flexural and split tensile strength values for concrete mix with RCA and mineral admixtures using the experimental data obtained during study. Figure 3 presents compressive, flexural and split tensile strength parameters developed for mixes RAC-F, RAC-RA and RAC-BA respectively.

Incorporating RCA as part replacement of coarse aggregates did lead to reduction in strength in comparison to mix with natural aggregates as discussed by Jindal and Ransinchung (2018). This behaviour of mix with recycled concrete aggregates was found to be similar to studies discussed by Xiao et al. (2005), Limbachiya et al. (2004), Akbari et al. (2011), etc. An increase in strength to the order of 15% for compressive strength and 24% for flexural strength for fly ash admixed mix i.e. RAC-F-3 mix were recorded from Figures 2-4 while the strength gain for rice husk ash admixed mix i.e. RAC-RA-3 mix were to the order of 12% for compressive strength and 25% for flexural strength in comparison to RAC mix. Similar increase in strength values were recorded for mix with bagasse ash i.e. RAC-BA-3 mix to the order of 13% for compressive strength and 20% for flexural strength. This increase in strength upon inclusion of fly ash, rice husk ash or bagasse ash is in accordance with results discussed by Kou (2012) and Tangchirapat (2010) for fly ash additions in recycled aggregate concretes.

Improvement in strength parameters could be attributed to the incorporation of fine particulate mineral admixtures which owing to their pozzolanic properties helped in better strength development for the mix thereby bringing them on par with that of the mix with natural aggregates only and greater than that for the mix with incorporation of recycled concrete aggregates and no mineral admixtures.

4.2. Hardened Density and Water Absorption

Hardened specimens of concrete mix under study were studied for density and water absorption properties in order to understand the benefits of including recycled concrete aggregates and mineral admixtures on the concrete matrix. Recycled concrete aggregates used in study themselves were found to be having inferior density and water absorption values in comparison to their natural counterparts. This inferiority was thus reflected profoundly in parameters recorded for RAC mix in comparison to NAC mix as discussed in past studies carried out by Joseph et al. (2015), Peng et al. (2013) and many more.

Incorporating fine particulate mineral

admixtures resulted in improving the density and water absorption parameters for different concrete mixes as visible from Figures 4 and 5, respectively. The density values recorded for mix RAC-F-3, RAC-RA-3 and RAC-BA-3 were found to be comparable to that for the NAC mix while similar trends were observed for water absorption parameters. This betterment in density and water absorption behaviour could be credited to ultrafine particulate mineral admixtures which have improved the mix thus making it less permeable.

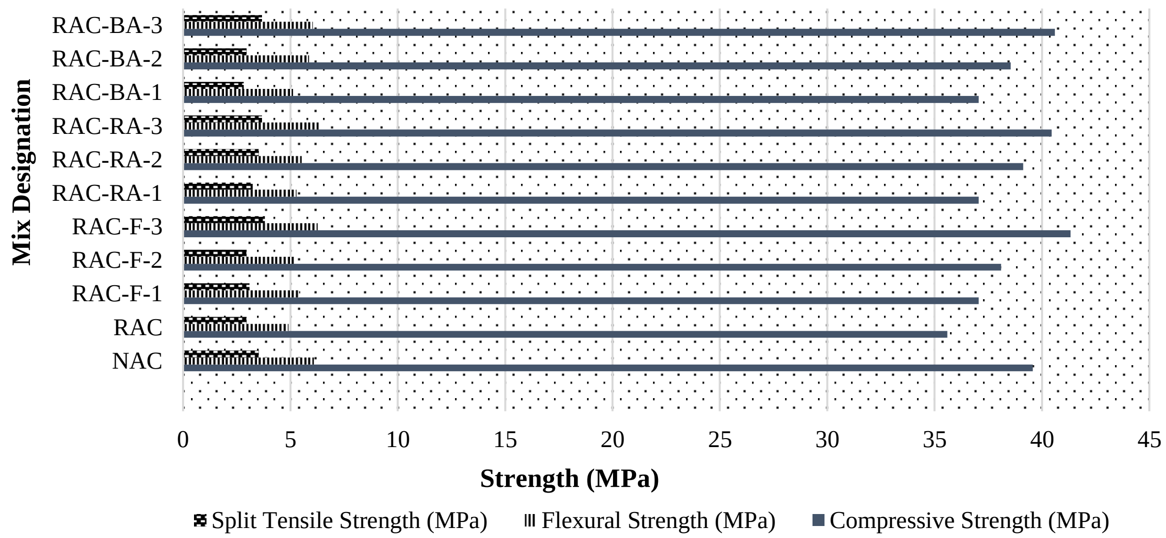

Fig. 3. Compressive Strength, Flexural Strength and Tensile Strength plots for different concrete mix under study

