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Research Article

Studies on durability, thermal and morphological property with partial replacement of single use waste plastic and complete recycled aggregate in eco-friendly self-compacting concrete

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Abstract

This study focuses on creating an eco-friendly self-compacting concrete (EF-SCC) by recycling waste materials like plastic and construction debris. The researchers collected High-Density Polyethylene (HDPE) and Polypropylene (PP) plastics, cleaned and shredded them, then used them to partially replace fine sand at different levels, from 5% up to 20%. They also replaced all the traditional coarse rock aggregate with recycled materials from construction waste. The concrete's flow and ease of pouring (workability) were tested, and it was found that mixes with recycled aggregates flowed faster, with the best result being a 6-second flow time when using 10% HDPE. Durability tests were done by exposing the concrete to acid and sulphate attacks over several weeks, showing that the recycled concrete with plastics held up well, with only minor weight loss after 56 days in acid. Thermal tests showed that adding plastic lowered the concrete's heat conductivity by 30-35%, making it better at insulating. Microscopic analysis showed that the plastic was well integrated with the cement mixture, and chemical tests confirmed there were no harmful reactions between the plastic and the cement. Overall, the study suggests that EF-SCC made with recycled aggregates and plastic waste can keep key properties needed for construction, making it a promising, sustainable building material.

1. Introduction

India is the only country after the USA and European Union to produce the world's largest polymers, and it even creates waste plastic, according to the National Circular Economy Roadmap (NCER). India alone produces 3,500,000 metric tons of waste plastic, of which only 30% is recycled according to The Economics Times India 2023. Therefore, waste plastic generation in India can be utilized in the preparation of concrete with partial replacement of Fine Aggregate (FA) [3, 9 and 42], Coarse Aggregate (CA) [36], or Cement (C) which protects from depleting natural resources and protect the environment.

Substantial work is carried out on ordinary concrete, with the replacement of plastic waste [8], High Density Polyethylene (HDPE) [9], Polyethylene Terephthalate (PET) [10-18], E-Plastic [26], polypropylene (PP) [19-24], and Poly Vinyl Chloride (PVC) [25]. The waste plastic was also used as a replacement for cementitious materials [22], as FA [10-13, 15, 17, 18], and CA [14, 21, 23] as plastic fibers in concrete [24]. Most researchers have worked on partial replacement of FA/CA from 0% to 100%. Among the waste plastic used worldwide, PP and PET are widely recommended to be used as CA in concrete. Most of the

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work is carried out on the fresh properties (workability), hardened properties (mechanical properties), durability properties (Acid attack, sulfate attack, RCPT), and thermal properties (temperature variation, thermal conductivity) of concrete. The slump value (workability) of concrete was increased by being replaced partially by PP and PET as plastic waste conventional concrete [10, 14, 21]. The FA, the PET material can improve the workability property, i.e., slump cone test in concrete; this is because the plastic material has low workability and is frictionless [10-11]. It was found that waste plastic (PET), which is round and smooth in shape when replaced with FA in concrete, helps to improve the workability property of ordinary concrete [14]. The partially replacing PP with brick and stone CA, they found that the slump value (workability) of concrete was increased with the percentage increase in PP content regardless of water/cement (W/C) ratios [21].

Nevertheless, an opposite study was observed when PET was partially replaced with concrete. Its workability decreased with PET material increase [13, 15, 18, and 28]. The same material (PET) was used when its rheology was changed; the workability was reduced [13]. When PET was replaced by 20% with FA, it was observed that its workability, and slump value, were reduced by 25% [15]. The slump value (workability) of concrete with PET material in concrete was decreased because of its irregular shape and size. The use of PET material to replace FA in concrete observed the same pattern of reduction in workability because of the surface area of PET material [18 and 28]. The plastics used to replace FA or CA have a more specific gravity (SG) when compared with virgin plastic. Nevertheless, the waste plastics SG is lower than the natural fine and coarse aggregates [14 and 21]. Consequently, plastic waste has negligible weight compared to conventional material and, when replaced with concrete, can reduce the weight on soil strata [14 and 21]. The replacement of PET FA with brick aggregate found that 10% replacement reduced concrete density by 50%. The heat treatment to PET materials, and when replaced in concrete with FA, a linear reduction in the density was observed [14 and 29]. With a maximum percentage of 15%, the dead weight was reduced by 5.6%. It was also found a linear reduction in density when replaced with PP in concrete. The optimum reduction percentage of 7.4% and 8.4% was observed with a 30% replacement of PP waste plastic with brick and stone aggregate in concrete [21]. The waste plastic material utilized to prepare self-compacting concrete to consider was lightweight concrete [40-41]

