

Abrasion-wear resistance of precarbonated and water-cured concrete made using ABS plastic derived from waste electrical and electronic equipment

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ABSTRACT

Due to the fast proliferation of electrical and electronic equipment (PCs, TVs, and cell phones, among others), the disposal of plastic waste, such as acrylonitrile butadiene styrene derived from discarded electrical and electronic equipment (e-Waste), is becoming a big issue. This paper addresses this subject by utilising granulated ABS as an aggregate replacement material in concrete. The compressive strength and abrasion resistance of granulated ABS derived from electronic waste in concrete were evaluated in different replacement intervals (0 %, 5 %, 10 %, 25 %, 50 %, 75 %, and 100 %). The current investigation included microstructural and morphological characterisation utilising scanning electron microscopy and X-ray diffraction pattern analysis. It was found that increasing the replacements of granulated ABS for the natural aggregate reduced concrete's workability, strength, and abrasion resistance. To compensate for the loss in strength and abrasion wear resistance, mixes were subjected to a precarbonation curing regime to densify the microstructure of the cementitious paste.

1. Introduction

Acrylonitrile-butadiene-styrene (ABS) is an engineering thermoplastic that consists of a glassy styrene and acrylonitrile resin, which forms part of the continuous phase, while the fine rubber butadiene forms part of the dispersed phase [1,2]. ABS comprises of 21 % to 27 % acrylonitrile, 12 % to 25 % butadiene and 54 % to 63 % styrene [3] and is often used in the automotive, and electrical and electronic equipment (EEE) industries [4].

ABS plastic, derived from Waste Electrical and Electronic Equipment (WEEE), termed ABS waste EEE plastic (ABS WEEEP), frequently has little or no monetary value depending on its state (mixed or separated) [5]. This is because ABS WEEEP often contains additives such as flame retardants (FRs), which prevent or slow the spread of fire. It is known that 90 % of the global production of flame retardants is used in EEE plastic [6], while some halogenated FRs contain bromine (Br) and antimony. These FRs are not covalently bonded but rather seeded in the polymeric structure, enabling the FR to migrate into the environment [7]. There are two main potential recycling routes for waste plastics such as WEEEP, namely physical and chemical [8].

Chemical recycling produces new raw materials by changing the chemical structure of recycled plastic, which can be achieved through

feedstock or energy recovery. According to Garforth et al. [9], feedstock recycling generally entails a process in which waste polymers are converted to their original monomers through either depolymerisation, partial oxidation or cracking (pyrolysis). Depolymerisation is limited to condensation polymers, which essentially entails depolymerising plastics back into initial diacids, dial or diamines using depolymerisation reactions, such as alcoholyses, glycolysis and hydrolysis [10]. Depending on the plastic composition, partial oxidation is a gasification process similar to direct combustion (burning of plastic) of polymer waste, but with more environmentally friendly technologies that use oxygen or steam to decompose plastics into hydrocarbons or synthesis gas. Lastly, cracking: hydro-thermal-catalytic processes involve the reaction of hydrogen over a catalyst using moderate temperatures and pressures (423 to 673 K and 3 to 10 MPa) to break the polymer chains down into lower molecular weight compounds [9]. One advantage of this process includes the potential removal of bromine from the slag, which can be reused and essentially close the bromine lifecycle loop [11]. On the other hand, the quality and organobromine pollutants remaining in oils require effective dehalogenation [12]. Although these processes could treat WEEEP, they are often only economically viable in large volumes [8]. Moreover, Achilias and Antonakou [13] state that plastics derived from feedstock recycling, such as polycarbonate, are often less resilient and have lower impact resistance than virgin polycarbonate. If the

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Nomenclature

ABS	Acrylonitrile-butadiene-styrene
ASTM	American Society for Testing and Materials
AWR	Abrasion-wear resistance
BSE	Backscattered Electron
CH	Calcium Hydroxide
CoV	Coefficient of Variance
CSH	Calcium Silicate Hydrate
HCP	Hardened Cementitious Paste
ITZ	Interfacial Transitions Zone
PCAR	Precarbonation
SANS	South African National Standards
SEM	Scanning Electron Microscope
SD	Standard Deviation
WC	Water Cured
w/c	Water-to-cement ratio
WEEEP	Waste Electrical and Electronic Plastic

plastic cannot be recycled, the last alternative could be energy recovery, whereby landfilling should be avoided at all costs [8] due to the poor biodegradability of plastics, generation of explosive greenhouse gases and legislative pressures [12]. Energy recovery is a process that uses the chemical energy from plastics to produce heat. The process requires sophisticated pollution control measures to prevent the release of toxins such as polybrominated dibenzo-p-dioxins and furans into the atmosphere. The presence of brominated flame retardants (BFRs) in plastics may also reduce the degree of energy released through combustion and thereby reduce the system's energy efficiency [14].

Mechanical recycling does not remove additives from the plastic but instead converts it into a manageable, clean fraction which can be used on its own or blended with virgin material. It does not remove chemical contaminants or additives such as BFRs, which can remain in the material after reprocessing and, therefore, be reintroduced into the new plastic product [15]. The process of mechanical recycling can be simplified into four steps. The mixed plastic should first be sorted into its relevant plastic type. Although this step is not entirely necessary, as the processing of mixed plastics reduces cost, it inadvertently results in lower mechanical and aesthetic properties of the final plastic [3]. Sorting can be done through manual labour, density, optical, spectroscopic or electrostatic separations, as mentioned by Merrington [16]. Thereafter, the plastic is washed and dried in the second step to remove any contamination and moisture. The third step involves the granulating of the plastic into smaller fractions, followed by the last step involving granulation with melt filtration to produce sizable pellets [8]. Mantia [17] proposed two main stages of degradation during the plastic life-cycle, which may influence the quality of the final recycled product. These include the degree of environmental exposure (oxidation and thermal, which aid in forming oxygenated groups and chain scission) and thermal-mechanical degradation during recycling. Thermal-mechanical degradation occurs during heating and mechanical shearing, promoting free radical formation. In this stage, the plastic undergoes a chemical reaction termed dipropionate, which promotes the scission of the carbon-carbon covalent bonds in the polymer backbone. This, in turn, results in both chain scission and chain branching, which has the potential to change the rheological and mechanical behaviour of the plastic [18].

Adding complexity to mechanical recycling, not all plastics will have the same melting temperature due to their relevant degradation and additives. This may lead to overheating some plastics, further degrading them and reducing their final properties. Lastly, processing difficulties may also arise due to coatings or paints on the plastic, which may not be wholly soluble and may even induce phase separation in some mixes [8].

Stenvall [19] reported that recycled ABS and HIPS by mechanical recycling often have higher stiffness and yield stress but lower elongation than their virgin counterparts. Alternatively, solvent-based technology developed by Fraunhofer IVV and CreaCycle GmbH has produced a product termed CreaSolv®, which alters the phase of a polymer and can, therefore, remove non-polymeric material such as BFR from styrenetic polymers. In brief, the process entails dissolving styrenetic polymers such as polystyrene and filtering them through a 400 µm sieve. The dissolved solution is precipitated in a stirred reactor, separating the dissolved contaminants from the precipitated polymer. Here, the extract may be subjected to solvent recovery, either disposed of or sent for Br recovery, while the polymer phase is further processed to remove the solvent [20]. Nevertheless, the processes involved in adding and then removing solvents are energy and time-consuming, while any solvent left behind has the potential to affect the polymer's properties. Lastly, dissolution yields a crystallised polymer that requires upgrading to obtain virgin-grade quality [21]. As mechanical recycling degrades the polymer or plastic while unable to remove harmful brominated additives and dissolution requires material to be subjected to numerous treatments, other recycling avenues should be explored.

While blending waste ABS into virgin plastic might be a popular route several manufacturers use to reduce the cost of their products, many EEE manufacturers would instead guarantee the quality of their products by using virgin ABS [22,23], as ABS waste may contain a variety of additives at various stages of degradation [17]. Then again, research by Lydall et al. [5] has shown that some plastic manufacturers have blended ABS WEEEP into products that do not require fire protection, such as building tools, wheelbarrow wheels and piping, among others. Although the ABS WEEEP is downcycled, the BFR remains in the plastic and complicates recycling should the plastic be recycled or downcycled [15]. This has resulted in complications in the plastic recycling industry where food contact and children's toys are contaminated, where BFRs have been detected in bird's eggs and human breast milk in South Africa [24]. These FRs are considered neurotoxins, endocrine disruptors and carcinogenic [7]. Then again, concrete may provide a safer way of sequestering such harmful waste materials when used as aggregate in concrete.

Previous research often used small quantities of WEEE plastic (WEEEP) ($\leq 50\%$ replacement of either the coarse or fine natural aggregate) in concrete due to the poor bonding between the aggregate and paste caused by the smooth surface associated with WEEEP [25]. Furthermore, most studies use a random mix of WEEEP types in various ratios of nominal size [26–30]. A study by Nwaubani and Parsons [31] concluded that structural concrete (characteristic strength ≥ 25 MPa at 28-days curing) made using ABS WEEEP replacement in concrete reduced the compressive and tensile strength and durability performance (oxygen permeability, water sorptivity and chloride conductivity indexes).

Another aspect of concrete durability is related to its abrasion-wear resistance (AWR) and, thus, its ability to resist erosion due to mechanical degradation [32]. AWR is a natural attack on concrete that can lead to other forms of deterioration, such as cracking and corrosion of reinforcing steel. Furthermore, excessive abrasion can altogether remove concrete from structural elements [33]. Most codes only provide AWR indexes as a measure of surface quality rather than the expected life of a structure. As a result, abrasion-wear resistance is often assumed adequate based on the compressive strength alone due to their respective negative linear relationship (an increase in compressive strength leads to a decrease in AWR) [34–36]. Although this is true to some extent as compressive strength depends on the aggregate's physical property [34], abrasion-wear resistance is a surface attribute. Attention should be given to different surface finishes, toppings and surface treatments (various epoxies, polyurethanes, acrylics and rubber-based solvents) [33,34,37,38].