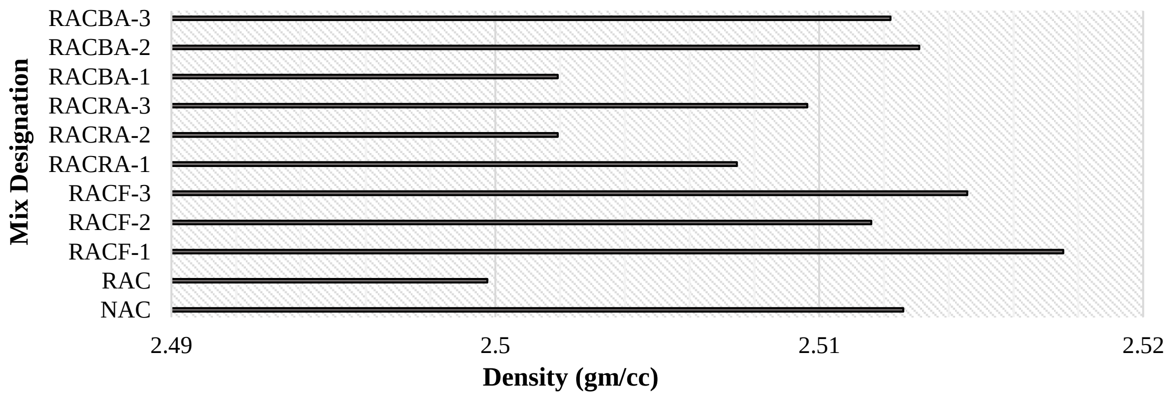

Fig. 4. Hardened density trends

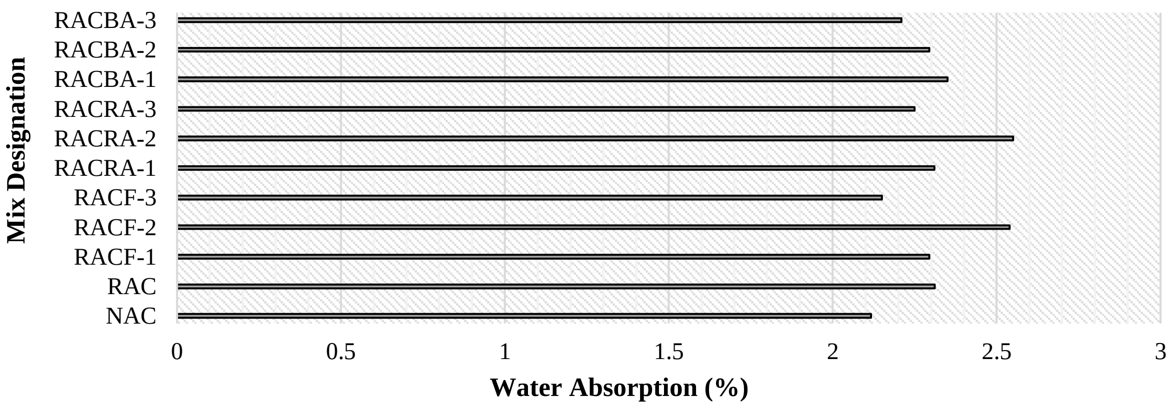

Fig. 5. Water absorption trends

5. Inter-Spatial and Compositional Study

5.1. SEM and EDS Analysis

Incorporation of micro sized particles influences the morphology of concrete in different ways, thus it becomes imperative to understand microscopic changes occurring in concrete with the inclusion of mineral admixtures and recycled concrete aggregates. The Scanning Electron Microscope (SEM) is an instrument, which is used very widely due to its versatility for examination and analysis of microstructural characteristics of solid objects. The microscope generates high-resolution images of shapes of objects which show spatial variations in chemical composition and surface morphology. Energy Dispersive Spectroscopy (EDS) measures the energy and intensity distribution of X-ray signals generated by the electron beam striking the surface of the specimen to help perform elemental analysis of surfaces in SEM. The specimens of concrete mix under study were observed for their SEM images at a curing age of 28 days in order to get a better idea about changes in hydration behaviour upon inclusion of fine particulate mineral admixtures.

The images developed from the SEM were analysed for identification of different hydration products present in the representative samples of different concrete mixes previously discussed by Jindal and Ransinchung (2018). SEM images obtained for different concrete mixes under study are presented in Appendix I.

It was found that hydrated matrix for natural aggregate concrete mix (NAC) had presence of calcium silicate hydrates (C-S-H) in abundance along with other hydration products such as hydroxides and ettringites identifiable as hexagonal prismatic and needle shaped components. On the other hand, the SEM image for RAC mix shows abundance of hydroxides and ettringites thereby suggesting improper hydration which might have led to less bonding and the same was visible from strength parameters discussed above.

Fly ash incorporated as a supplementary cementitious material is responsible for additional hydration products and filler effect when incorporated in concrete mix as discussed by Panesar (2019). SEM images for concrete mixes with recycled concrete aggregates and fly ash (RAC-F mixes) show profound presence of CSH gels and other hydrated products. This is also reflected as increase in strength of concrete mixes upon incorporation of fly ash. Similar trends for concrete with recycled concrete aggregates and fly ash were reported in studies carried out by Shi et al. (2013) and Singh and Singh (2016) depicting more hydration products.

SEM images for concrete mix prepared with inclusions of rice husk ash highlighted the presence of increased quantity of products of hydration and less voids. This has led to gain in strength which has been discussed by other researchers such as Jongpradist et al. (2018) and Zareei et al. (2017) and attributed to the pozzolanic behaviour of rice husk ash.

SEM images obtained for concrete mix specimens prepared upon the addition of bagasse ash as mineral admixture also show increased hydration products in comparison to SEM images for NAC and RAC mix. These variations are similar to those visible for RAC-F and RAC-RA mix. Reduction in voids and profound increase of prismatic components confirms the presence of more hydration products. Studies carried out by Amin (2019) also concluded that concrete containing rice husk ash reported better pozzolanic activity in comparison to natural counterpart.