Some of the researchers on the replacement of Waste Foundry Sand (WFS) with fine aggregate showed interesting facts and figures for M60 grade SCC. The replacement can be till 30% without any changes in the virgin properties of SCC. The waste generated from the foundry is considered one of the meaningful utilization techniques. It was even observed that treated WFS can reduce the density of concrete and make SCC a lightweight, sustainable, and green material [43]. The usage of waste PET plastic as fiber with the substitute of fine aggregate showed that the entire replacements (0.25, 0.5, 0.75, 1.0, and 1.25) % showed a decrement in compressive strength after 28 days of curing [44]. He also observed that the coefficient of correlation between the porosity and compressive strength is inversely weak relation. The use of fly ash with PET bottles to ameliorate the flexural and compressive strength of SCC was analyzed by [6, 34, 35, and 45]. The test results showed that the increase of PET fibers decreased the flowability of SCC. It was observed that fly ash with PET fiber reduced in its compressive strength but increased its flexural properties.

When replaced with FA or CA in concrete, the above waste plastic materials have many advantages and must be cross verified using statistical tools. The Response Surface Methodology (RSM) is a specific approach within the broader Design of Experiments (DOE) framework, used to model and analyze the effects of multiple factors on responses with fewer experiments. This method is usually applied in concrete technology (CT) to predict the mix proportions and the strength properties of various grades of concrete [2, 27-29].

With the increasing demand in infrastructure and construction industries and models with solid/perfect performance, ANN [32-33] and RSM increasingly handle various civil engineering projects, primarily in material science engineering. ANN has been widely used in many engineering disciplines to counter the drawbacks of empirical formulas and approaches to assess or predict the model with non-linear multivariate interrelationships between concrete's mechanical properties [30].

The present study aims to evaluate the workability, durability, thermal and morphological properties of Eco Friendly –Self Compacting Concrete (EF-SCC) with partial (5%, 10%, 15%, and 20%) replacement of HDPE and PP material and complete replacement of recycled coarse aggregate (RCA).

2. Materials and Methods

The concrete mix in this study used 43-grade Ordinary Portland Cement, following the IS 8112:1989 standard. Fine sand from river sources was used as the fine aggregate and was screened through a 4.75 mm sieve to meet the IS 2386 (Part-1):1963 specifications. To improve the concrete's performance and keep it workable for longer, a superplasticizer called Conplast was added. This additive makes the concrete easier to pour without needing vibration, and it's both chloride-free and low in alkali, helping ensure a durable and high-quality mix.

Table 1. Physical Properties

Properties	Cement	Fine Aggregate (FA)	Coarse Aggregate (CA)	Recycled Aggregate (RA)	HDPE	PP
Specific gravity	3.15	2.61	2.75	2.45	0.864	1.225
Water absorption (%)	12%	2.64	0.85	0.92	0.38	0.27
Fineness modulus	-	2.45	8.35	6.25	3.12	5.36
Maximum particle size (mm)	50 µm	4.75	20	20	3.75	27.50
Density	1.44 g/cm^3	2400-2900 kg/m^3	1200-1450 kg/m^3	1750 kg/m^3	0.90-0.94 g/cm^3	0.90 to 0.91 g/cm^3

In this study, local High-Density Polyethylene (HDPE) and Polypropylene (PP) were chosen for their similar strength profiles. HDPE has a tensile strength ranging from 31.37 MPa to 42 MPa, while PP falls between 27.5 MPa and 39.9 MPa. Their flexural strengths differ more, with HDPE ranging from 10 to 50 MPa and PP from 10 to 20 MPa, making both suitable for enhancing the strength properties of concrete. The recycled aggregates were collected from broken concrete test cubes; they were soaked in water for 24 hours to help remove the old cement paste, then thoroughly dried in either sunlight or an oven. Full details of their physical characteristics are listed in Table 1.