Although very little information is available on the abrasion-wear resistance of concrete made using WEEEP, much literature exists on

the use of waste tyre rubber (WTR) and polyethylene terephthalate (PET) as aggregate in concrete. For example, a study by Ullah et al. [39] showed a 25.58 % reduction in abrasion-wear (improved durability) of concrete made using a w/c of 0.5 and 20 % replacements of the fine natural aggregate with melted ABS WEEEP. Alternatively, Abdelmonem et al. [40] showed a higher abrasion-wear (reduced durability) for concrete using WTR as a partial replacement for the fine aggregate. Using a w/c of 0.3, the AWR increased from 0.15 % weight loss for the control to 0.25 % at 15 % WTR replacements. This is contradictory to a study by Thomas and Gupta [41], which showed a 32.39 % improvement in AWR, reducing from 1.42 mm for the control to 0.96 mm for 20 % WTR replacements. Then again, Jingfu et al. [42] showed a 116 % increase in AWR (improved durability) when replacing coarse aggregate with 15 % WTR. A similar result of improved durability performance was observed from a study by Saxena et al. [43], which found that 20 % polyethylene terephthalate replacement for the coarse aggregate increased AWR from 0.42 mm for the control mix to 0.23 mm.

Considering the aforementioned studies, it is generally accepted that hard aggregates protect the softer paste from premature abrasion-wear, provided that the aggregate-paste bond is strong enough to hold the aggregate securely during abrasion [38]. The abrasion-wear resistance of most aggregates is higher than the hardened cementitious paste, and therefore, the hardness of the aggregate often dictates the hardness of the concrete. However, ABS WEEEP is generally softer than the natural aggregate used in normal-weight concrete and may thus be susceptible to premature wear and removal from concrete due to abrasion-wear during its service life. Furthermore, the aggregate-paste bond is a function of the aggregate physical characteristics (texture, shape, grading and soundness) [44] and the paste strength (binder type and microstructure, such as the pore size and pore distribution in the paste and interfacial transition zone (ITZ)). The ITZ is often considered the third phase in concrete and is the weak link that exists between the two phases of aggregate and bulk paste [45]. A study by Lucas [46] suggests that abrasion resistance is lower in the ITZ compared to the bulk paste [47]. Research by Scrivener et al. [48] suggests a refinement of the ITZ can improve the abrasion resistance of concrete. One way to refine the microstructure of concrete can be found by reducing the original water content, while another can be done by densifying the microstructure of the hardened cementitious paste using an accelerated carbon curing technique termed precarbonation (or early carbonation).

Precarbonation (PCAR) curing is a method of curing by exposing fresh concrete (< 24 h after casting) to a carbon dioxide (CO₂) gas-rich environment under low pressure [49]. During PCAR curing, the CO₂ gas reacts with unhydrated cement compounds (such as tricalcium silicate and dicalcium silicate) and hydrate products such as calcium silicate hydrate (CSH) and calcium hydroxide to produce secondary CSH gel and calcium carbonate (CaCO₃) crystals, which are binding materials that densify the pore structure of the hardened concrete [50]. X-ray diffraction (XRD) is extensively used for quantifying and identifying cement-based materials that evolve due to carbonation reactions [51].

There is presently very little information available on the AWR of concrete made using granulated ABS WEEEP, the use of the PCAR curing regime to increase the AWR of concrete made using ABS WEEEP, the relationship (if any) between the AWR of concrete made using ABS WEEEP and pore size and distribution at the ITZ for concrete subjected to PCAR curing or the strength and AWR for concrete made using 100 % ABS WEEEP as a replacement for the coarse natural aggregate in concrete. Accordingly, further studies are required to address the aforementioned gaps in knowledge.

This study only assessed concrete's mechanical (compressive strength) and durability (AWR) performance using ABS WEEEP since ABS is one of the most common plastic types used in EEE (generally constitutes 80 % of telecoms, 70 % of toys and 50 % of computer hardware) and produces concrete with lowest strength than high-impact polystyrene or polycarbonate-ABS copolymers [31]. The experimental study was limited to replacements of the coarse aggregate (as it

Table 1

Oxide composition of cement obtained through WDS analysis.

Oxide	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO
%	22.57	66.33	4.82	2.72	1.58	1.81

contributes to the largest fraction of concrete) and to reduce the effort of mechanically grinding, thus reducing the processing costs [52]. ABS WEEEP was granulated to match the grading curve of the natural coarse aggregate. Granulated ABS WEEEP (referred to as ABS WEEEP from here on out) replaced the natural aggregate in different proportions (0 %, 5 %, 10 %, 25 %, 50 %, 75 % and 100 % by volume). Lastly, only one water-to-cement ratio (w/c) of 0.6 was used to achieve a medium spread of 405 ± 25 mm, which was required to achieve medium workability [40]. All concrete mixes were subjected to either water curing alone or PCAR, followed by water curing. An analysis of the fresh and hardened properties of concrete was performance, which included the spread, setting time, compressive strength, and AWR. In an attempt to understand observations made for macroscopic test observations, morphological and mineral characterisations of representative specimens were made through XRD and scanning electron microscopy analysis.

2. Materials used

The materials used section covers a wide range of chemical, mineralogical and physical tests performed on either the binder or aggregate. These tests are important as they aid in the reproducibility of results presented in this paper and are used to link the behaviour of fresh and hardened concrete properties.

2.1. Binder material chemical, mineralogical and physical properties

A high-strength rapid hardening Portland cement (CEM I 52.5R) was used as binder material due to the adverse effect of ABS WEEEP substitution on concrete's mechanical and durability performance. The cement was sampled from freshly opened 50 kg bags using a stainless steel scoop. The following subsections will present the cement oxide and mineralogical composition and physical properties.

2.1.1. Oxide composition of cement

The anhydrous cement powder oxide composition was qualitatively determined using wavelength dispersive X-ray spectroscopy (WDS) using a CAMECA SX5-FE electron probe microanalyser, which yielded the results shown in Table 1, which fall within the suggested range for cement [44,53,54].

2.1.2. Mineralogical composition (X-ray diffraction)

A Bruker D2-Phaser bench-top diffractometer using Cu-K_α radiation ($\lambda = 1.5418 \text{ \AA}$) over a 2θ range of 10 to 70° in steps of 0.01° 2θ was used to identify the crystalline phases of anhydrous cement powder. Fig. 1 shows that the tricalcium silicate and dicalcium silicate crystals produced the highest intensity peaks, followed by smaller peak intensities for tetracalcium aluminoferrite, tricalcium aluminate, magnesium oxide and gypsum.

2.1.3. Particle size distribution curve of cement

LASER diffraction spectrometry is one of the most popular methods to analyse the particle size and distribution of powders used in civil engineering laboratories due to its simplicity, wide range of particle sizes (0.1 to 2500 μm [55]) and excellent repeatability of the results obtained [56,57]. The cement's average particle size distribution curve from three consecutive tests is presented in Fig. 2, which was measured by LASER diffraction using an Anton Paar PSA1190 particle size analyser conforming to American Society for Testing and Materials (ASTM) E3340 [58] and ISO 13320 [55,59].

This study sampled 40 g of dry, anhydrous cement powder directly

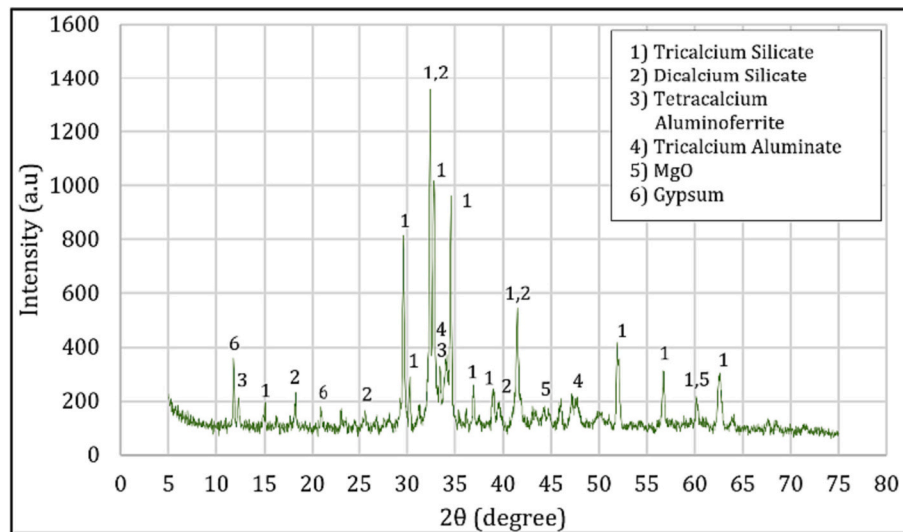


Fig. 1. Diffractogram of anhydrous cement powder.

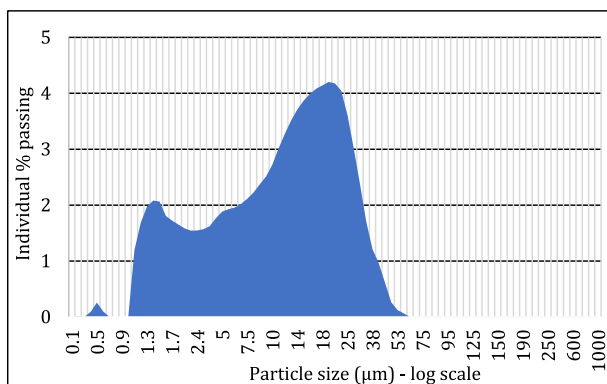


Fig. 2. Average particle size distribution of anhydrous cement powder.

from a 50 kg sealed bag using a small scoop. The instrument used a dry dispersion, venturi free fall setup using a vibrating tray (hopper) set at a frequency of 50 Hz to disperse the particles and a compressor set at 500 mBar to circulate the air into a vacuum bag and thus never remeasures the same group of particles. A collimated LASER was directed into the dispersed cement for 10 s, causing the light to diffract over various angles. The angular distribution of the intensity of the scattered light by the cement particle depended on its respective size [59]. A Fourier transformation lens focused the diffracted light onto a detector, which converted the incident energy into electric signals [56]. A computer was used to store and process the data using Kalliope™ software based on the Mie theory to analyse the scattering patterns produced. The Mie theory converts the measured scattering patterns into particle size distributions while taking into account various parameters, including the particle size, shape, and refractive index, as well as the wavelength of the incident light (contained within the software) to accurately interpret the scattering patterns produced and obtain reliable particle size information [56].

It was noted that the cement used was relatively coarser than Nwaubani and Parsons' previous results [31], and other researchers who using similar binders [60]. Even so, the cement was well-graded (contains a wide range of particle sizes), which effectively increases the packing density of the system and reduces the overall water demand [61] since less water is required to fill the voids in the cement before it contributes to flow [62].

