Strength, durability and microstructure of concrete made using waste electrical and electronic plastic as partial replacement for the natural aggregate in concrete

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ABSTRACT

Electronic waste (e-Waste) is the waste product derived from electrical and electronic equipment (EEE) which has reached its end of life. Although South Africa is one of the largest generators of e-Waste in Africa at 5.7 kg/inhabitant, only 11 % is recycled while a mere 25 % of the plastic fraction termed waste electrical and electronic plastic (WEEP) is recycled per annum. This is because WEEP contains a wide range of polymers and heavy elements at different stages of degradation. Thus, recycling WEEP as a replacement material for the natural aggregate in concrete can be advantageous.

This research aimed to produce structural concrete with a minimum compressive strength of 25 MPa at 28 days of curing while replacing both the coarse and fine natural aggregates simultaneously with different types of granulated WEEP in increments of 0 %, 5 %, 10 %, 20 % and 30 % by volume while maintaining a constant w:c ratio of 0.52. The paper reviews the material and mineralogical properties, microscopy analysis of hardened concrete, compressive and tensile splitting strength and durability.

Results showed that replacements of 30 % WEEP attained the minimum compressive strength requirements while achieving acceptable water sorptivity and oxygen permeability indices..

Keywords: Aggregate, concrete, durability, strength, waste electrical and electronic plastic.

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1. INTRODUCTION

South Africa is one of the largest generators of e-Waste in Africa at 5.7 kg/inhabitant/annum which is much compared to Africa's average e-Waste generation of 1.9 kg/inhabitant/annum [1]. More troubling is the fact that only 11 % of South Africa's annual e-Waste is recycled and that e-Waste volumes are expected to grow by 10 % per annum [2]. This growth rate is influenced by: social and economic development, increased consumer demand, perceived obsolescence and shorter replacement cycles among others (ibid). Electrical and electronic plastic (EEP) is the plastic fraction used for insulation, noise reduction, sealing, housing, structural parts and functional parts in electrical and electronic equipment (EEE) and contributes to on average 30 % by weight. The most common plastic types found in EEP include: acrylonitrile butadiene styrene (ABS), polypropylene (PP), polystyrene (PS), polycarbonate (PC) and polyurethane (PU) which represent more than 70 % of plastics found in EEE.

On the other hand, waste electrical and electronic plastic (WEEP) is the plastic fraction derived from EEP once it has reached its end of life. Sadly, the recycling of WEEP is very low at recycling percentages of less than 25 % per annum globally [3]. This may be due to the difficulties faced when recycling WEEP such as: numerous amounts of additives incorporated into EEP (cadmium, chlorine, antimony and brominated flame-retardant compounds), insufficient labelling of EEP according to its plastic type and the wide range of different types of resins used [4]. Furthermore, in both the use and recycling phase the polymers in EEP degrade resulting in plastics with unpredictable and insufficient properties [5]. As such, alternative methods must be investigated to utilise this problematic plastic waste.

One industry in which the use of WEEP is currently being considered, is in the construction sector. Previous studies have shown that the use of WEEP as a partial replacement for aggregates in concrete is possible. However, inconsistent or incomplete results were found in some literature. Lakshmi and Nagan conducted Studies on Concrete Containing e-Plastic Waste and found a significant decrease in the compressive strength of the control mix at 25 % replacement of the coarse natural aggregate with WEEP dropping from 19.8 MPa to 6.2 MPa [6]. Liu et al., investigated the Performance of Recycled Plastic-Based Concrete by replacing 20 % of the fine natural aggregate with PC/ABS WEEP and found a decrease in the compressive strength from 44.7 MPa to 28.6 MPa [7]. It is clear that although some research has been conducted on the use of WEEP as a replacement material for the natural aggregate, very little has been researched pertaining to the microscopy, strength and durability of concrete made using different types of WEEP as aggregate replacement material.

2. EXPERIMENTAL

2.1 Materials used

2.1.1 Binder material

This study used a high strength, rapid hardening ordinary Portland cement (CEM I 52.5 R) as a binder material. Tables 1 and 2 present the chemical oxide composition and characteristics of the cement.