Table 2. M40 grade Eco-Friendly Self-Compacting Concrete (EF-SCC) mix proportion

Nomenclature	W/C=0.40					
	Cement (kg/m3)	CA (kg/m3)	FA (kg/m3)	100% RA (Kg)	HDPE	PP
HDPE5	273.5	776.52	60.52	776.52	3.21	-
HDPE10			54.10		6.42	-
HDPE15			44.47		9.63	-
HDPE20			31.63		12.84	-
PP5			60.52			3.21
PP10			54.10			6.42
PP15			44.47			9.63
PP20			31.63			12.84

2.1 Methods

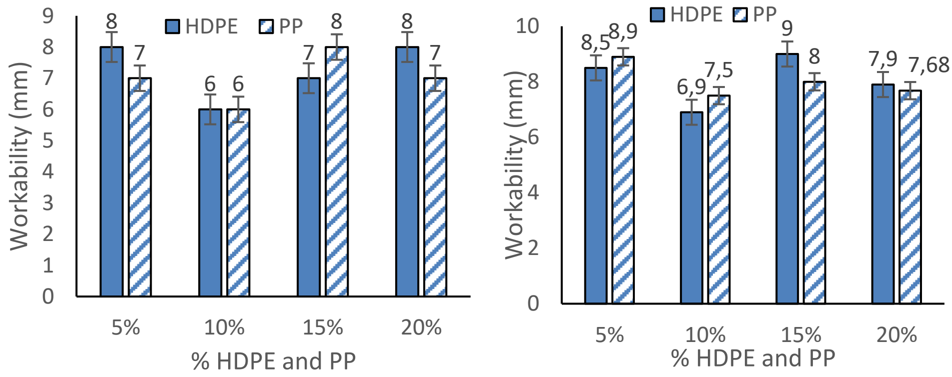
To understand how HDPE and PP perform in concrete, various tests were done to measure their physical properties, which are shown in Table 1. Concrete mixes were made with a water-to-cement ratio of 0.40, designed for M40 grade Eco-Friendly Self-Compacting Concrete (EF-SCC) according to the standards in IS 456:2000 and IS 10262:2019 (mix details are in Table 2). The testing included a V-funnel test for workability, acid and sulfate resistance tests at 28, 56, and 90 days (using 100x100x100 mm samples), a thermal conductivity test on samples sized 180 mm in diameter and 20 mm thick, and detailed analyses with Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) to study the concrete's structure and composition.

3. Results and Discussion

The current article focuses on the use of recycled coarse aggregate and waste plastic in the construction sector to improve the study of the long-term characteristics of EF-SCC. The greatest amount of plastic trash should be used in the development of various infrastructure projects to reduce the increase of plastic garbage at dumping yards, therefore protecting the environment. Similarly, recycled aggregate from building and demolition debris will be considered best practice in the construction business.

3.1 Workability

The workability test was performed on freshly mixed concrete of various compositions to know the flowability of the concrete (EFNARC) 2002). The findings show whether concrete workable is if it's a self-compacting concrete compacted with the help of its self-weight. The below results are taken when 100% replacement of RCA was used instead of natural coarse aggregate with various percentage replacements of HDPE and PP.



(a) (b)

Fig. 1. V funnel test (a) 100% Recycled Aggregate (RA) (b) 100% Natural Aggregate (NA)

3.1.2 V-Funnel test

The V-funnel test is used to check how easily the concrete can flow and fill spaces, especially for concrete with aggregate sizes up to 20 mm, based on EFNARC 2002 standards. In this test, 12 liters of concrete are poured into a V-shaped funnel. When the lid is opened, the time it takes for all the concrete to flow out is measured, giving an indication of its flowability. It is observed that the RA took less time to empty the funnel than the NA. The RA with 10% of HDPE and PP both recorded 6secs to empty the funnel, whereas RA with the same percentage showed 6.9secs and 7.5secs respectively as shown in Fig 1. The RA showed with 5% HDPE showed 8secs but as the percentage of HDPE was increased to 10% it was reduced by 2secs. The optimum percentage of HDPE with RA is 10% and it is the same case with PP also. This was the same case with measuring the workability of SCC to find the errors with different materials [22-23]