The largest particle size was measured at 56 μm , suggesting that all of

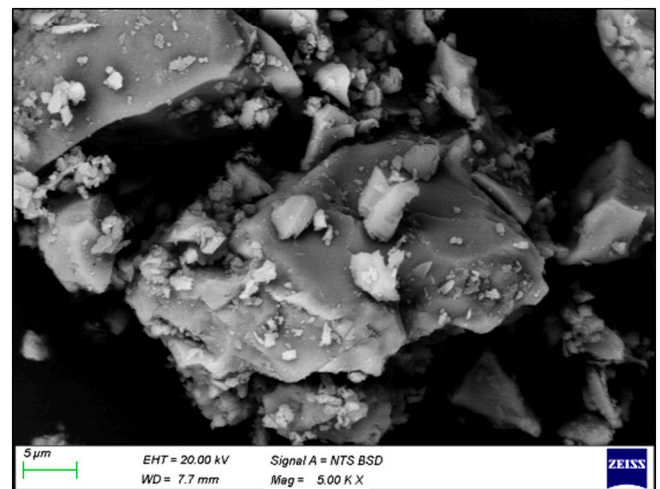


Fig. 3. Topography of cement at 5 K magnification.

the material should participate in hydration as larger particles ($> 60 \mu\text{m}$) generally only have a filling effect [63]. Particles below $3 \mu\text{m}$ contribute to 1-day compressive strength, while particles between 3 and $25 \mu\text{m}$ contribute to 28-day compressive strength [64]. Results show that 72.53 % of the particles range between 3 and $30 \mu\text{m}$ and have a mean size of $13 \mu\text{m}$.

2.1.4. Topography of cement powder

Sampled cement was placed onto carbon tape, which was adhered to an aluminium stub and coated with 10 nm gold-palladium and 30 nm carbon layers. A Carl Zeiss Sigma field emission scanning electron microscope was used to study the surface topography of cement, as shown in Fig. 3. The image partially represents the results found for the particle size distribution in Fig. 2. This, in turn, provides a clearer understanding of the results obtained by visually comparing the different particles in one image. In the photomicrograph, it is clear that the particles are irregularly shaped, if not angular or platy. It is observed that most of the cement particles range in size from <1 and $50 \mu\text{m}$.

2.1.5. Specific gravity of powder cement

The specific gravity (SG) of the cement can influence the degree of bleeding that occurs in fresh concrete, as dense cement particles often

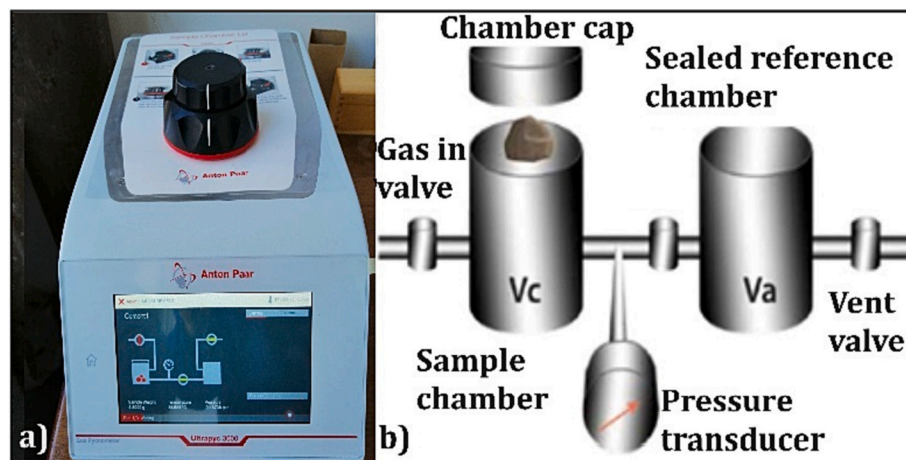


Fig. 4. Ultrapyc 3000 gas pycnometer used (a) principal of operation (b) (adapted from Quantachrome [68]).

tend to segregate to the bottom while the water migrates to the top [65]. The cement-specific gravity of hydraulic cement can be measured using ASTM C188 [66] or a gas pycnometer, which is based on measuring a liquid's displaced volume by adding a powder specimen. The SG measured by ASTM C188 involves the addition of cement and kerosene to a Le Chatelier flask of known mass and set dimensions, at a controlled temperature variation of <0.2 °C during the test. The density is measured by dividing the measured mass of cement over the displaced volume of kerosene. On the other hand, a gas pycnometer is based on principles similar to ASTM C188 but operates on the principle of gas volume displacement. The gas pycnometer method is considered more accurate at determining cement's hydraulic density than ASTM C188, which is subjected to operator error and requires the safe handling and disposal of materials [67].

This study used an Anton Paar Ultrapyc 3000 helium gas pycnometer, as shown in Fig. 4 (a), to determine the cement-specific gravity. Here, the expansion valve opened, allowing the helium gas to expand into the sealed reference chamber. Once stabilised, the change in pressure was recorded and compared to the original set pressure, as shown in Fig. 4 (b).

A sample of 2.5 g was analysed using pure chemical helium gas at a temperature of 14.616 °C. The average measurement from three tests showed that the cement used had an average SG of 3.35 g/cm³, with a standard deviation (SD) of 0.001 % and a coefficient of variance (CoV) of 0.034 %. The measured SG is slightly higher than recommended for CEM I 52.5R of 2.95 to 3.20 g/cm³ [69], but lower than 3.63 g/cm³ measured by Anton Paar using a Pentrapyc 5200e in a study conducted by Teggin and Nwaubani [70] using the same cement type and supplier. Even so, the test was redone a few months later (after completion of the results presented in this study), which showed cement had an average SG of 3.10 g/cm³ with a SD of 0.004 % and a CoV of 0.103 %. The cement manufacturer shared their results with the authors at a later date, which measured an average SG of 3.17 g/cm³ per ASTM C188.

It is clear that the SG of anhydrous cement varied greatly between different authors, operators, machines, and samples, which could be due to human or instrumentation errors, hydration due to moisture present in the atmosphere or exposure to atmospheric carbonation during sampling. However, based on results shown in this study, carbonation of cement could be ruled out as no carbonation products, such as calcium carbonate, were present in the XRD results, shown in Fig. 1. Furthermore, the oxide composition presented in Table 1 showed no inconsistencies with previous literature, and the SEM analysis presented in Fig. 3 revealed no signs of hydration products. Thus, it could be assumed that either human error, instrumentation error or variation in cement production yielded inconsistent results.

2.1.6. Specific surface area of cement

The surface area of cement can influence concrete's fresh and hardened properties. Finer cement often reacts more rapidly with water than coarser cement due to the increased surface area, which, in turn, increases the rate of hydration, the intensity of heat evolved, and strength development occurring from the chemical reaction. Moreover, finer cements often have higher water demands as they have larger surface areas [71].

The cement industry often determines the fineness of Portland cement based on the Blaine air permeation method (commonly known as the Blaine test), as described in ASTM C204 [72], which involves measuring the resistance of air through a well-packed powder placed on a porous bed under an air pressure gradient. The test often yields constant results and is less time-consuming than nitrogen adsorption tests [72,73]. On the other hand, most academics prefer nitrogen adsorption tests to determine the specific surface area of cement as the test does not rely on semi-empirical equations used in the Blaine test and is thus more reliable. The Brunauer, Emmet and Teller (BET) surface area test was used to determine the cement specific surface area, which is based on the amount of nitrogen gas absorbed on the cement surface at a given pressure [74].

The BET-specific surface area of anhydrous cement powder was measured using a multi-point nitrogen physisorption apparatus (Quantachrome NOVAtouch LX gas sorption analyser). The nitrogen adsorption tests are based on quantifying the volume of nitrogen molecules needed to cover a sample surface. The anhydrous cement sample weighed 0.7501 g and was subjected to an initial degassing at 40 °C under nitrogen gas flow for 16 h to ensure minimal thermal dehydration of gypsum [73]. The analyser measured the specific surface area of cement powder as 1.984 m²/g, which is higher compared to the coarse particle size and distribution previously shown in Fig. 3. The test was redone (after the results presented in this study) using an Automated Gas Sorption Analyser Quantachrome Autosorb-I-KR/MP-XR gas sorption analyser, which measured a specific surface area of 1.680 m²/g, which is similar to results by Mantellato et al. [75], for a cement grade similar to that used in this study. Furthermore, the cement manufacturer shared their data with the authors, which measured a specific surface area of cement of 1.580 m²/g using a Mastersizer 2000 laser diffraction particle size analyser.

The results measured using the nitrogen adsorption tests and particle size analyser measured a much larger specific surface area of cement than the Blaine air permeation method, as nitrogen can access cracks, crevices and pore that the Blaine test is not able to distinguish [75]. The Blaine test often measures surface areas of 0.546 m²/g for higher-early strength Portland cement and 345 m²/g for ordinary Portland cement [65].

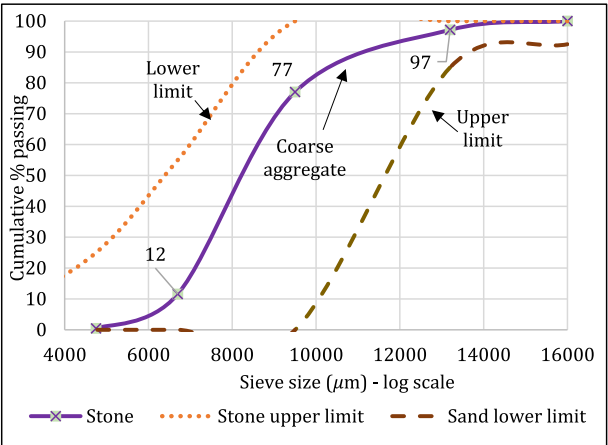


Fig. 5. Average particle size distribution of coarse (stone) aggregate.



Fig. 6. Sorted and cleaned ABS WEEEP fractions.

2.2. Aggregates

Crushed natural coarse and fine aggregate was mined from andesite lavas at the Eikenhof quarry in Roodepoort, while various companies in Gauteng donated WEEEP.

2.2.1. Physical properties of the aggregate

The average particle size distribution of the coarse (stone) aggregate was performed per SANS 201 [76] using a set of sieves (ranging in sizes from 16 to 4.75 mm), as shown in Fig. 5. The fineness modulus of the fine aggregate was measured as 3.48, with a dust content of 8.3 % determined according to SANS 1083 [77]. The natural aggregate was observed to have well-graded curves, which fell within the minimum and maximum grading limits prescribed in the British Standards (BS) 882 [78].

The ABS WEEEP was cleaned, and small pieces of steel (screws) were removed prior to granulating, as shown in Fig. 6. It was noted that ABS WEEEP was mainly derived from telecommunication devices (phones and routers), personal computers and television sets.