The concrete mix incorporating recycled concrete aggregate showed more voids and less hydration products in comparison to reference or conventional concrete mix. This could be explained as improper hydration due to recycled concrete aggregates which absorb water from the mix resulting in reduction of strength. Using mineral admixtures however, led to reduction in voids due to additional hydration products owing to their pozzolanic properties. This reduction of voids is supported by reduced values of water absorption and increase in hardened density parameters indicating better durability and increased strength values.

5.2. XRD Analysis

Incorporation of micro-sized mineral admixtures resulted in variations in properties of pavement quality concrete containing RCA. These variations observed on a macro scale by investigating concrete properties are incurred due to variations at micro levels in concrete. The variations concerning morphological changes were studied with the help of SEM while the variations in hydration products were analysed by studying XRD patterns of different mixes.

The crystallographic data obtained after phase analysis for powdered samples of concrete mixes incorporating different types and proportions of mineral admixtures were needed to be further analyzed. Xpert High Score Plus a tool competent for analyzing the crystallographic data was used for analyzing the XRD data. XRD patterns obtained for different mixes under study after analysis are presented in Appendix II.

Interpretations made from the XRD study are discussed below:

i) Influence of Fly ash

The inclusion of fly ash in concrete mix tends to improve the chemical rate of reactions during hydration. More ettringite and C3A was observed for mixes containing fly ash than those for NAC and RAC mixes. Visible improvements in formation of C-S-H gels with the increase in incorporation level of fly ash falls in conformity with strength improvements observed during investigations of mechanical properties. This could be attributed to the presence of silica in fly ash which reacts with free calcium hydroxide to produce calcium silicate hydrate which adds up to the hydration products resulting in improved mechanical and durability of concrete mix.

ii) Influence of Rice husk ash

The crystallographic examination of concrete mixes incorporating RCA and rice husk ash showed variations in compound compositions in comparison to RAC mix. The increased presence of C-S-H gels and ettringite as hydration products shows similar composition as those of NAC mix. This is attributed to pozollanic properties of rice husk ash due to which the amorphous silica in rice husk ash reacts with calcium hydroxide to produce excess calcium silicate hydrates which results in better strength and durability of concrete.

iii) Influence of Bagasse ash

The hydration products identified for concrete mixes incorporating RCA and bagasse ash were observed to be similar to those of RAC-F and RCA-RA mixes with minor variations. The presence of silica leading to formation of excess C-S-H gels was observed as in the case of mixes with fly ash or rice husk ash, however a few peaks of calcium aluminum iron oxide were also identified for mixes with bagasse ash. This may be attributed to reaction between calcium oxide, alumina and a part of iron oxide present in RCA thus producing calcium aluminum iron oxide. The presence of ettringite, tri calcium aluminate and reductions in portlandite indicates improved hydration which is reflected as improvement in concrete properties.

Finally, it was established that the mineral admixtures used in this study were siliceous in nature, this resulted in formation of more hydration products which is visible from XRD analysis. Formation of additional CSH resulted in improved strength and durability of concrete.

5.3. Porosity Studies

Durability of concrete is a very important factor while assessing its performance. Determination of pore structure including pore size, pore distribution and cumulative surface area gives an idea about the permeability of a concrete specimen under study which in turn leads to assessment of its durability. Including micro sized mineral admixtures contributes in the hydration process thereby altering the pore structure of concrete, thus the pore structure of concrete specimens incorporating different mineral admixtures was investigated using the mercury intrusion technique which provides information on relative contribution of different sized pores. Figure 6 presents the Mercury Porosimeter used for porosity studies as well as the representative specimens of concrete mix under study.

The concrete mixes containing RCA and different mineral admixtures were investigated for average pore diameter, total pore volume, total mercury intrusion and cumulative surface area. In order to determine the variations, concrete specimens prepared without RCA and mineral admixture, and one mix containing RCA and no mineral admixtures were also investigated for similar properties. The specimens were tested in pressure ranging from atmospheric pressure to 34.5 Mpa. The results obtained from porosity investigations are summarized in Table 7.

The size of pores for the NAC mix specimen were observed to be varying from a few microns to around 100 microns. The total volume of mercury intruded in the concrete specimen was found to be 0.0287 cc/g while the average pore diameter was observed to be 0.1297 microns. It was also observed that pressurized mercury could achieve contact with micro pores sized up to 1 micron which contributed towards the cumulative contact surface area.

(a) **(b)**

Fig. 6. a) Mercury Porosimeter; and b) Concrete specimens

Table 7. Porosity data for concrete mix under study

Mix	Total intrusion volume (cc/g)	Total surface area (m^2/g)	Median pore diameter (microns)		Average pore diameter (microns)
			Based on volume	Based on surface area	
NAC	0.029	0.886	0.162	0.076	0.130
RAC	0.034	0.271	0.592	0.174	0.355
RAC-F-1	0.046	1.249	0.186	0.077	0.147
RAC-F-2	0.035	0.271	0.158	0.062	0.121
RAC-F-3	0.024	0.194	0.093	0.043	0.050
RAC-RA-1	0.133	5.153	0.109	0.063	0.103
RAC-RA-2	0.090	3.585	0.103	0.065	0.100
RAC-RA-3	0.030	1.073	0.108	0.071	0.111
RAC-BA-1	0.051	1.777	0.134	0.070	0.115
RAC-BA-2	0.014	0.098	1.562	0.215	0.553
RAC-BA-3	0.038	1.268	0.123	0.075	0.119