With NA in EF-SCC, the HDPE material at all the percentage replacements showed better results when compared with PP as shown in Fig 1b. The last time recorded was 10% of HDPE followed by 7.9secs, 8.5secs & 9secs at 20%, 5%, and 15% partial replacement respectively. When PP material was partially replaced with FA in EF-SCC it showed a slight increase in time when compared with HDPE. The optimum percentage of PP materials was the same as that of HDPE i.e., 10% of FA. The time recorded at various percentages of PP material in EF-SCC is 8.9secs, 7.5secs, 8secs, 7.6secs at 5%, 10%, 15% & 20% partial replacement respectively. The same pattern of even recorded by other authors to find the mixed proportion of EF-SCC [22-24]

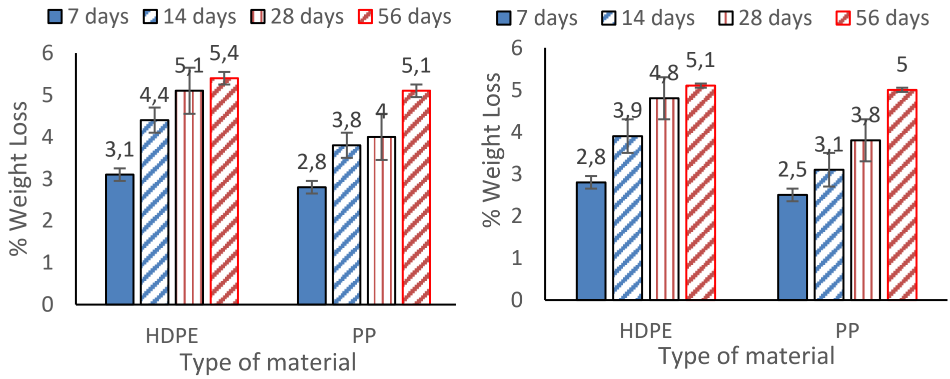
3.2 Durability

3.2.1 Acid Attack

The acid attack was performed on both RA and NA with different percentages of waste plastic. The test is conducted according to ASTM C, 262-2001 for EF-SCC with NA/HDPE-PP & RA/HDPE-PP. The percentage of weight loss increased with an increase in days. It was observed that the NA showed less loss in weight because of its alkalinity present [46] in it as shown in fig 2. The pattern for both RA and NA was the same at all ages with both HDPE and PP material.

The maximum weight loss was observed by RA with HDPE at 56 days i.e., 5.4%. Similarly, with NA the maximum weight was with the same material i.e., HDPE at 56 days i.e., 5.1%.

The weight loss is nearly less those 5% after 28 days of acid attack in both RA and NA with both HDPE and PP material. This weight loss is negligible and can be considered to be utilized in the construction industry.

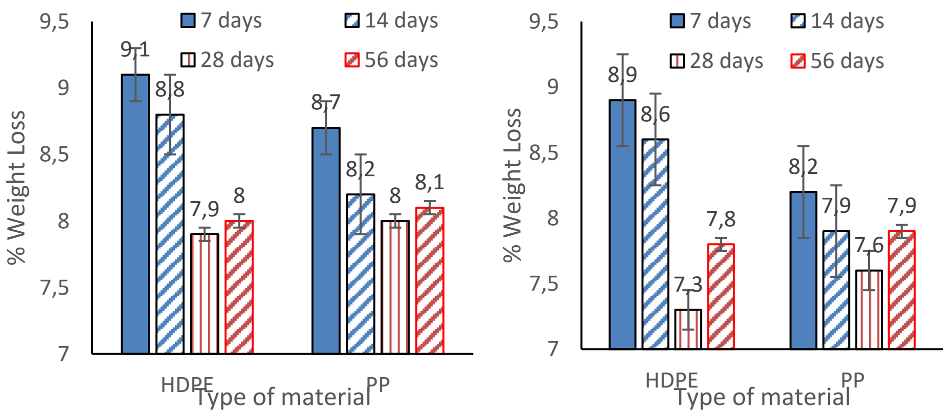


(a) (b)

Fig. 2. Acid attack (a) RA and (b) NA

3.2.2 Sulphate Attack

A sulfate attack test, as per ASTM C 1012-2012, was performed on concrete with HDPE and PP. In M40 EF-SCC mixes, both materials exhibited low weight loss at 28 days. For PP, weight loss continued to decrease until day 28, but both HDPE and PP showed a slight increase by day 56, regardless of using recycled or natural aggregates (see Fig 3). The greatest weight loss occurred at 7 days, reaching 9.1% for HDPE and 8.7% for PP. Across all testing periods, weight loss for both materials stayed under 10%.