The ABS WEEEP was then granulated into 13, 10, 7, and 5 mm fractions, as shown in Fig. 7, which was subsequently combined in proportions to replicate the coarse natural aggregate's grading curve.

Table 2 presents the physical properties of the natural and ABS WEEEP according to SANS codes.

Fig. 8 shows the natural aggregate and WEEEP surface topography.

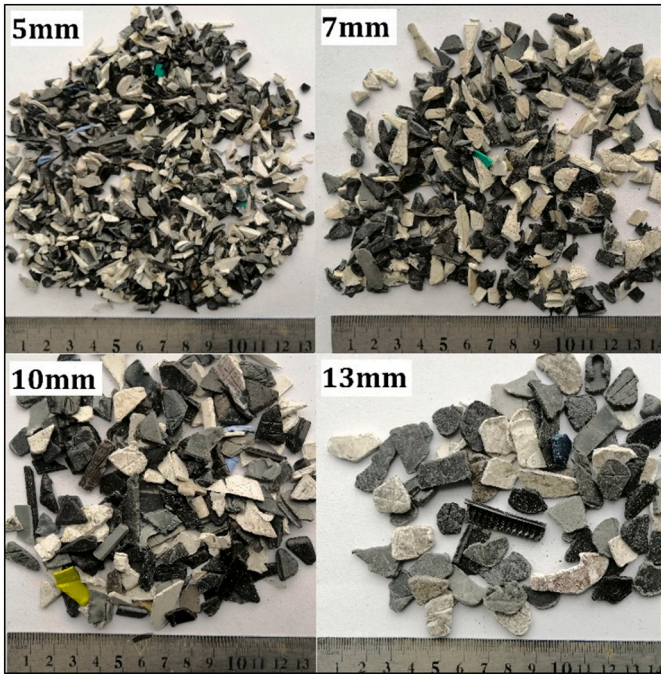


Fig. 7. ABS WEEEP granulated into various size fractions.

Table 2
Physical properties of coarse and fine aggregate.

Test performed	Coarse aggregate	Fine aggregate	ABS WEEEP
Fineness modulus [77]	–	3.48	–
Dust content (%) [77]	–	8.3	–
Particle density (kg/m ³) [79]	2630	–	1050
Compact bulk density (kg/m ³) [80]	1670	2050	580
Uncompacted bulk density (kg/m ³) [80]	1660	1830	–
Water absorption (%) [81]	0.56	–	1.75

The natural aggregate had various peaks and valleys, which may provide good bonding between the aggregate and hardened cementitious paste (HCP). Then again, ABS WEEEP had a much smoother surface compared to the natural aggregate and long, parallel vertical lines imprinted on the surface. These imprints are believed to be from the mould during manufacturing.

2.2.2. Elemental composition of ABS WEEEP

The elemental composition of six randomly selected ABS WEEEP was analysed using WDS on a CAMECA EPMA, as shown in Table 3. The ABS WEEEP were mounted onto aluminium stubs with carbon tape and coated with a 10 nm layer of gold palladium. Since plastics generally comprise of carbon-carbon bonds, the gold-palladium coating was chosen to avoid contamination of the qualitative findings. The results confirm that the polymeric matrix of ABS WEEEP includes heavy elements such as bromine (Br) and antimony (Sb). Both of these elements are used in WEEEP as FRs, which increase the plastic's hazardousness.

2.3. Superplasticiser admixture

Sika®ViscoCrete® 3088 superplasticiser was used to maintain a flow table spread of 405 ± 25 mm. The superplasticiser is based on an aqueous solution of modified polycarboxylate ethers.

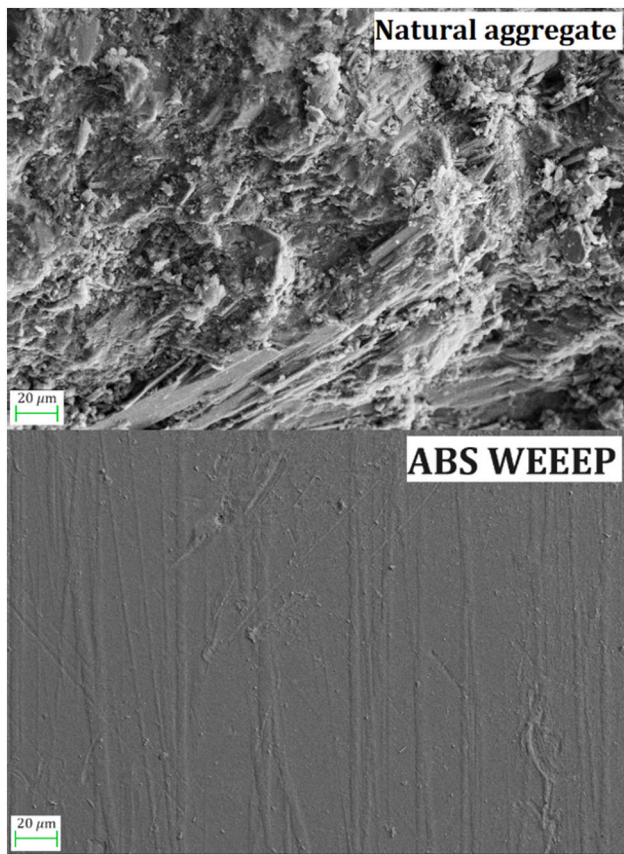


Fig. 8. Topography of the natural and ABS WEEEP aggregate at 1 K magnification using a secondary electron detector.

2.4. Mixing water

Johannesburg Water provided municipal potable water for this study. The water is deemed appropriate for use in concrete, and no testing is required [82].

3. Experimental details and procedures

3.1. Mix procedures and compaction of fresh concrete

Mixing was performed using a 50 L pan mixer at a laboratory temperature and relative humidity, as shown in Table 5. All materials were weighed using an electronic scale with an accuracy of 0.1 g, while the superplasticiser was volume-batched using a graduated cylinder. Mixing of the dry materials was done for approximately 1 to 2 min.

Potable water was gradually added, and mixing was continued for an additional 2 min. A flow test was conducted directly after mixing per SANS 5862-2 [83] specification, using a flow table, wooden tamping rod and mould. The desired spread of 405 ± 25 mm was required to achieve medium workability [53] for each mix design. A superplasticiser

admixture was added directly into the fresh mix if this was not obtained. Mixing continued for an additional 1 to 2 min until the desired spread was obtained. The concrete cubes and prisms were manufactured by compacting the mixed material in intervals of 20 ± 3 s and were filled in two layers of the volume of the mould. As compaction affects concrete microstructure, all mixes were compacted using the same method and given similar compaction durations to produce a comparable processing influence.

3.2. Curing

Two different curing regimes were employed and discussed below.

3.2.1. Water curing

After compaction, the cubes were covered by a plastic sheet and demoulded after 22 ± 2 h. The cubes were transferred to a water curing tank maintained at a consistent temperature of 23 ± 2 °C, as described by SANS 5861-3 [84].

3.2.2. Precarbonation curing followed by water curing

Precarbonation (PCAR) curing of concrete is a curing process that entails the diffusion of carbon dioxide (CO_2) gas in concrete within 24 h of casting [85]. PCAR has been shown to produce concrete with higher strengths and enhanced long-term durability compared to conventional curing practices. The test is often performed on concrete with a lower water-to-cement ratio (w/c) (< 0.3) so as not to impede the diffusion of gas into the concrete matrix [86]. This is because excessive moisture content can fill concrete pores and reduce the diffusion of CO_2 gas into concrete, reducing the efficiency of the CO_2 sequestration process [50]. As such, for concrete containing higher w/c (> 0.3), preconditioning is often required to remove excess water (ibid). Zhang and Shao [87] showed that preconditioning could be done to concrete with a w/c of 0.4 and a slump of 151 mm by exposing concrete to fan drying in the open air after the initial set was reached to remove free water. Similarly, Liu et al. [88] preconditioned their samples by placing them in an environmental chamber maintained at 20 °C and relative humidity (RH) of 50 % for 3 h.

In this study, concrete samples required around 4 h to attain the initial set as determined by SANS 50196-3 [89], following which they were carefully removed from the steel moulds. Similar to Zhang and Shao [87], specimens were fan-dried for around four and a half hours at a wind speed of 1.2 m/s across the surface of the specimen until 40 % water loss was reached. The specimens were subsequently transferred to a carbonation chamber, where the specimens were precarbonated for 48 h using 100 % laboratory pure CO_2 gas, set at a concentration of 20 % at a temperature of 20 ± 3 °C at atmospheric pressure, as suggested by Chen and Gao [50]. The RH of 57 ± 4 % was maintained using saturated salt of sodium dichromate. The specimens were subsequently transported to a water curing tank, and curing continued until the day of testing.

3.3. Carbonation depth using phenolphthalein solution

The carbonation depth was measured using a phenolphthalein in-

Table 3
Elemental properties of ABS WEEEP.

Element									
N	Cl	P	Sb	K	Ca	Ti	Fe	Br	C
0.00	0.01	0.86	0.00	0.00	0.01	0.03	0.00	0.02	77.56
3.32	0.73	0.02	2.53	0.09	0.06	1.20	0.05	7.77	75.78
1.29	0.38	0.03	0.68	0.05	0.09	0.59	0.03	4.94	81.45
0.00	0.02	0.02	0.04	0.04	0.04	0.14	0.02	0.00	91.95
0.00	0.02	0.58	0.02	0.02	0.02	0.00	0.00	0.01	77.25
0.00	0.01	0.00	0.00	0.01	0.02	0.14	0.00	0.00	95.34

indicator solution on freshly broken 100 mm³ carbonated concrete specimens along opposite faces using an Amsler Universal Testing Machine with a capacity of 2000 kN on the test date. The indicator was made by combining 1 g of phenolphthalein powder per 70 mL of ethanol and 30 mL of distilled water. The indicator remains colourless when exposed to a pH < 9 (indicating the complete carbonation zone where CO₂ reduced the alkalinity) and turns magenta at a pH ≥ 9 [90]. The carbonation depth was measured by taking the average of eight measurements (two measurements per side) to an accuracy of 0.5 mm using a Venier calliper.

3.4. Compressive strength

The compressive strength of concrete cubes (100 mm³) was determined by applying a perpendicular load to the casting direction across opposing cube surfaces using a concrete cube press with a capacity of 2000 kN. All samples were tested by SANS 5863 [91] at a constant load rate of 0.25 MPa/s.