The pore structure of the concrete specimen from RAC mix was observed to be different from that of NAC mix. The average size of pores was found to be 0.3547 microns which was much higher in comparison to 0.1297 microns for NAC mix. This increase in pore size was previously anticipated due to porous adhered mortar surrounding aggregate particle and is supported by increased water absorption values for RAC mix. It was found that around 99% of the total volume of pores was constituted by pores sized up to 3 microns which also increased the total contact surface between mercury and specimen pores. It could be easily interpreted that the RAC mix has higher and bigger sized pores in the specimen in comparison to NAC mix which increased the porosity of the mix and was reflected in corresponding water absorption values.

It was observed for the specimen of RAC mix that inclusions of RCA led to increase in total pore volume along with increase in pore diameter. Mix RAC-F-1 incorporated 5% fly ash along with RCA due to which the micro fine particles of fly ash participated in the hydration process thereby contributing to hydrated products. This led to slight reduction in total pore volume along with visible reductions in pore size. Around 99% of total pore volume for this specimen was found to be consisting of pores sized around 3 microns. Also the pores contributing to cumulative surface area were found to be smaller in size in comparison to those in RAC mix. The minimum size of pores contributing towards cumulative surface area was observed to be around 1 micron.

The pore structure of RAC-F-2 mix was observed to be very similar to the pore behaviour of RAC-F-1 mix with minor alterations. The average pore diameter for the RAC-F-2 specimen was observed to be 0.1214 microns compared to 0.1469 microns for RAC-F-1 mix. The total intrusion volume of mercury was also observed to be reduced from 0.0459 cc/g for RAC-F-1 mix to 0.0347 cc/g for RAC-F-2 mix. This shows that increasing the content of fly ash in concrete with RCA altered the pore structure of concrete by reducing the pore volume along with the size of pores.

Among the specimens tested for concrete mix containing RCA and fly ash, RAC-F-3 showed significant variations in pore structure in comparison to NAC and RAC mix. The average pore diameter for RAC-F-3 mix was found to be 0.0502 microns which was even smaller than 0.1297 microns for NAC mix. Also the total volume of mercury penetrated into the specimen was observed as 0.0244 cc/g for RAC-F-3 mix which is silently less than 0.0287 cc/g for NAC mix.

Reductions observed in parameters of pore diameter and intrusion volume indicate improved pore structure attributed to fly ash incorporation in mix. Calcium rich minerals present in fine particulate fly ash tend to react with free lime during hydration which increases the products of hydration, leading to refinement in pore structure thus making the concrete mix more durable.

Subsuming rice husk ash in the mix along with RCA led to variations in pore behaviour of concrete. The average size of pores was observed to be reduced from 0.3547 microns for RAC mix to 0.1029 microns for RAC-RA-1 mix which was also less than 0.1297 microns for NAC mix . The total volume of intrusion of mercury into the specimen is an indication of the volume of pores present in the sample which could be intruded by mercury under pressure. Around 80% of total pore volume in the tested specimen was observed to be constituted by pores with size less than 1 micron while RAC mix showed a majority pore volume consisting of pores sized less than 3 microns. This shows that incorporation of rice husk ash helped in reducing the pore size of concrete. Rice husk ash has pozzolanic properties due to presence of silica, alumina and calcium oxide which adds to the hydration process thereby resulting in less pores and thus less permeable concrete.

Pore parameters for mix RAC-RA-2

showed that increasing the content of rice husk ash from 5% in RAC-RA-1 to 10% in RAC-RA-2 led to marginal variations in porosity parameters and pore structure. The average pore size was observed to be 0.0999 microns which was that of both NAC and RAC mix however when compared with RAC-RA-1, the reduction was marginal for average pore size. For RAC-RA-2, around 83% of total pore volume was found to be consisting of pores sized less than 1 micron while for RAC-RA-1 this quantity was around 80% indicating a slight decrease in pore size on increasing the content of rice husk ash.

The reduction in pore volume was visible for concrete with increase in proportions of rice husk ash. This is in accordance with reduced values of water absorption and increased hydration products visible in SEM images for the respective mixes. Similar behaviour was observed for all the mixes with rice husk ash showing improved pore structures which will enhance the durability of concrete. Mix RAC-RA-3 showed average pore size around 0.1113 microns with a total intrusion volume of mercury as 0.0298 cc/g approximately. These parameters show improvement in pore structure in comparison to RAC mix which will correct the deficiencies incurred due to usage of RCA in concrete.

Adding bagasse ash to concrete containing recycled concrete aggregates showed similar effects on concrete with reductions in quantity of pores and also the pore size. Mix RAC-BA-1 recorded an average pore size to be 0.1151 microns which was smaller than those for RAC mix and marginally smaller than the pore size of NAC mix. The total volume of mercury penetrated in the specimen was also found to be lowered in comparison to parameters recorded for RAC mix. This indicates improvement in pore structure of recycled aggregate concrete thereby reducing the volume and size of pores due to enhanced hydration filling up micro pores.