(a) (b)

Fig. 3. Sulphate attack (a) recycled aggregate and (b) natural aggregate

The sulfate attack test showed an opposite pattern of the graph when compared with the acid attack. This is because the EF-SCC is placed in sulphuric acid which dissolves all the carbonated & hydroxides ($Ca(OH)_2$, $CaO \bullet SiO_2 \bullet nH_2O$) present in cement paste which causes strength and weight loss.

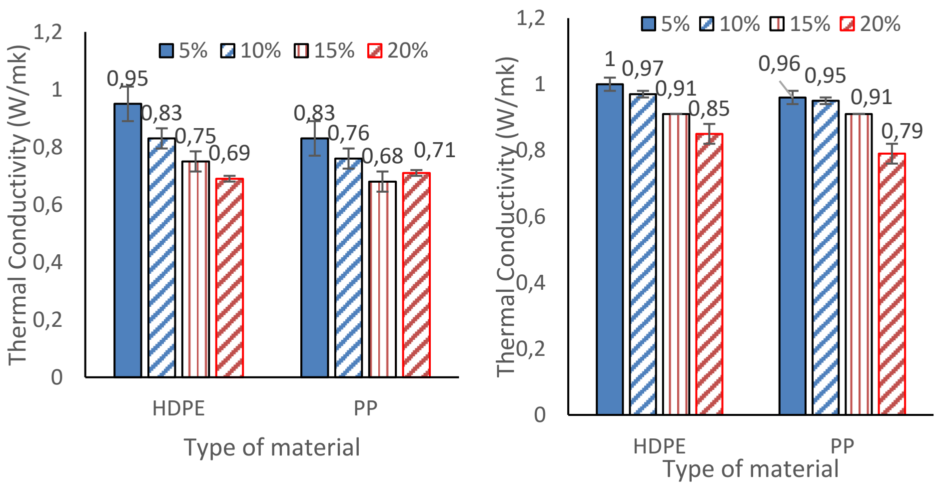
3.3 Thermal Conductivity

Thermal conductivity testing was done on all samples according to IS 3346:1980. Each sample was sized at 180 mm in diameter and 20 mm in thickness to allow heat to pass in only one direction. To ensure accuracy, two samples were prepared and tested for each mix, so heat flowed exclusively through the specimens. The thermal conductivity (k) was then determined using a specific calculation method.

$$K = \frac{Q}{2A}\left(\frac{L}{Th-Tc}\right) \tag{1}$$

Where K= Thermal Conductivity in W/m.K; Q= amount of heat transferred through the material in Joules/second or Watts; A= is the area of the surface in square meters; Th-Tc= difference in temperature in Kelvin.

The thermal conductivity (K) was less than 1 w/mk for all the specimens after 7days of curing in both HDPE and PP material with complete RA in EF-SCC. As the percentage of waste plastic was increased from 5% to 20% the K value was linearly reduced. This is the main purpose of HDPE and PP material to improve the thermal properties of building envelopes. If HDPE and PP material is used in the construction of houses, it can regulate the heat flow and can control the room temperature. The least K value is 0.69 w/mk at 7 days for HDPE material. The value of K increased after 7 days of curing till 14 days and then it slowly reduced till 28 days of curing as shown in Fig 4. The value of K after 28 days of curing is most important to analyze the heat flow in buildings as it achieves full strength. It was observed that PP material (0.71 w/mk) showed optimum reduction in the value of K when compared with HDPE (0.76 w/mk) at 20% partial replacement. When NA was used with HDPE and PP material it was observed that the thermal conductivity K was more than 1 w/mk for 5% of both HDPE and PP material at all ages. The maximum value of K was observed in 5% of HDPE material at 14days of curing. There was a drastic reduction in K value at 14 days of testing for more than 5% of HDPE material as shown in Fig 5.