The chemical oxide composition was determined by the author using a CAMECA SX5-FE electron probe micro analyser. The mean particle size was determined using an Anton Paar PSA 1190 particle size analyser while the specific density and surface were determined using a Pentrapyc 5200e gas pycnometer and NOVAtouch LX gas sorption analyser.

2.1.2 Admixture

The superplasticiser Sika®ViscoCrete®-3088 was used in this study which is chemically based on an aqueous solution of modified polycarboxylate ethers.

2.1.3 Aggregates

This study used both the fine and coarse (13.2mm) crushed natural aggregate as well as granulated WEEP. Granulated ABS, chemically blended PC and ABS (PC/ABS) and high impact polystyrene (HIPS) WEEP was bought from e-Waste recycling companies in Gauteng, South Africa. The granulated WEEP used had a maximum size of 6.7mm. Fig. 1 provides a sample representation of the granulated ABS, PC/ABS and HIPS WEEP used while Fig. 2 presents the images of the aggregates surface topography at 5 000 times magnification using a Carl Zeiss Sigma Field Emission Scanning Electron Microscope (FESEM).

Table 3 presents the chemicalcomposi-tions of all the different WEEP types used. The data was determined by the author using a CAMECA SX5-FE electron probe micro analyser. It is clear that ABS WEEP contained heavy elements in its polymeric matrix, namely: bromine (Br) and antimony (Sb), both of which are used as a flame retardant in EEP. Table 4 presents the particle density (SANS 5844), bulk density (SANS 5845), fineness modulus and dust content (SANS 1083) [8] [9] [10].

2.2 Concrete mix design

The mix design replaced both the coarse and fine natural aggregate simultaneously by volume in percentages of 5 %, 10 %, 20 % and 30 % with either ABS, PC/ABS, HIPS or an equal blend of WEEP in a ratio of 1:1:1 using a water:cement (w:c) ratio of 0.52 and a superplasticiser to maintain a slump of 80mm

Table 1: Chemical oxide composition of Portland cement.

Chemical oxide composition (%)	Al_2O_3	CaO	Fe_2O_3	MgO	SiO_2
	1.01	67.05	0.68	1.23	23.52

Table 2: Characteristics of Portland cement.

Characteristics of Portland cement	Mean particle size (μ)	Specific density (g/cc)	Specific surface (m^2/g)
	16.199	3.632	1.934

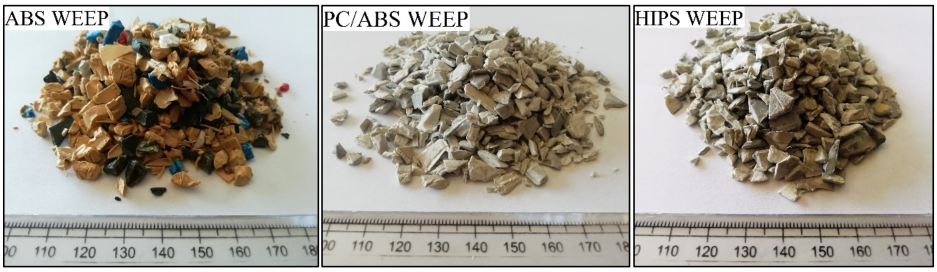

Figure 1: Granulated WEEP.