3.5. Materials and procedures used to measure the abrasion resistance of concrete

Selecting the right test for abrasion-wear resistance (AWR) for concrete is complex due to the host of abrasion tests available, such as sandblast, rattler, rotating ball bearing or rotating wire brush test, among others [38]. The actual abrasion mechanism of concrete is complex due to the use of various replacement intervals of ABS WEEP, particle shape and orientation. This means that abrasion may occur on either the front or back side of the ABS WEEP, the fractured surface (often much smaller than the front and back side) or a combination of both. Furthermore, the perpendicular load exerted by the blast media onto the concrete surface will also produce a shear component as the softer paste is removed, leaving large aggregates protruding from the surface, as discussed by Huovinen [92]. The abrasion-wear resistance of concrete by sandblasting was performed according to ASTM C418 [93] (*Standard Test Method for Abrasion Resistance of Concrete by Sandblasting*). The choice of test was based on a set of criteria shown below:

- 1) The test should be in current use locally or abroad.
- 2) Existing information should be available for comparison.
- 3) Test equipment required should be locally obtainable.

ASTM C418 [93] defines three ways abrasion could affect concrete surfaces, including wear due to human or vehicular traffic, abrasive materials in water affecting hydraulic structures and high-water velocities creating cavitation at the concrete surface. Abrasion by sandblasting is a dry test that entails subjecting a concrete specimen to the impingement of air-driven silica sand to abrade the components of concrete, which are less resistant. This test simulates the action of waterborne particles such as sand and abrasives under traffic on a concrete surface [94].

3.5.1. Blast media oxide composition

The AWR of concrete relates to the ability of the material's surface to resist abrasive forces caused by friction, grinding, impact, rolling, or the action of fluids, among others [34].

This study used glass grit blast media as an abrasive material instead of the recommended use of silica sand by ASTM C418. This was due to the potential health risks associated with the use of silica sand as blast media, such as silicosis, lung cancer and breathing problems for exposed workers. Thus, to protect the wellness of workers, The Factories Act (1949) prohibits silica sand for sandblasting operations [95]. Silica sand is a naturally occurring material which has a chemical composition containing >95 % silicon dioxide (SiO₂) [96], is highly friable, has an angular to spherical shape and a Mohs hardness ranging between 5.0 and 6.0 [97]. In contrast, glass grit blast media is produced from post-

Table 4

Elemental oxide composition of glass grit blast media.

Oxide	SiO ₂	Na ₂ O	CaO	MgO	Al ₂ O ₃	K ₂ O
%	72.30	16.94	3.37	3.06	2.96	1.36

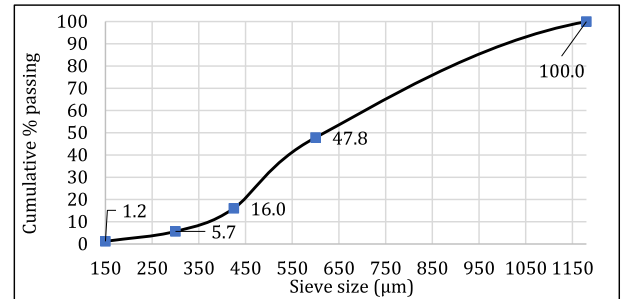


Fig. 9. Average particle size distribution of virgin glass grit blast media.

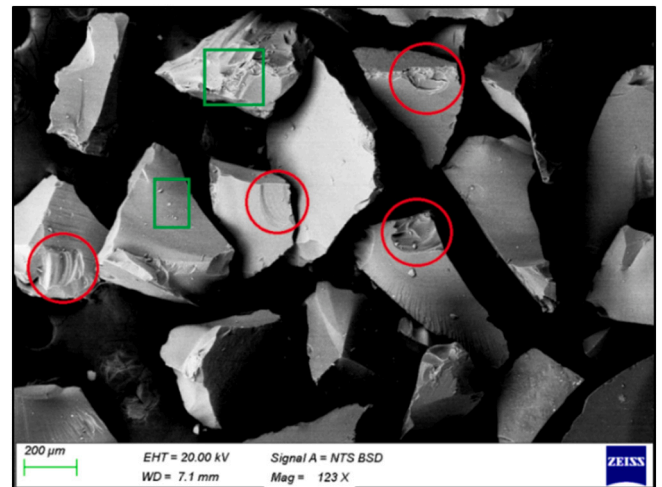


Fig. 10. Topography of glass grit blast media.

consumer recycled bottle glass, has an angular shape, a Mohs hardness of 6, and is non-toxic and inert [98]. The elemental composition of glass grit blast media was determined using energy dispersive spectroscopy on an SEM and presented in Table 4. Results show that the silicon and sodium oxide ratios are similar to soda-lime (container) glass [99].

3.5.2. Blast media particle size distribution

The particle size distribution of virgin glass grit blast media is graphically presented in Fig. 9, which was determined by SANS 201 [76], while the calculated fineness modulus of 0.55 was conducted per SANS 3001-PR5 [100].

3.5.3. Surface topography of blast media

The surface topography of the glass grit blast media was assessed using an SEM equipped with a backscatter electron (BSE) detector, which showed the particle shape (round to angular), which can determine the degree of surface profiling. Fig. 10 provides the surface topography of glass grit at 0.123 K magnification, where it was observed that most particles had sharp jagged edges. The grit had small quantities of glass dust attached to the larger particles, as shown in the green squares, which may have originated from its processing. It is also noted that most particles have colloidal fractures, as indicated in the red circles, which are commonly associated with rapid brittle glass fractures [99].

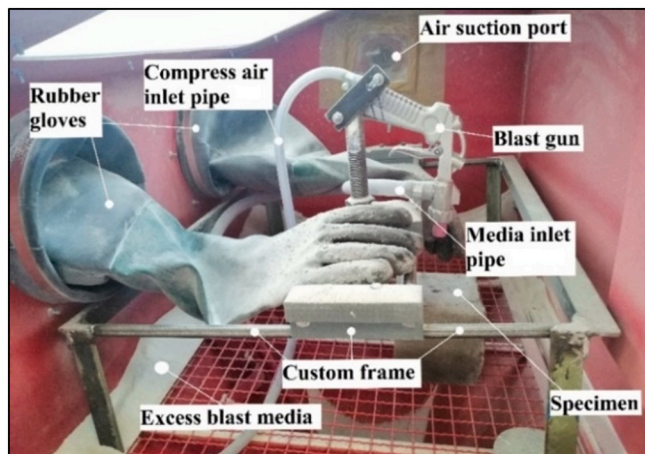


Fig. 11. Internal configuration inside the blasting cabinet before sandblasting.

3.5.4. Sandblasting equipment

The abrasion-wear resistance of concrete was performed using a sandblasting setup specified per ASTM C418 guidelines. This study used a manual hand-operated sandblast cabinet to contain the glass grit as blast media during the abrasion process. The sandblast cabinet is based on the induction siphon blast system founded on the venturi principle, which has a high-velocity air jet fed with a controlled flow rate for the blast media. The cabinet has a working space of $840 \times 550 \times 550$ mm. The air pressure was maintained at 410 kPa to produce an abrasive flow rate of 600 ± 25 g/min. The nozzle has an inner hole diameter of 2.8 mm and bevels at 45° on the inside at the upper end.

3.5.5. Sandblasting test procedures

The test procedure used to determine concrete abrasion-wear resistance was performed according to ASTM C418. The specimen was removed from the curing bath and dabbed with a paper towel to its saturated surface dry condition. It was subsequently placed in the sandblasting cabinet at a fixed angle of attack of 90° to the nozzle at an attacking distance of 75 ± 2.5 mm using a custom build device, as shown in Fig. 11. The cube was secured, and the exposed surface was abraded for 60 s. Subsequently, the cube was readjusted such that

abrasion continued for 60 s on a non-abraded section of the cube. This process was repeated at eight different locations around the cube. The abrasion process for each cube took approximately 12 min to complete. The abraded cube mass was recorded using an electronic scale to the nearest 0.01 g. Subsequently, the cavities were periodically filled manually with an oil-based modelling clay using moderate finger pressure until flush with the straight edges of the cube, and reweighed after each cavity was filled to determine the mass of the clay used, as stated in the code. The duration from the initial weighing of the abraded cube to periodically filling the cavities and weighing took about 15 min to complete.

The volume of the clay was determined by measuring the mass of the clay in the cavity. Subsequently, the abrasion coefficient loss on a volumetric basis was calculated using Eq. (1):

$$A_c = V/A \quad (1)$$

where A_c is the abrasion coefficient (cm^3/cm^2), V is the volume of the clay (cm^3), and A is the area of the surface abraded (cm^2).

3.6. Mix designs and proportions

All mix designs used a w/c of 0.6 and a spread of diameter 405 ± 25 mm. ABS WEEEP replaced the coarse natural aggregate in percentages of 5, 10, 25, 50, 75 and 100 % by volume. As WEEEP had a lower specific gravity than the natural aggregate, WEEEP replacements reduced the unit density of concrete, as shown in Table 5. The concrete had a nominal cement-to-sand-stone ratio of 1:2.2:2.7. This paper used various acronyms to identify each mix presented. For example, a mix WC(ABS-5)-6 can be broken down into water-cured (WC), plastic-type (ABS), replacement percentage (5 = 5 %) and 6 presents the w/c = 0.6. The WC acronym can also be replaced with PCAR, indicating that the mix was subjected to precarbonation curing followed by water curing. It should be noted that although results in Table 2 indicate higher average water absorption for ABS WEEEP compared to the natural aggregate (1.75 % and 0.56 %, respectively), no corrections were made to the mix design as WEEEP may have alternating absorption based on its history.

3.7. BSE image analysis, acquisition and processing

Backscatter electron (BSE) image analysis directly observes the

Table 5
Mix proportions.