For mix RAC-BA-2 increasing the quantity of bagasse ash from 5% to 10% led to reduction of total mercury volume from 0.0511 cc/g for RAC-BA-1 to 0.0136 cc/g. The maximum size of pores contributing towards cumulative surface area of contact between mercury and pores was found to be around 3 microns. The porosity associated parameters for mix RAC-BA-3 show visible reductions in pores and their size in comparison to RAC mix. The specimen tested for mix RAC-BA-3 recorded an average pore size of 0.1189 microns which was less than the average pore size for both NAC and RAC mix, thus showing appreciable pore variation corresponding to reference natural aggregate concrete mix and mix incorporating recycled concrete aggregates.

Mix with 5% fly ash i.e. RAC-F-1 showed pore behaviour quite similar to that of RAC; however, increasing the proportions of fly ash to 15% led to pore structure refinement of concrete observed with reductions in average pore size and total intrusion volume. Incorporation of rice husk ash also tends to modify the pore structure of concrete thereby improving its mechanical and durability properties. Specimens representing mix RAC-RA-1 and RAC-RA-2 reflected minor variations in porosity parameters, however much improvement was observed for the mix with 15% rice husk ash i.e. RAC-RA-3. Concrete mixes containing bagasse ash were also observed to have improved pore structure with reduction in total pore volume as well as the average size of pores.

This shows that the volume of pores for concrete mix incorporating higher dosage of mineral admixtures i.e. 15% are amounting a few microns which indicates the concrete mix being less permeable thus indicating concrete being more durable. This modification in pore structure of concrete mix is attributed to the pozollanic properties of mineral admixtures which participate in the hydration process thereby filling the micro pores which is reflected as improvement in mechanical and durability properties of concrete thereby rendering concrete mix more durable and strong and bringing it to par with that of natural aggregate concrete.

6. Conclusions

The following conclusions were drawn from the above study:

i) Inducing 15% mineral admixtures in PQC mix having recycled concrete aggregate resulted in improved mechanical properties. An increase in compressive strength in the order of 4%, 2% and 2.5% was observed for mix admixed with fly ash, rice husk ash and bagasse ash respectively, in comparison to NAC mix.

ii) The improvement trends obtained for flexural strength parameters were similar to those of compressive strength. When compared with RAC mix, the increase in flexural strength was found to be more pronounced for mixes with 15% mineral admixture. In comparison to RAC mix, an increase of about 24% for RAC-F-3 mix, 25% for RAC-RA-3 mix and 20% for RAC-BA-3 mix was recorded. This gain in flexural strength was also higher than NAC mix to the order of 3.5 % for RAC-RA-3 mix and 3% for RAC-F-3 mix.

iii) The split tensile strength of concrete mix with RCA improves with increase in percentage of mineral admixtures. Using 15% fly ash, rice husk ash or bagasse ash as an addition to cement in PQC mix consisting 30% RCA provides similar split tensile strength as that of NAC mix.

iv) Using fine particulate mineral admixtures as an addition to binder reduces the water absorption of PQC mix with RCA significantly. Addition of 15% fly ash, rice husk ash and bagasse ash results in reduction of water absorption of concrete mix by 7.2%, 2.69% and 4.5% respectively.

v) An SEM study helped in understanding the improved strength behaviour of PQC mix with different mineral admixtures. The pozzolanic behaviour of mineral admixtures resulted in increased quantity of hydration products and thus less voids were observed.

vi) The mineral admixtures used in this study were siliceous in nature, this resulted in formation of more hydration products which is visible from XRD analysis. Formation of additional CSH resulted in improved strength and durability of concrete.

vii) Introduction of mineral admixtures led to refinement of pore structure of concrete. The ultra-fine particles of fly ash, rice husk ash or bagasse ash reduced the average pore size and cumulative pore volume of concretes. PQC mix with 15% mineral admixtures observed average pore size amounting to a few microns which indicates reduced permeability.

7. Acknowledgement

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8. APPENDIX – I

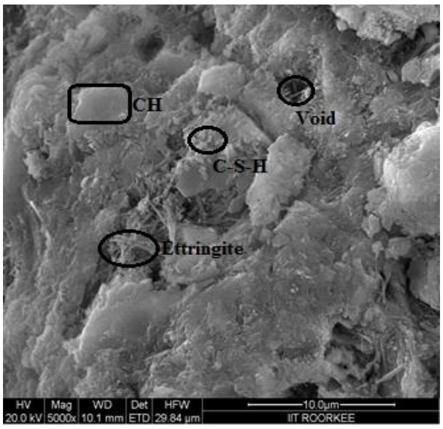


Fig. 1. SEM image for NAC mix

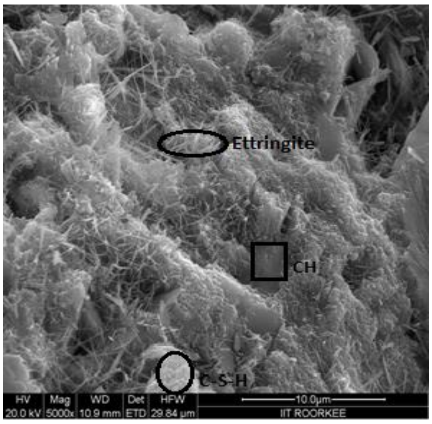
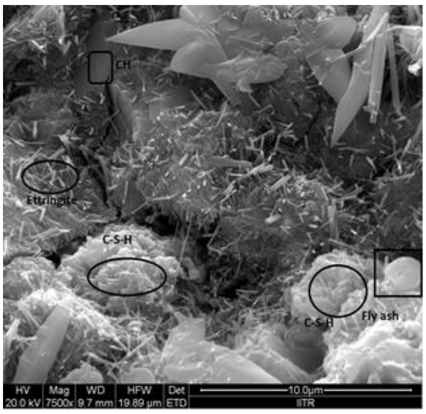