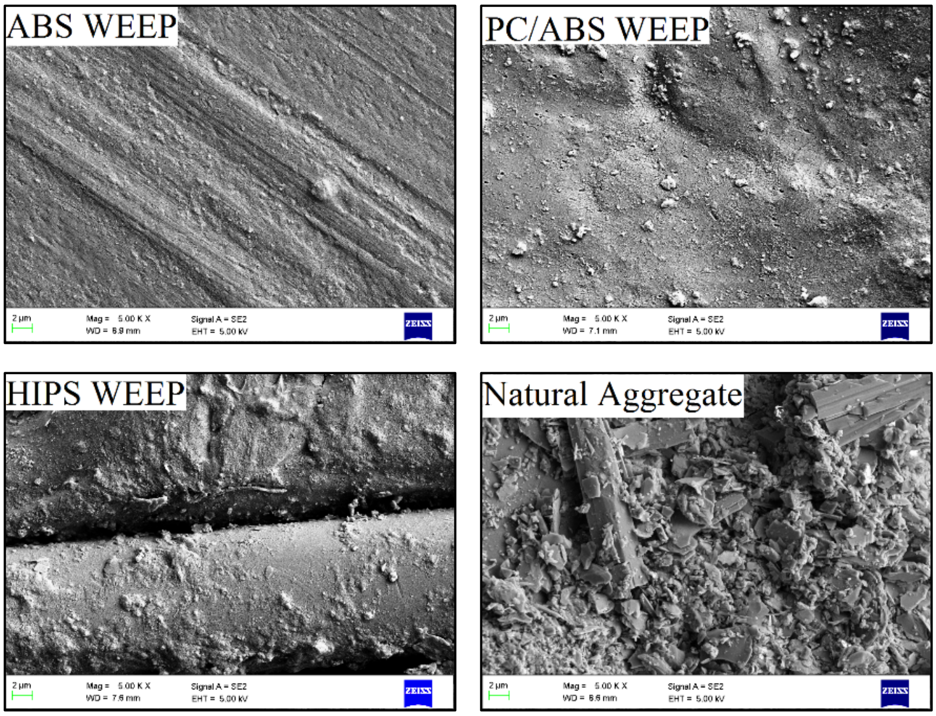

Figure 2: SEM imaging of the aggregates surface topography at 5 000 times magnification.

Table 3: Granulated WEEP elemental composition.

WEEP type	Normal weight (%) of elements						
	C	O	Cl	Br	Sb	N	Total
ABS	77.19	3.26	1.76	14.49	3.30	0.00	100
PC/ABS	91.65	1.03	0.00	0.00	0.00	7.33	100
HIPS	81.47	17.55	0.97	0.00	0.00	0.00	100

Table 4: Aggregate physical properties.

Physical properties	Stone	Sand	ABS	PC/ABS	HIPS
Particle density (kg/m^3)	2 890	2 580	940	1 190	1 390
Bulk density (kg/m^3)	1 660	2 060	520	580	580
Fineness modulus	-	3.4	-	-	-
Dust content (%)	2.1	8.3	-	-	-

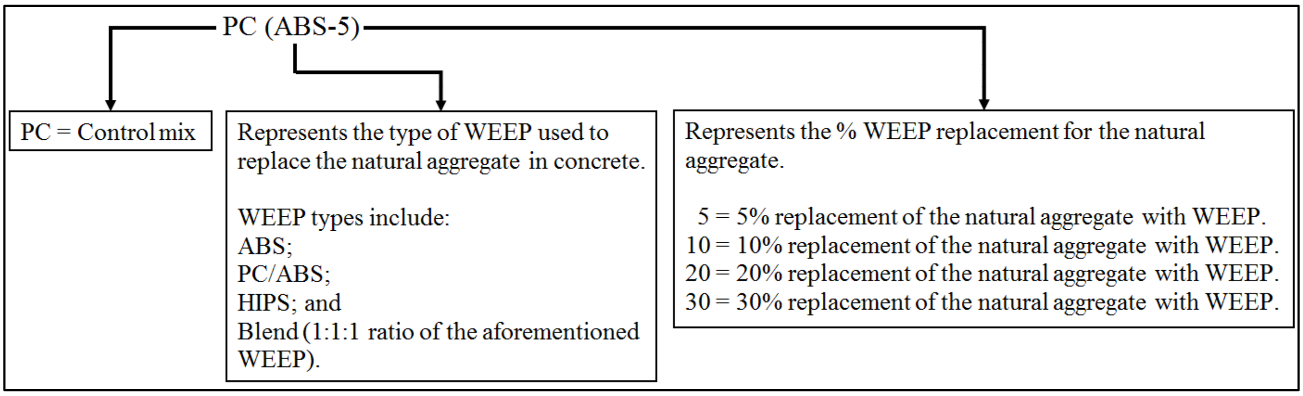

Figure 3 : Mix design acronyms and meanings.

Table 5: Mix design.