Mix design label	Sand (kg/m^3)	Stone (kg/m^3)	ABS WEEEP Coarse (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	Super-plasticiser (%)	Design density (kg/m^3)	Slump flow (mm)	Room temperature ($^\circ\text{C}$)/Humidity (%)
WC(Control mix)-6	823	1020	0	224	373	0.00	2440	430	25,3/47
WC(ABS-5)-6		969	20			0.00	2409	425	25,3/48
WC(ABS-10)-6		918	41			0.00	2379	425	25,3/47
WC(ABS-25)-6		765	102			0.00	2287	380	24,9/48
WC(ABS-50)-6		510	204			0.06	2134	400	24,9/48
WC(ABS-75)-6		255	305			0.07	1980	420	25,1/48
WC(ABS-100)-6		0	407			0.10	1827	415	24,8/47
PCAR(Control mix)-6		1020	0			0.00	2440	425	22,2/49
PCAR(ABS-5)-6		969	20			0.00	2409	420	19,2/48
PCAR(ABS-10)-6		918	41			0.00	2379	425	23,1/52
PCAR(ABS-25)-6		765	102			0.00	2287	380	23,2/56
PCAR(ABS-50)-6		510	204			0.06	2134	405	23,5/52
PCAR(ABS-75)-6		255	305			0.07	1980	420	23,8/54
PCAR(ABS-100)-6		0	407			0.10	1827	410	20,1/49

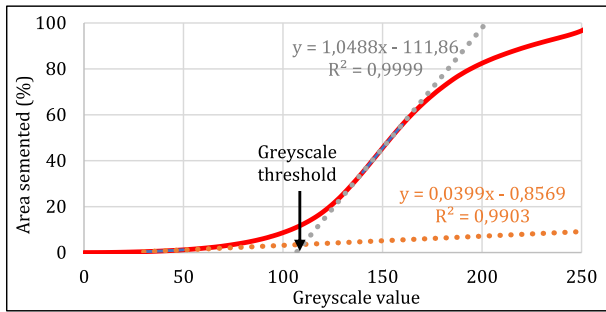


Fig. 12. Determination of the upper threshold value for pores using the overflow method for WC(ABS-25)-6.

morphology of the concrete microstructure [101]. BSE use a greyscale level to distinguish different phases based on the measured atomic number. Phases with a high atomic number appear brighter (higher grey image), while phases with low atomic numbers will appear dark (lower greyscale image) [102]. Thus, BSE imaging can distinguish three primary phases in concrete: hydration products, anhydrous clinker and pores [103]. Since pores are epoxy-impregnated during sample preparation, pores have a low BSE coefficient and appear dark on the BSE image. Therefore, voids can be separated from the concrete matrix through a threshold grey filter value. The accuracy of the quantitative analysis is related to the quality of the BSE image.

3.7.1. Sample preparation for BSE image analysis

Cubes of size 100 mm^3 were cored through the centre at 28-days using a 25 mm inner diameter water-cooled diamond-tipped barrel. Hydration was ceased by immersing the core in a container containing isopropanol solution with a volume of 10 times the core, as suggested by Mitchell and Margeson [104]. Isopropanol exchange is a drying process in which isopropanol solvent replaces water in the open pores of hardened concrete [105]. The isopropanol solvent was replaced daily for three days and then kept in the same solution for an additional four days. The cores were weighed and placed in an oven maintained at 50°C for 24 h to remove the solvent. The samples were subsequently weighed and placed back into the oven for an additional 24 h until the weight remained constant. The cores were cut in half along the length of the core. The half-cores were then partially immersed in EpoFix epoxy and placed in a vacuum chamber at six bars for 12 h to allow the epoxy to penetrate the concrete matrix. After curing, the samples were ground for 8 min at 300 rounds per minute using 400, 600, 800, and 1000-grit silicon carbide paper. The samples were mounted onto glass slides using a mounting press at 34°C for 12 h, resulting in a smooth surface. The samples were ground again using the same grit range previously

mentioned, but this time, silicon carbide powder was used. The samples were subsequently polished using a diamond polishing paste of 15, 9, 6 and $3 \mu\text{m}$ particle sizes. Since concrete and ABS WEEEP materials are non-conductive, thin sections were coated with 30 nm gold-palladium before BSE analysis at the Microscopy and Microanalysis Unit department.

3.7.2. BSE image acquisition

Thin sections were scanned under a BSE detector using a Vega Tescan SEM. The observations were conducted at a set magnification of 1 K, accelerating voltage of 30 kV and a working distance of 16.5 mm to eliminate the operator's bias and enable comparability. The brightness and contrast values were obtained from trials and set at a constant for each sample to ensure the reliability of the test. The size of each image was 1024×1024 pixels, and the corresponding field size was $274.71 \times 274.71 \mu\text{m}$. Hence, the pixel size was $0.27 \times 0.27 \mu\text{m}$ with a greyscale ranging from 0 (black) and 255 (white).

3.7.3. BSE thresholding

The greyscale thresholding level for porosity was based on the overflow method proposed by Wong et al. [106] and was adopted for thresholding. The method is considered an objective and reliable greyscale threshold selection strategy [45,101,106,107]. The method aids in locating the upper greyscale value of the pore from the inflection of the cumulative percentage against the greyscale histogram curve, which is estimated from the intersection between two linear points, as shown in Fig. 12 [101,103,106].

3.7.4. BSE processing using ImageJ software

The image was pre-treated in the first step to increase the quality for qualitative analysis, similar to Lyu et al. [103]. A “smooth” filter function was applied to the image to enhance the boundary between phases, while the despeckle filter reduced noise. The second step changed the 16-bit image to a binary 8-bit image whereby the pixels have only two grey scales, namely white (255) and black (0). The white pixels represent the solid phases, such as hydration products and anhydrous clinkers, while the black pixels represent pores [106].

The data was transferred to an Excel spreadsheet, and the data was processed. The overflow point was used to find the upper threshold for the pores in the accumulative histogram. The upper threshold was used in step four, and step five used the processing power of ImageJ software to analyse the pore size and distribution.

Subsequently, the data was imported into an Excel spreadsheet. To compare the size and distribution of pores, the equivalent circular diameter (ECD) (μm) was calculated by equating the pixel area of a pore to that of a perfect circle, as shown in Eq. (2) [103]:

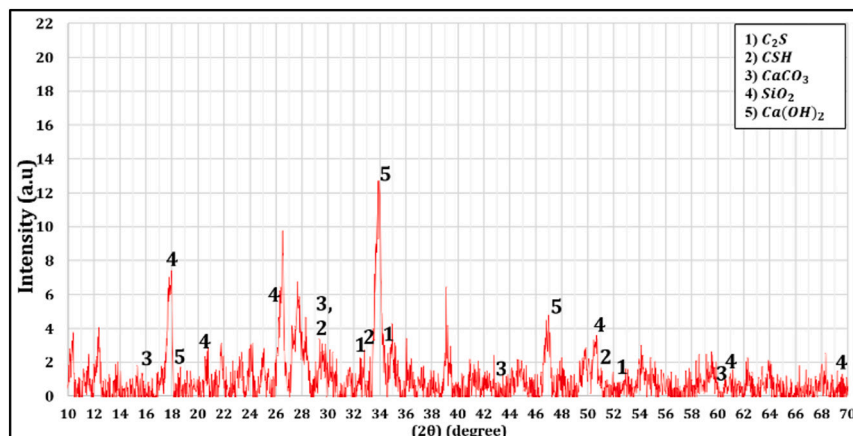


Fig. 13. Diffractogram of WC(Control mix)-6 at 28-days of curing.

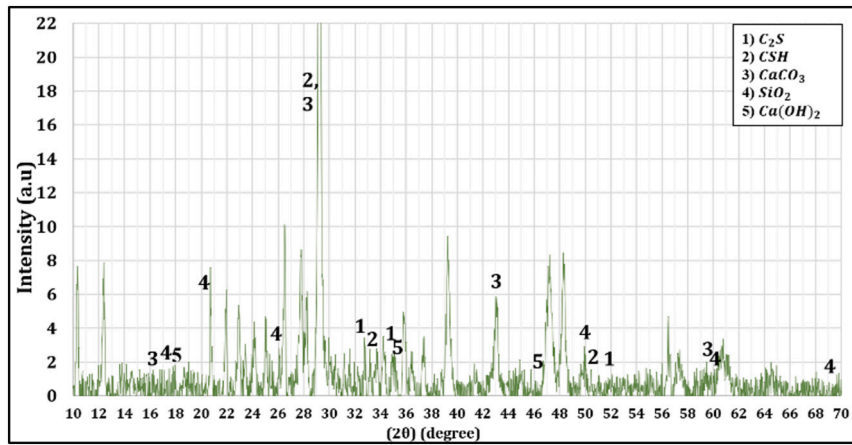


Fig. 14. Diffractogram of PCAR(Control mix)-6 at 28-days of curing.

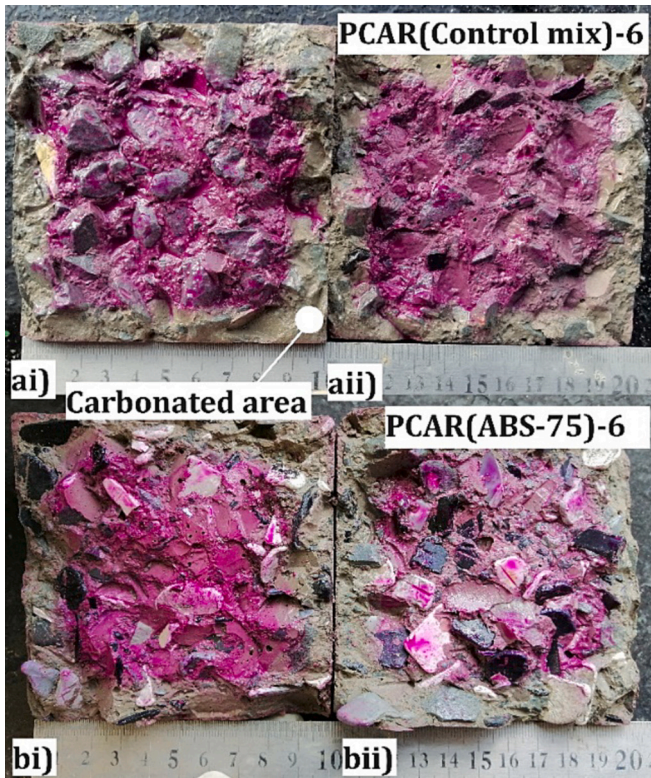


Fig. 15. Carbonation depth of mixes containing 0 % and 75 % ABS WEEEP.

$$ECD = \sqrt{4 \times \frac{A_p}{\pi}} \quad (2)$$

where A_p (μm) is the number of pixels included within each pore. The value was multiplied by the pixel size to convert the pixel size into an actual size (ibid). Following, the data was plotted on a histogram, which presents the pore size and distribution of a mix.