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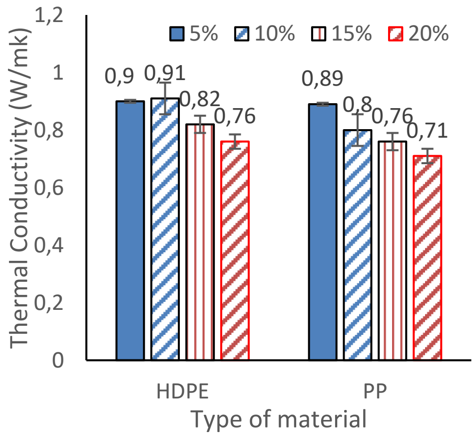
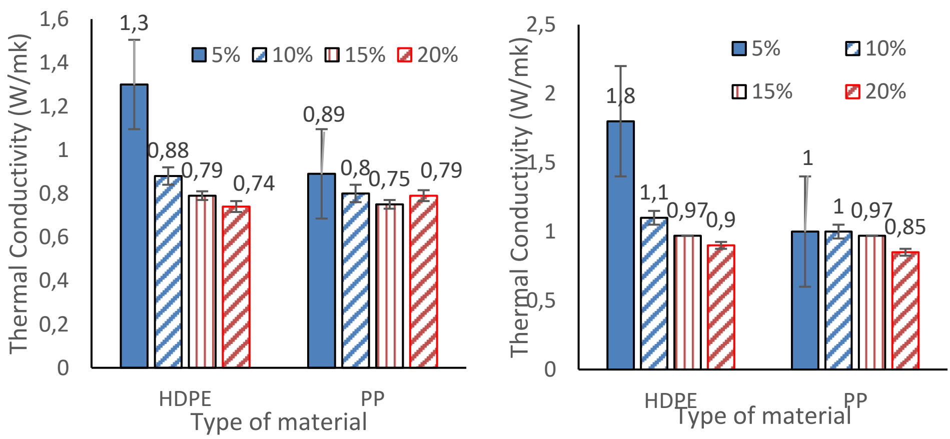


(c)

Fig. 4. Thermal conductivity with RA in EF-SCC for a) 7days b) 14days c) 28days

The lowest value of K was recorded after 28 days of curing with 20% of PP material i.e., 0.8 w/mk. The PP material showed better thermal conductivity than HDPE material at all ages. At 7 days only for 5% the HDPE material showed 1.3 w/mk whereas PP material showed 0.89 w/mk. The least value of K in both the material was 0.74 w/mk and 0.79 w/mk as shown in fig 5. At 14 days only HDPE material showed **a** drastic reduction in K value when compared with PP material. At 28 days the linear relation to that of RA pattern was observed in NA material also. It is recommended to use the RA with HDPE and PP material to improve the thermal performance of buildings**.**

A correlation between all the percentages of HDPE and PP for NCA sing excel sheet is given in Table 3. It was observed that at 7 days the correlation is 0.935 which is in good relation for both the materials but as the days of curing increased the correlation has reduced by 36% to 0.57 and then increased to 0.952, because initially in starting days of curing the cements heat of hydration is rapid and them it slowly reduces.



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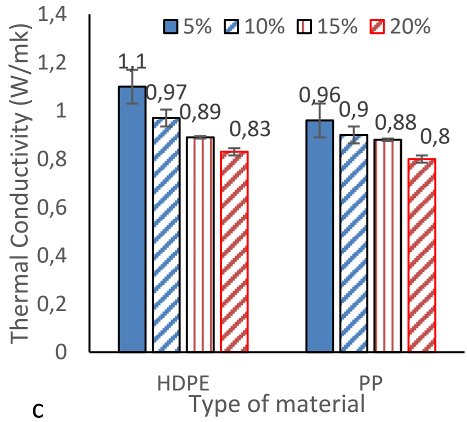

(c)

Fig. 4. Thermal conductivity with RA in EF-SCC for a) 7days b) 14days c) 28days

When RCA was used in concrete and it was tested for thermal conductivity, it was observed that the correlation at 7 days and 14 days was 0.918 and 0.948 respectively, but the relation was reduced to 0.845 at 28days. This can be because of the RCA material in concrete which consist of cement paste around the material of RCA.