Mix design	Sand	Stone	WEEP	Water	Cement	Total mass	Super-plasticiser	Slump
	kg/m³						% cement	mm
PC (Control)	931	706	0			2 312	0.00	80
PC(ABS-5)	908	688	14			2 285	0.00	75
PC(ABS-10)	884	671	28			2 259	0.00	70
PC(ABS-20)	838	635	57			2 205	0.09	65
PC(ABS-30)	791	600	85			2 152	0.16	68
PC(PC/ABS-5)	908	688	18			2 292	0.00	80
PC(PC/ABS-10)	884	671	36			2 272	0.00	80
PC(PC/ABS-20)	838	635	72			2 232	0.00	55
PC(PC/ABS-30)	791	600	108	231	444	2 193	0.12	55
PC(HIPS-5)	908	688	21			2 289	0.00	75
PC(HIPS-10)	884	671	42			2 266	0.00	75
PC(HIPS-20)	838	635	84			2 220	0.04	60
PC(HIPS-30)	791	600	126			2 174	0.12	60
PC(Blend-5)	908	688	18			2 289	0.00	65
PC(Blend-10)	884	671	36			2 266	0.00	65
PC(Blend-20)	838	635	71			2 219	0.06	60
PC(Blend-30)	791	600	107			2 173	0.18	65

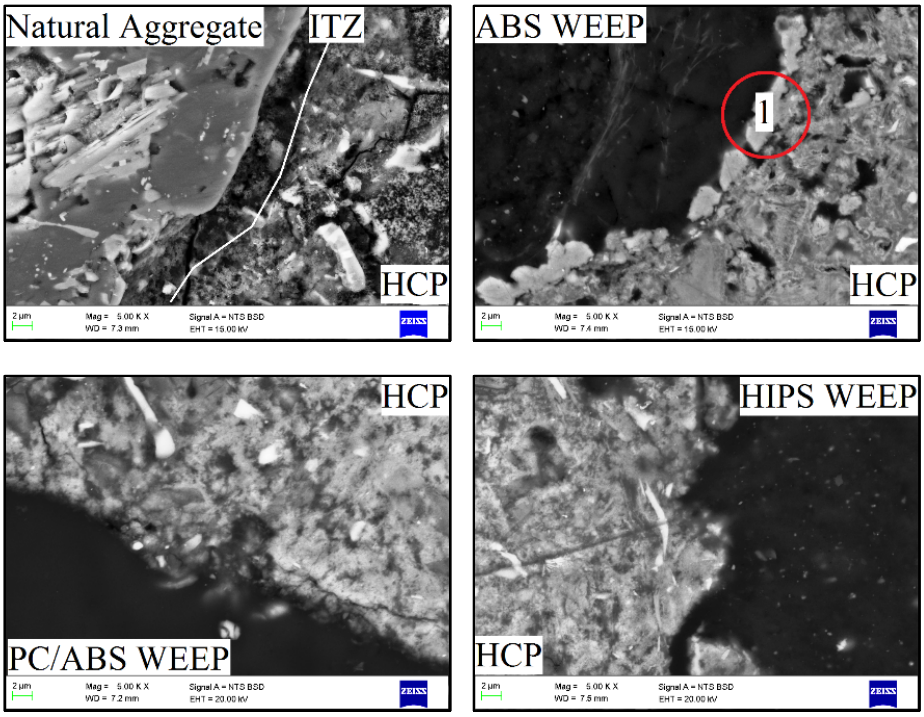

Figure 4: ITZ between aggregates used and the HCP.

± 25mm. Figure 3 describes the acronyms used to describe the mix designs presented in Table 5.

The natural aggregate and cement were added to a 50L pan mixer. In the use of WEEP as a replacement for the natural aggregate, WEEP was added before the stone. This was done to prevent the granulated WEEP from bouncing out of the pan during the initial mixing. The dry materials were mixed for approximately 2 - 3 minutes, after which the potable water was added.

The fresh concrete was mixed for approximately 2 - 3 minutes. A slump test was performed according to SANS 5862-1 [11]. If the mix did not have a slump of 80mm ± 25mm, a superplasticiser was added directly into the fresh concrete and mixed for 1 - 2 minutes. Once the desired slump was achieved, compaction was carried out using a vibrating table. Concrete cube moulds were filled with approximately one-third fresh concrete. They were then vibrated for approximately 5 - 8 seconds, after which they were filled with another third of the cube's volume and vibrated again.