Fig. 2. SEM image for RAC mix



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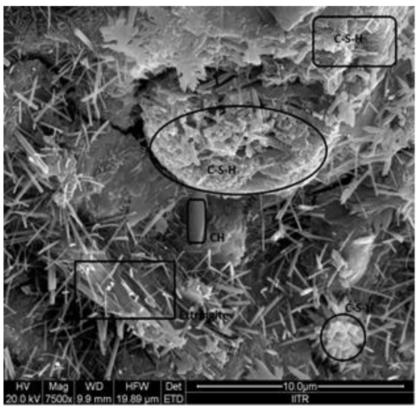

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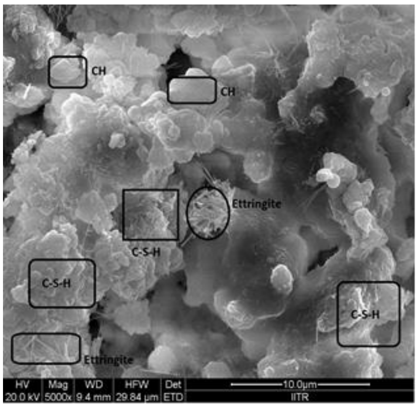
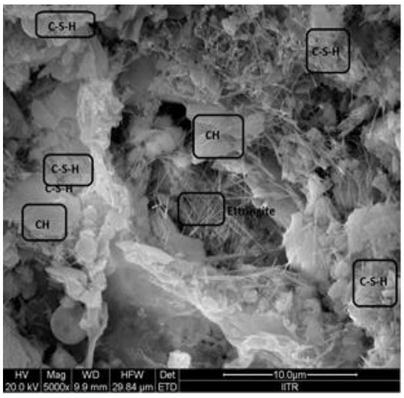


(c)

Fig. 3. SEM images for RAC-F: a) RAC-F-1; b) RAC-F-2; and c) RAC-F-3



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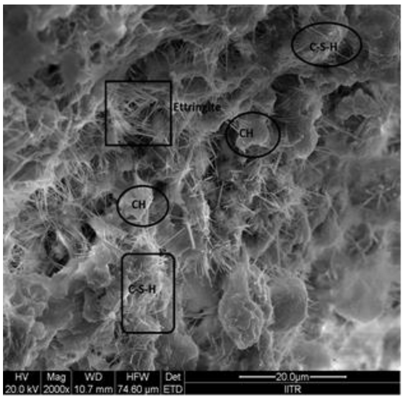

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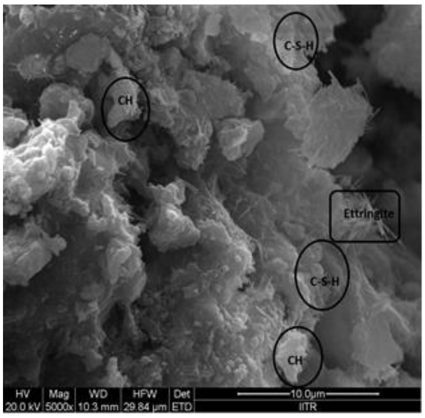
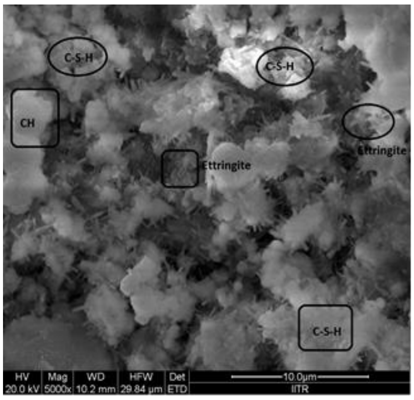


(c)

Fig. 4. SEM images for RAC-RA: a) RAC-RA-1; b) RAC-RA-2; c) RAC-RA-3



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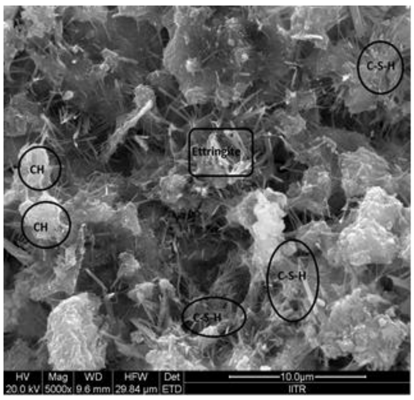