4. Results and discussions

4.1. Mineralogy of concrete

X-ray diffraction (XRD) pattern analysis was used to identify crystalline phases and observe alterations in hardened concrete. A D2-Phaser diffractometer was used to identify the peaks and positions of

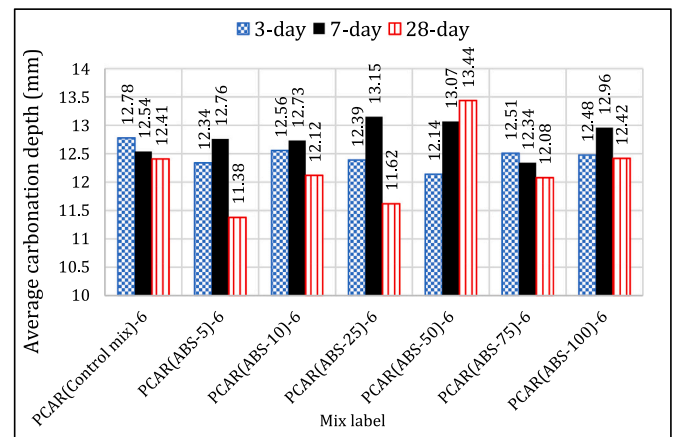


Fig. 16. Carbonation depth of mixes containing ABS WEEEP at alternating replacement increments at 3, 7, and 28-days.

concrete precarbonated, followed by water curing (PCAR) and water-only cured (WC) mixes. Figs. 13 and 14 present the XRD spectrums of tricalcium/dicalcium silicate (C_2S/C_3S), calcium silicate hydrate (CSH), calcium carbonate ($CaCO_3$), ettringite (AFm), silicon dioxide (SiO_2) and calcium hydroxide ($Ca(OH)_2$ or CH). $CaCO_3$ shared its dominant peak with CSH, which is centred around 2θ (29.2°), while other peaks of calcite were observed at 2θ (23.0° , 35.9° , 39.3°) and the presence of CSH were noted at 2θ (16.9° , 32.0° , 42.7° , 49.8° , 55.3°) [108]. Similarly, CH can be found at 2θ (18.1° , 34.1° , 47.1°). Comparing Figs. 13 to 14, it is clear that as the calcite peaks increase, CH peaks decrease due to carbonation [50]. Furthermore, the presence of CH in carbonated mixes suggests that further hydration of calcium silicates occurred after PCAR curing [109]. It was observed that PCAR-cured concrete had higher $CaCO_3$ peaks at 2θ (42.7°) compared to water-only cured mixes made using the same w/c.

4.2. Carbonation depth

Fig. 15 visually presents freshly broken concrete sprayed with a phenolphthalein indicator. The colourless region observed on the outer perimeter of the cube presents the complete carbonation zone ($pH < 9$). Fig. 16 presents the average carbonation depth at various ABS WEEEP replacement intervals at 28-days. It was noted that there was little variation (maximum 2.06 mm) between the depth of carbonation with increased ABS WEEEP replacements or ages of curing.

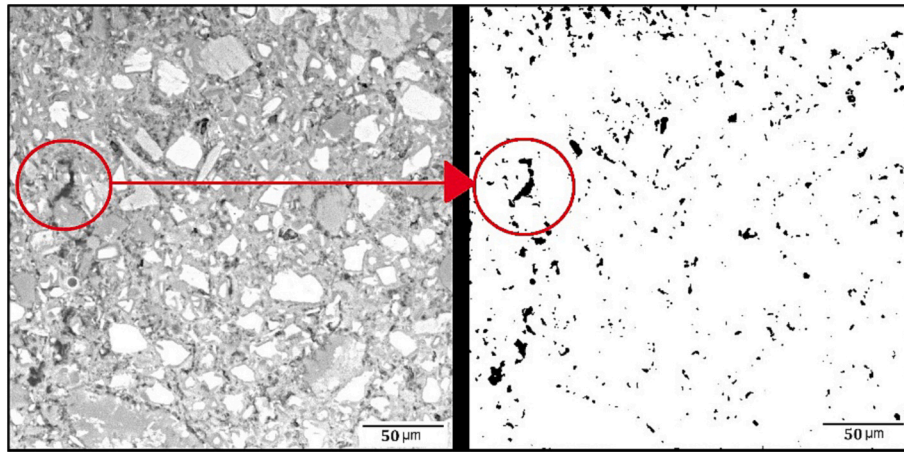


Fig. 17. Raw BSE image of the HCP (LHS) and pore size and distribution in HCP (RHS) for PCAR(Control mix)-6.

4.3. Pore size and distribution in the HCP

It is widely known that the pore structure dictates concrete's mechanical strength, permeability and long-term durability [110] and that concrete with the same pore volume with varying pore size distribution can have different mechanical and transport behaviour [111]. Concrete pores come in various shapes and sizes, subdividing into gel, capillary and macro pores. Gel pores are found in calcium silicate hydrate (CSH) gel, ranging in size from 0.5 to 10 nm [65]. According to the Powers–Brunauer model [71], CSH has a layered structure with randomly arranged colloidal particles with a surface area of 100 to 700 m²/g, while the Feldman–Sereda [112] model suggests that CSH gel is composed of a kinked array of layers, which are randomly arranged to create interlayer spaces of different shapes and sizes. A recent study by Taha [113] suggests that CSH exists in at least two structurally distinct forms, which are compositionally similar but differ in packing density (namely low and higher density). Then again, a study by Constantinides and Ulm [114] suggests CSH behaves like a nanogranular material whose behaviour is driven by the force at particle-to-particle contact parts rather than the material properties themselves. The 28-day compressive strength is generally accepted to be related to the gel/space ratio [65] (the ratio between the solid hydration product and total space). Thus, a higher ratio indicates a more solid material and increased strength. The gel/space ratio (X) is defined as shown in Eq. (3).

$$X = \frac{\text{volume of gel (including gel pores)}}{\text{volume of gel and volume of capillary pores}} \quad (3)$$

The capillary pores typically range in size from 10 nm to 10 µm [65], which are created by chemical shrinkage resulting from the volume occupied by hydration products compared to the volume of anhydrous clinker and water during hydration [103,115]. Macropores range in size from 100 µm to 1 cm, which are formed due to deliberate air entraining or incomplete compaction [27,115].

Imaging analysis is a powerful tool for studying capillary pore size, distribution and connectivity. BSE image analysis directly observes the morphology of the concrete microstructure [101]. It should be noted that the SEM resolution limits the detectable pore sizes [103], and thus, the pores shown in the BSE images in this study are all capillary pores. Furthermore, the particle size and porosity of ABS WEEEP were not considered.

Figs. 17 and 19 below presents the raw (unfiltered) BSE image on the left-hand-side (LHS) and segmented images of the HCP on the right-hand-side (RHS) of PCAR(Control mix)-6 and PCAR(ABS-100)-6 at 28-days of curing. The segmented images contain black areas representing pores size and distribution in the HCP. A visual comparison between mixes containing no WEEEP and mixes containing 100 % WEEEP shows

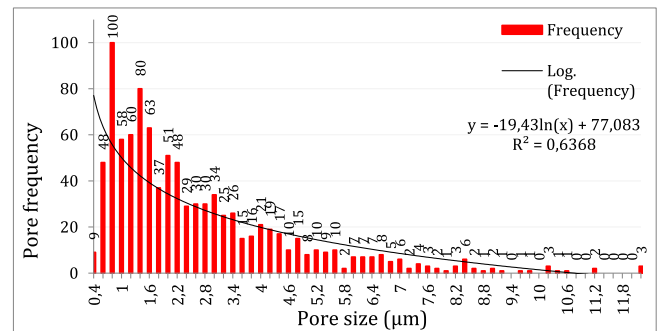


Fig. 18. Pore size and distribution for PCAR(Control mix)-6.

Table 6

Details of pore size and percentage coverage from BSE image analysis.

Mix design	Average pore size (µm)	% Area of the map covered by pores
WC(Control mix)-6	4.078	7.089
WC(ABS-25)-6	5.579	8.153
WC(ABS-100)-6	8.169	10.442
PCAR(Control mix)-6	3.549	3.193
PCAR(ABS-25)-6	4.750	4.261
PCAR(ABS-100)-6	7.275	8.765

an apparent increase in the pore size and fraction with the addition of ABS WEEEP. Figs. 18 and 20 present the pore frequency to the pore size for the respected mix, which is summarised in Table 6 for both WC and PCAR mixes, which presents the total number, average size and percentage area covered by pores.

Referring to Table 6, mixes subjected to the WC curing regime have an average pore size in the following order:

WC(Control mix)-6 < WC(ABS-25)-6 < WC(ABS-100)-6
i.e. (4.078 < 5.579 < 8.169) µm

Here, it is seen that replacing 25 % WEEEP increased the average pore size by 36.81 %, while 100 % WEEEP replacements increased by 100.31 %. The percentage area of the map covered with pores is higher for mixes containing 100 % WEEEP, as shown:

WC(Control mix)-6 < WC(ABS-25)-6 < WC(ABS-100)-6
i.e. (7.089 < 8.153 < 10.442)%

Similarly, for mixes subjected to the PCAR curing regime, the order from smallest to largest average pore size is presented in the following order:

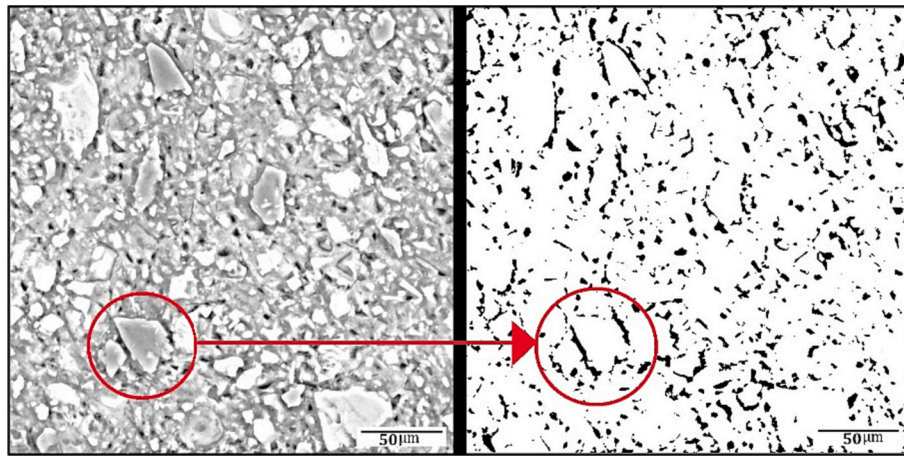


Fig. 19. Raw BSE image of the HCP (LHS) and pore size and distribution in HCP (RHS) for PCAR(ABS-100)-6.