It should be noted that replacing 30 % of the natural aggregate with different types of WEEP by volume will vary the overall density of the mix design. This is because WEEP have different particle size densities as shown in Table 4.

2.3 Interfacial transition zone

The interfacial transition zone (ITZ) is often the weak link in concrete and is formed during compaction of fresh concrete whereby a film of water forms around the aggregate, leading to higher w:c ratios close around the aggregate [12]. Fig. 4 provides imaging of the ITZ between the natural aggregate in PC (Control) and WEEP in PC(Blend-30) at 5 000 times magnification. The ITZ is noticeable by the clear dark-sheath band between the natural aggregate and hardened cementitious paste (HCP) for PC (Control). Between the ABS WEEP and HCP there were numerous

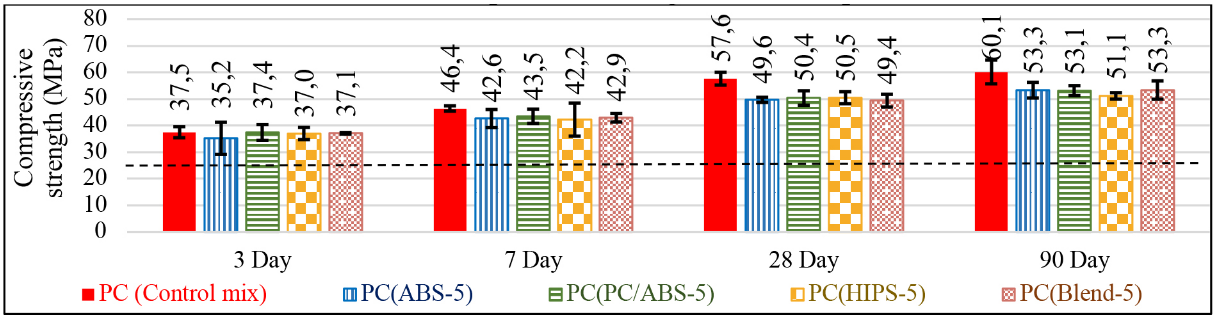

Figure 5: Compressive strength results at 3, 7, 28 and 90 days curing at 5% replacement.

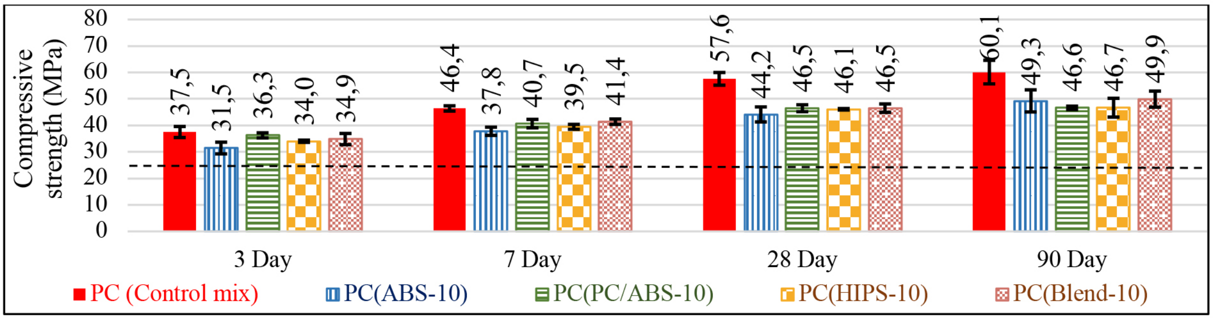

Figure 6: Compressive strength results at 3, 7, 28 and 90 days curing at 10% replacement.