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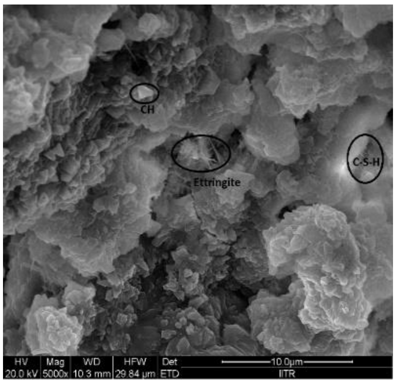
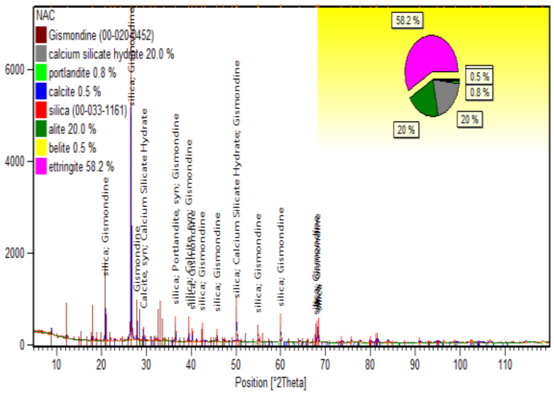


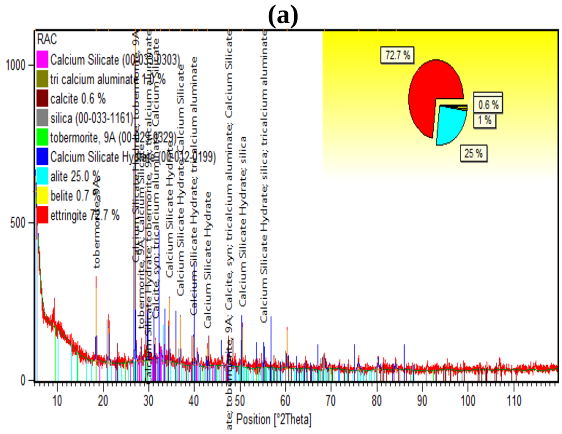
(c)

Fig. 5. SEM images for RAC-BA: a) RAC-BA-1; b) RAC-BA-2; and c) RAC-BA-3

8. APPENDIX – II



(a)



(b)