Fig. 5. Thermal conductivity of NA in EF-SCC for a) 7days b) 14 days c) 28days

Table 3. Correlation between HDPE and PP material

Days / Material	7	14	28
	Natural Coarse Aggregate (NCA)		
HDPE PP	0.9352	0.575	0.9528
	Recycled Coarse Aggregate (RCA)		
HDPE PP	0.918	0.948	0.845

3.3 Morphological Analyses

The Fig 6 displayed below is from an examination of the wetting and spreading coefficient, which suffers from numerous unknown and many causes. Primarily the surface tension and interfacial tension lead to many errors if the temperature variation is not so accurate, secondly, the temperature with high melting points degrades the polymers & nanoparticles changing their surface properties, and even in high viscous polymers it has different crystallization and melting temperatures. Therefore, it is most important to analyze the morphological properties of HDPE and PP material and to interpretation of this material characterization.

The SEM images show the dispersion of HDPE and PP materials in M40 grade SCC. The majority of PP materials form in spherical droplets with an average radius of 4.3 +/- 1mm which is suspended as a matrix of polyolefin. Closer magnification of HDPE and PP revealed that it looks like a continuous microstructure. It is observed that it has two phases which are recognized by the different textures of fractured surfaces, as the HDPE material is more ductile and exhibits a corrugated texture because of localized yielding, similarly, PP material is very fragile and has a smooth surface and it is also visible in its appearance. Differentiating between both PP and HDPE material allows noticing droplets of PET which are embedded in the PP phase. It is also observed that the surface energy of PET when processing of high reactivity of ester linkage [26]. Future the morphological study observed that the HDPE and PP are in good agreement with the EF-SCC.

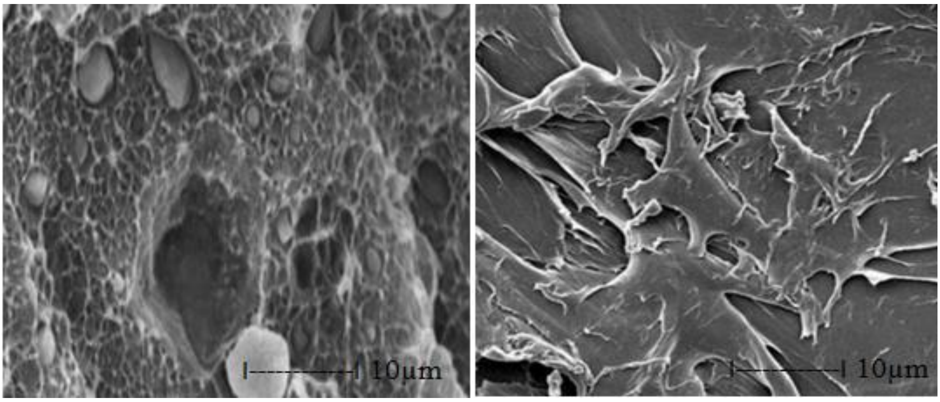

Fig. 6. SEM images (7.5% replacement) of a) HDPE b) PP. (The scan is 10μm)

3.4 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR analysis was carried out on all mixes with the highest amounts of HDPE and PP, following ASTM E168 and ASTM E1252 standards. This analysis helps identify significant chemical bonds in the materials. In the conventional concrete samples, a broad peak at 3445 cm^{-1} was detected, suggesting the presence of water bonds. There were also weaker peaks at 777.86 cm^{-1} and 693.43 cm^{-1}, indicating bending vibrations associated with the C-O bond.