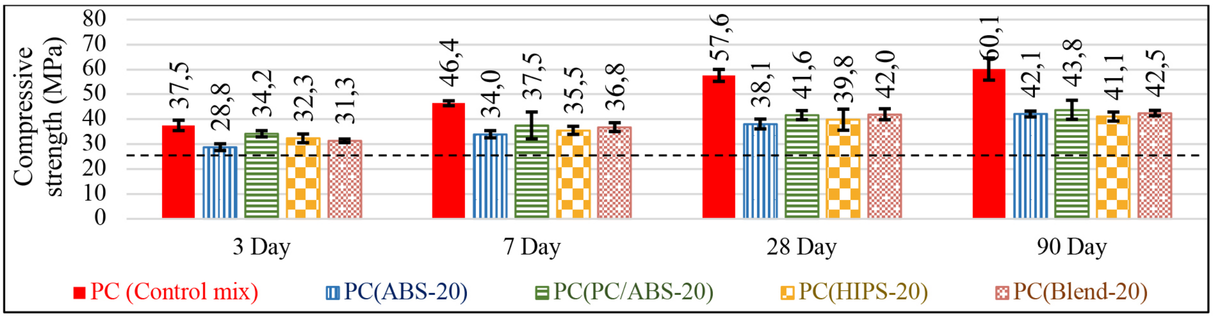

Figure 7: Compressive strength results at 3, 7, 28 and 90 days curing at 20% replacement.

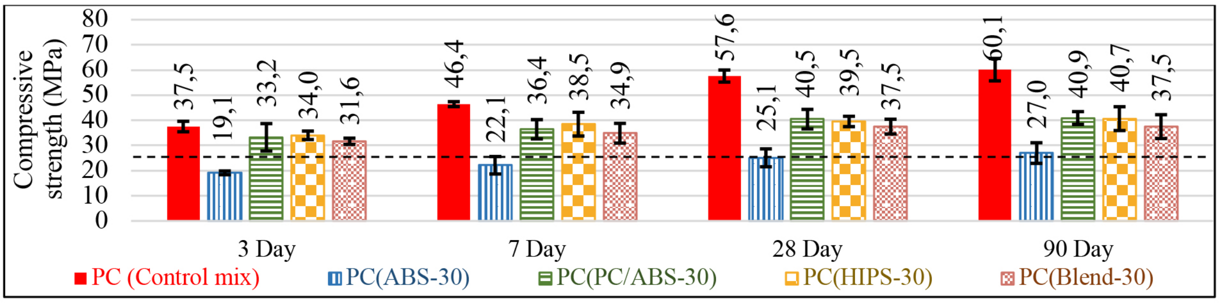

Figure 8: Compressive strength results at 3, 7, 28 and 90 days curing at 30% replacement.

crystal formations as indicated by "1". These crystals were formed during the hydration process, whereby calcium hydroxide (CH) formed between the aggregate and bulk paste when critical saturation was reached due to the dissolution of calcium silicate, forming calcium and hydroxyl ions. CH grew into very large plate-like crystals due to the excess water around the aggregate producing a more porous system. As the hydration process continued these pores were filled with poorly crystallised calcium silicate hydrates, small crystals of ettringite and CH formed between the framework [12].

3. RESULTS AND DISCUSSION

3.1 Hardened concrete properties

Concrete cubes of size 100 x 100 x 100 mm were cast for both the compressive and durability tests. Concrete cylinders of size of 150 x 300 mm were cast for the tensile splitting strength tests. The specimens were water cured at a temperature of 23°C ± 2. The compressive strength tests were performed at 3, 7, 28 and 90 days at 0 %, 5 %, 10 %, 20 % and 30 % WEEP replacements while the tensile splitting strength and durability tests were performed at 28 days at 30 % WEEP replacement.

3.1.1 Compressive strength results

The concrete cubes were tested per SANS 5863[13]. The cubes were loaded using a cube press-foote machine which had a maximum loading capacity of 1 000kN. Fig. 5-8 compares the average compressive strengths of PC (Control mix) at different ages of curing, types of WEEP and percentage replacement levels.

The compressive strength of the mixtures containing WEEP were observed to decrease as the percentage of substitution increased. Furthermore, it is interesting to note that there was little difference in the compressive strength of concrete made with WEEP at 20

% replacement. However, there was a large drop in strength for concrete made using ABS WEEP at 30 % replacement.

Furthermore, it was found that replacements of 30 % ABS WEEP continued to significantly reduce the compressive strength of PC (Control mix) by 55.1 %, Blend WEEP by 37.7 %, HIPS WEEP by 32.4 % and PC/ABS WEEP by 32.0 %. This could be a result of the crystal formation between the ABS WEEP and HCP reducing the bond between the HCP and ABS WEEP which in turn reduced the compressive strength more compared to other mixes.