Fig. 1. XRD patterns: a) NAC mix; and b) RAC mix

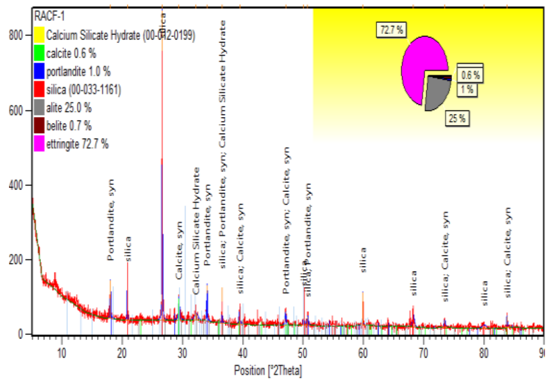


Fig. 2. XRD patterns for RAC-F-1 mix

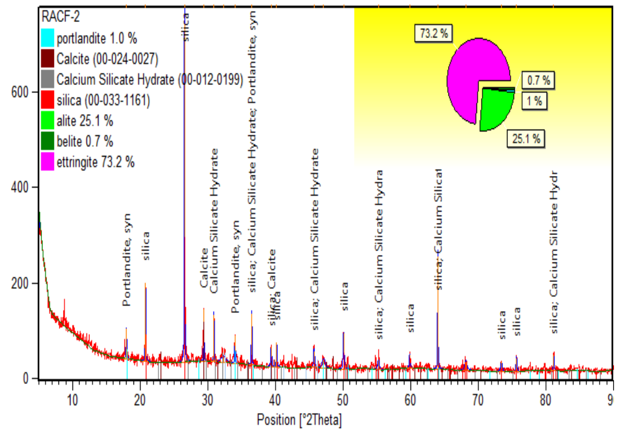


Fig. 3. XRD patterns for RAC-F-2 mix

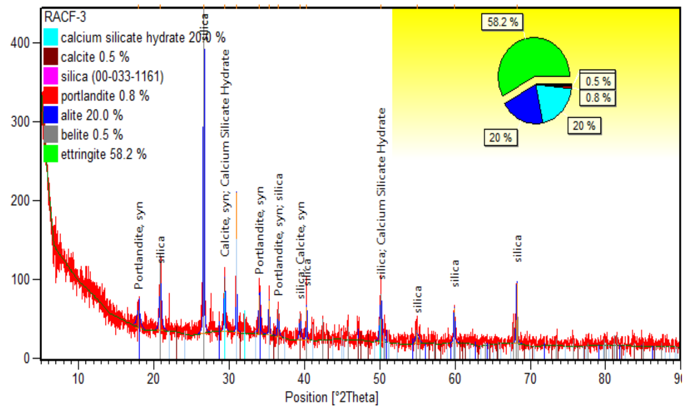


Fig. 4. XRD patterns for RAC-F-3 mix

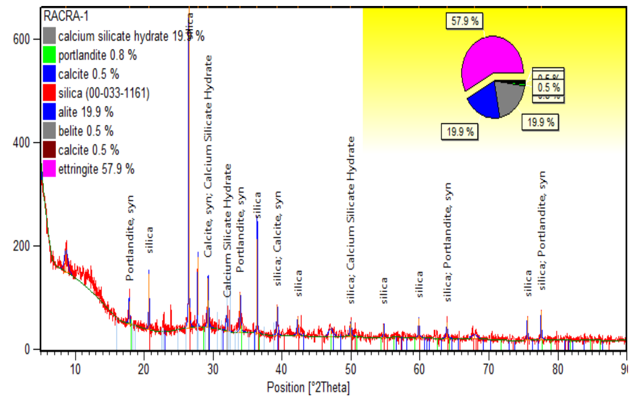


Fig. 5. XRD patterns for RAC-RA-1 mix

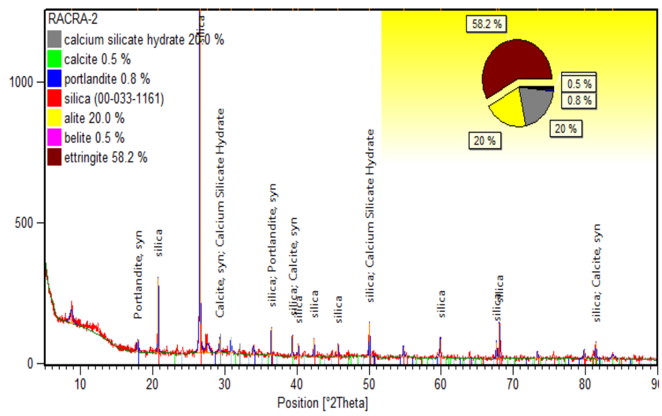


Fig. 6. XRD patterns for RAC-RA-2 mix

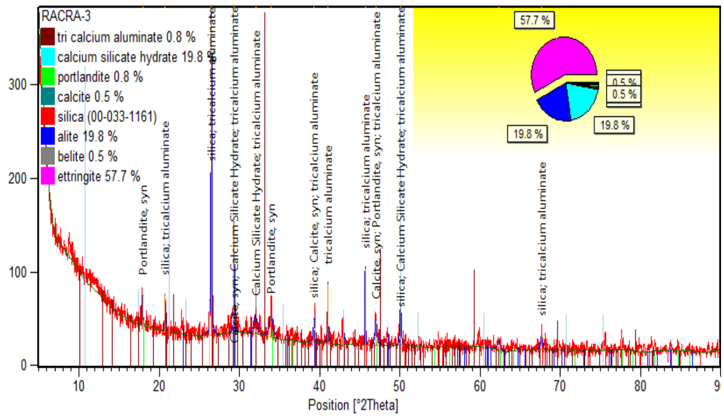


Fig. 7. XRD patterns for RAC-RA-3 mix

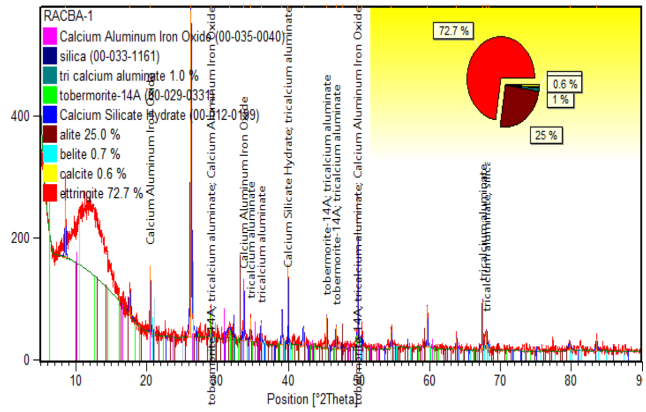


Fig. 8. XRD patterns for RAC-BA-1 mix

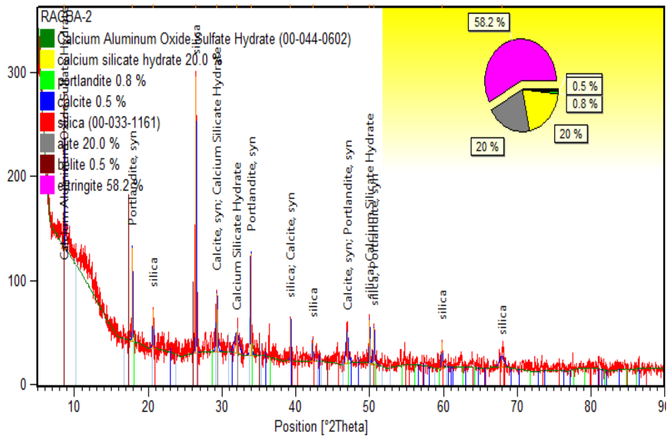


Fig. 9. XRD patterns for RAC-BA-2 mix

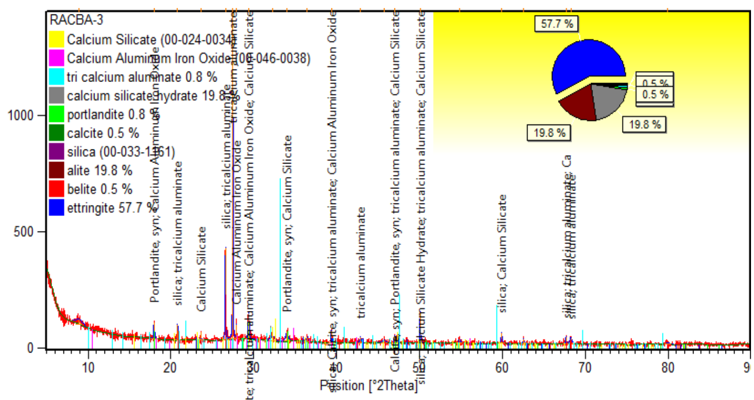


Fig. 10. XRD patterns for RAC-BA-3 mix