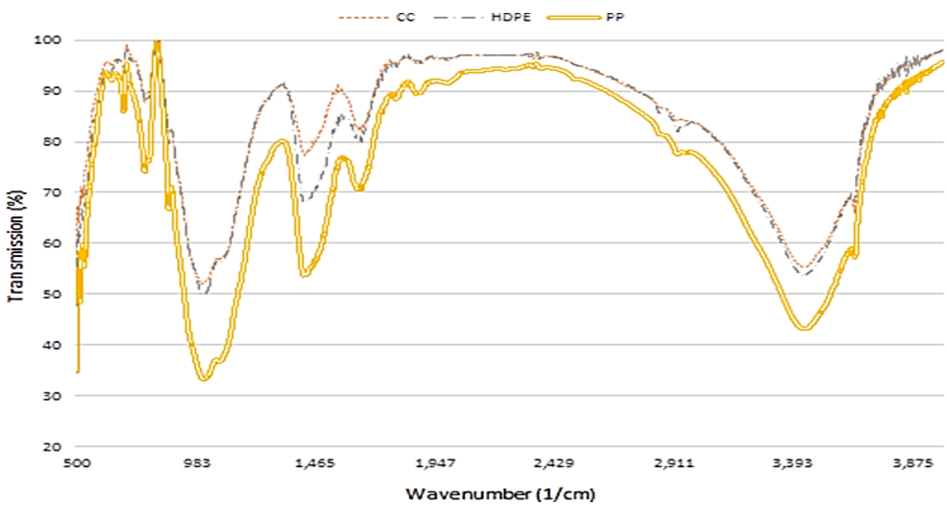

Fig. 7. FTIR analysis of conventional concrete, HDPE, and PP material

The broad peak at 1000 cm^{-1} indicates stretching of the Si-O-Si bond. In the HS24 sample, Si-H stretching is observed at 526.58 cm^{-1}, corresponding to the CO2 transmittance spectrum. A peak at 1016.04 cm^{-1} confirms the presence of the Si-O-Si bond, while the alkaline groups CH2 and CH3 are noted at 1427.19 cm^{-1}. The C=C stretching in aromatic groups appears at 1641.02 cm^{-1}, and a peak at 3443.94 cm^{-1} indicates the presence of OH and Si-OH bonds. Additionally, multiple stretching vibrations of OH can be seen at 3854.49 cm^{-1}. These same trends were also observed in the cement mixed with HDPE.

A new absorption bond is not noticed for cement mortar with HDPE and PP, which indicates that partial replacement of waste plastic does not alter the chemical bond of cement mortar significantly. Whereas a weak bond of OCH3 was noticed at 534.5 & 515.7 respectively. The above results state that the reduction in strength and heat evolution in concrete is due to the interaction between sand and cement interface or chemical effects or due to the mechanical properties but not due to the alternate reaction of waste plastic with cement or sand Phases.

4. Conclusion

The above materials HDPE and PP for different mechanical, durability, and thermal properties were evaluated.

- The workability of the EF-SCC is good compared to conventional concrete. When recycled coarse aggregate (RCA) was completely replaced with natural coarse aggregate (NCA) its workability in V funnel test slightly less.
- Both the materials HDPE and PP took 6sec to empty the v funnel with RCA in concrete which is the lowest of all the mixes. With NCA the difference with HDPE and PP material was approximately 0.4secs in each mix.
- The percentage weight loss when measured for concrete cubes of EF-SCC in acid attack, showed continues increase in its weight loss at all ages for both RCA and NCA.
- The sulphate attack test for RCA material with both HDPE and PP material showed same pattern. The difference in percentage weight loss at different ages was continuously decreasing till 28 days but at 56 days the percentage weight loss was again increased. The same pattern was even observed with NCA, but as much as RCA.
- The acid attack was observed less in PP compared to HDPE but as for sulphate attack the PP material has more impact.
- As the curing days increased to 28days the K value was less for PP material rather than HDPE material i.e., 0.71w/mk. But for NA concrete K value at 28 days is 1.1. Thermal conductivity observed at 14 days of curing is good at 100% RA concrete as well as 100% NA concrete.
- As the above results show the 100% RA can be used in EF-SCC which gives approximate equal values to NA in EF-SCC.
- The SEM images of the morphological study observed that the HDPE and PP are in good agreement with the EF-SCC.
- The FTIR results state that the reduction in strength and heat evolution in concrete is due to the interaction between sand and cement interface or chemical effects or due to the mechanical properties but not due to the alternate reaction of waste plastic with cement or sand Phases.

5. Further Studies

It is recommended to conduct microstructural properties, different thermal properties, and use of different waste plastics in different types, and different grades of concrete.

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