3.1.2 Tensile splitting strength results

The tensile splitting strength test was conducted according to SANS 6256 [14]. The cylinders were loaded using an Amsler machine which has a maximum loading capacity of 2 000kN. The tensile splitting strength test results are presented in Fig. 9. It was observed that the tensile splitting strength of concrete made without WEEP replacement had a higher tensile splitting strength compared to concrete made with WEEP replacement.

There was little difference in the average tensile splitting strength between substitutions of HIPS or Blend WEEP. As with the average compressive strength of concrete,

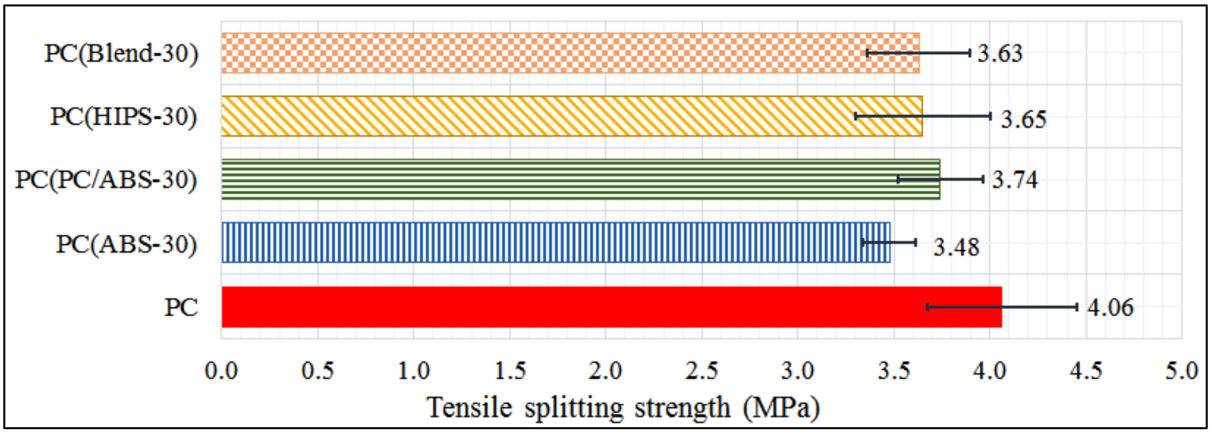

Figure 9: Tensile splitting strength results at 28 days.

Table 6: Suggested ranges for the durability of concrete [15].

Durability class	OPI (log scale)	Sorptivity (mm/√h)	Chloride conductivity (mS/cm)
Excellent	> 10	< 6	< 0.75
Good	9.5 - 10	6 - 10	0.75 - 1.50
Poor	9.0 - 9.5	10 - 15	1.50 - 2.50
Very poor	< 9	> 15	> 2.50

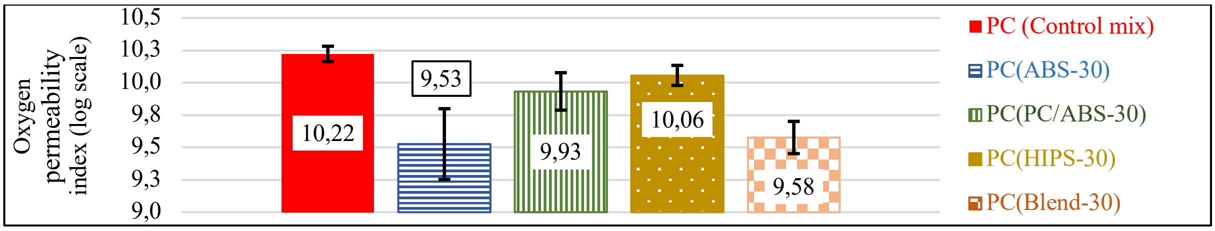

Figure 10: OPI for concrete containing no WEEP and containing 30% WEEP.

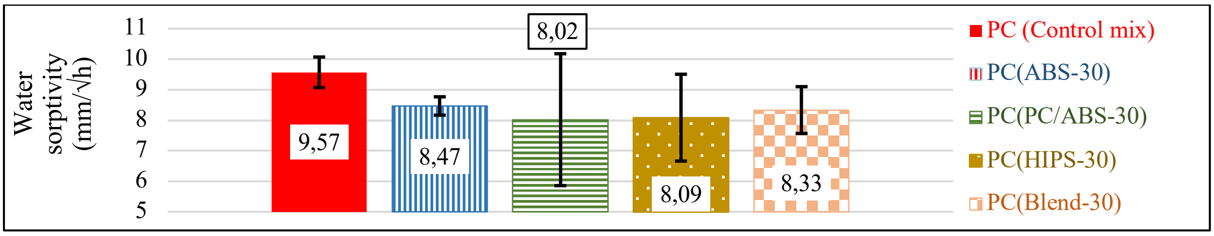

Figure 11: Water sorptivity for concrete containing no WEEP and containing 30% WEEP.

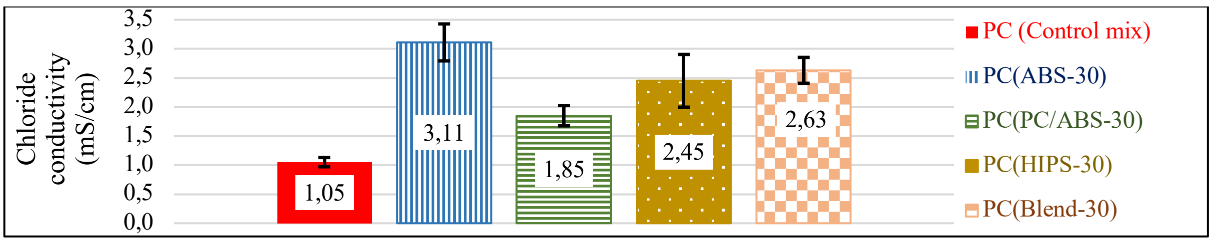

Figure 12: Chloride conductivity for concrete containing no WEEP and containing 30% WEEP.

replacements with ABS WEEP yielded the lowest average tensile splitting strength results.

Here it is clear that ABS WEEP substitution decreased the average tensile splitting strength of concrete mixed with ABS WEEP the most at 14.4 %, followed by Blend WEEP at 10.7 %, HIPS WEEP at 10.2 % and PC/ABS WEEP at 7.9 %.

3.2 DURABILITY OF CONCRETE

3.2.1 Concrete durability indices

The durability of concrete in South Africa can be measured by the oxygen permeability index, water sorptivity and porosity, and chloride conductivity tests and should meet the acceptable limits for durability indexes [15], as presented in Table 6.

3.2.2 Oxygen permeability index

The oxygen permeability index (OPI) test was conducted according to SANS 3001-CO3-2 [16]. The average OPI results are graphically illustrated in Fig.10. All mixes had average OPI-values > 9.5, indicating a good durability class.

3.3.3 Water sorptivity

The water sorptivity test was conducted in accordance with the Durability Index Manual [17]. The average water sorptivity results are shown in Fig 11. It was observed that the water sorptivity decreased with an increase in WEEP replacements. This indicated that the overall durability class increased for the majority of concretes made using WEEP.

3.3.4 Chloride conductivity

The chloride conductivity test was conducted according to SANS 3001-CO3-3 [18]. The average water sorptivity results are graphically presented in Fig 12. Results clearly show that ABS WEEP had the overall highest chloride and is classified as having poor durability.

4. CONCLUSIONS

The increase in EEE has resulted in vast quantities of WEEP discarded with no intention of re-use. This study has confirmed that ABS, PC/ABS, HIPS and an equal combination of the aforementioned WEEP can be used to partially replace both fine and coarse aggregates up to 30 % and attain the minimum compressive strength requirements for structural concrete (> 25 MPa) at 28 days. Replacement of WEEP for the natural aggregate reduced the compressive strength of concrete at 28 and 90 days while replacements of 30 % ABS WEEP significantly decreased the compressive and tensile splitting strength of concrete the most. Concrete made using WEEP at 30 % replacement for the natural aggregate had a good or higher durability result in the OPI and water sorptivity tests but poor or lower durability result in the chloride conductivity test. **CB**

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