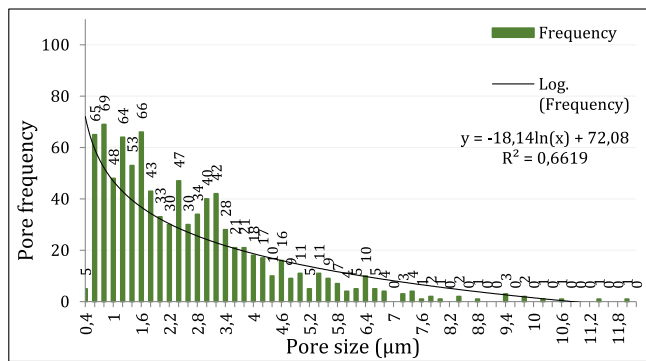


Fig. 20. Pore size and distribution for PCAR(ABS-100)-6.

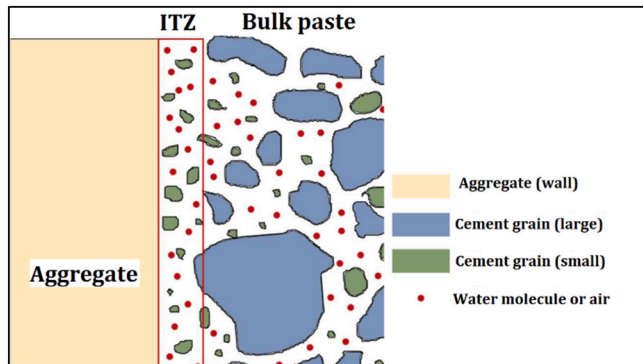


Fig. 21. Wall effect [36].

PCAR(Control mix)-6 < PCAR(ABS-25)-6 < PCAR(ABS-100)-6
i.e. (3.549 < 4.750 < 7.275) μm

It was noted that 25 % of WEEEP replacements increased the average pore size by 33.84 %, which is similar to WC using the same w/c, which increased by 36.81 %. Similarly, 100 % WEEEP replacements increased the pore size by 104.98 % compared to the control mix. This is similar to concrete subjected to WC, which increased by 100.31 %. This suggests that although the pore size is smaller in PCAR mixes, the effect on the size increase is similar for both curing methods.

Lastly, there was an overall increase of 5.572 % in the area covered by pores made using 100 % WEEEP compared to the control mix, as shown below:

PCAR(Control mix)-6 < PCAR(ABS-25)-6 < PCAR(ABS-100)-6

i.e. (3.193 < 4.261 < 8.765)%

The increased pore size and frequency with increased WEEEP replacements could negatively affect concrete's mechanical strength and abrasion-wear resistance.

4.4. Pore size and distribution at the interfacial transition zone

The interfacial transition zone (ITZ) has an entirely distinct microstructure despite being made of the same material as the bulk paste. It is controlled by the aggregate size and quantity, the w/c, and the particle size distribution of the cement. Cement particles are typically 1 to 100 μm in size, whereas aggregate is much larger. When cement and aggregates are blended, the particle size distribution of the cement is disrupted, and the packing pattern around the larger aggregate is altered [116]. As shown in Fig. 21, the "Wall Effect" occurs when smaller cement particles concentrate near the aggregate surface, and larger particles accumulate further away (ibid). As a result of the Wall Effect, considerable cement is excluded from the region of the aggregate, resulting in increased porosities around the aggregate face [117].

This suggests that the ITZ is not a fixed zone with a set porosity but rather a transition from a highly porous microstructure to the bulk paste that normalises outwards from the aggregate face. Because the ITZ is porous, it can convey aggressive entry into the concrete microstructure. This is particularly true if nearby ITZs overlap, resulting in continuous porous routes [117]. As a result, the ITZ significantly impacts the strength and durability of hardened concrete [45].

The same thin sections, apparatus (including settings), and programs used to determine the average pore size and distribution for the mixtures presented in this paper were used to investigate the average pore size in the ITZ. The highest porosities are found in the first 20 μm from the aggregate, while zones >40 μm are similar to the bulk paste. This study analysed the microstructure between the aggregate and the transition zone with a size of approximately 30 μm , similar to Diamond and Huang [117]. Fig. 22 below presents the BSE images for PCAR mixes with 0 % (a) and 100 % ABS WEEEP (c) replacements at 28-days.

When the content and individual pores in Fig. 22 (b-2) and (d-2) are compared, it is apparent that concrete with no WEEEP has fewer, smaller, and less interconnected pores than the identical mix with WEEEP. Concrete with 0 % WEEEP replacements has an average pore size of 4.453 μm , whereas concrete with 100 % WEEEP replacements has an average pore size of 12.107 μm . This shows that concrete created with WEEEP significantly impacts the pore structure in the ITZ, which may alter its strength and abrasion wear resistance. The average pore size in the ITZ for concrete made with 0 %, 25 %, and 100 % ABS WEEEP replacements for WC and PCAR mixes is shown in Fig. 23.

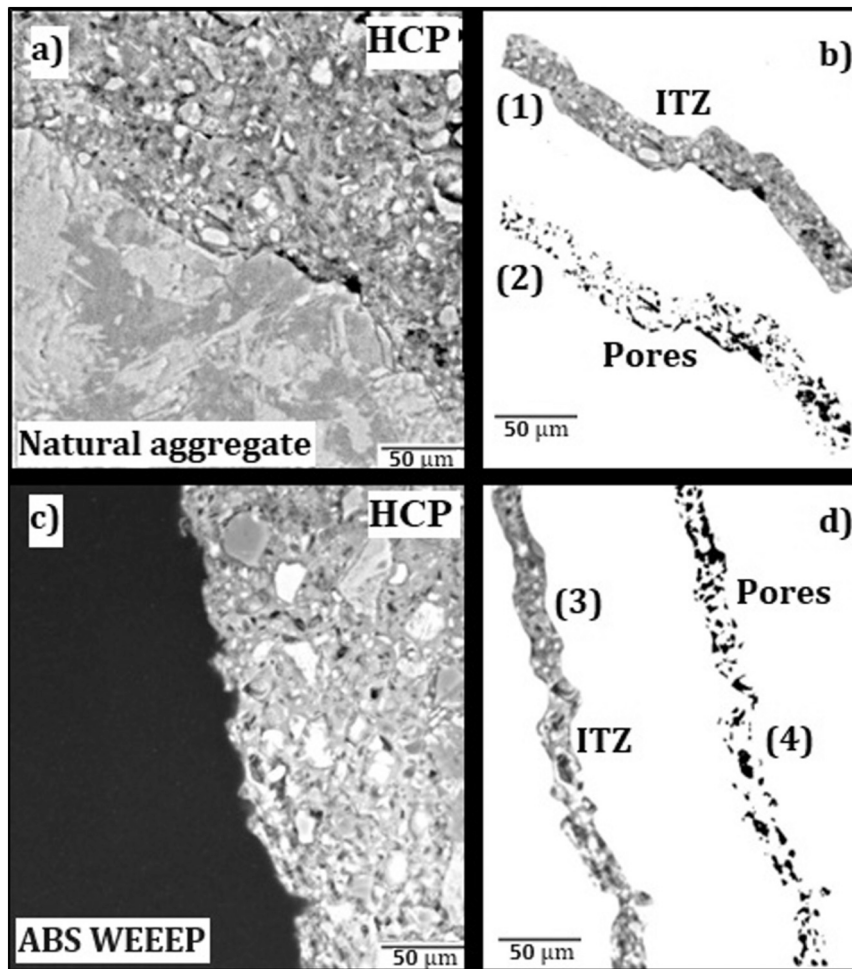


Fig. 22. ITZ between PCAR(Control mix)-6 and PCAR(ABS-100)-6 at 28-days curing.

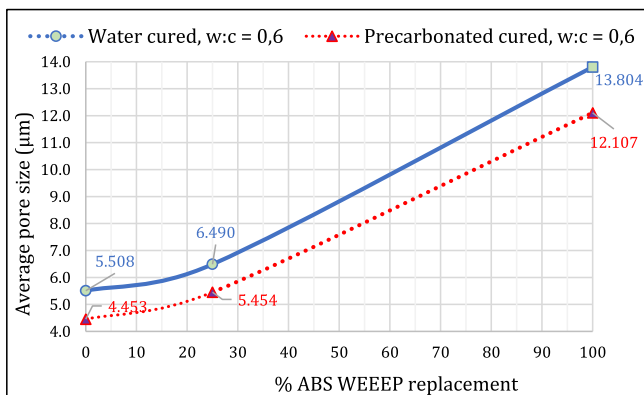


Fig. 23. Average pore size for WC and PCAR mixes containing 0 %, 25 % and 100 % ABS WEEEP replacements at 28-days.

4.5. Compressive strength of concrete

Table 7 shows the average compressive strength (fcu) of mixes prepared with ABS WEEEP after 7 and 28 days of curing.

Comparing WC and PCAR mixes, it is clear that PCAR(ABS-50)-4 had the highest strength gain of 3.7 MPa at 7-days. Similarly, it was observed that PCAR curing had little impact on the compressive strength at 0 %, 5 % and 10 % ABS replacements. Mixes made using 75 % ABS WEEEP replacements, subjected to PCAR, increased by 2.9 MPa but decreased

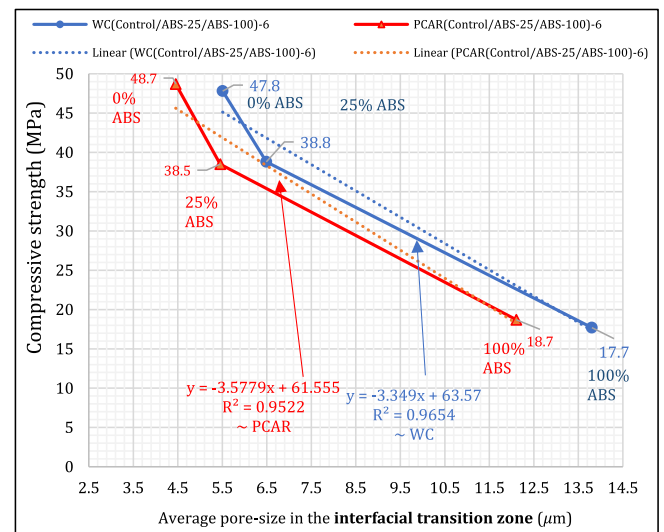


Fig. 24. Correlation between compressive strength average and pore size in the ITZ.

by 1.8 MPa when replaced with 100 % WEEEP.

Fig. 24 shows the relationship between the average compressive strength and average pore size in the bulk HCP. These figures indicate a strong linear relationship between compressive strength and average

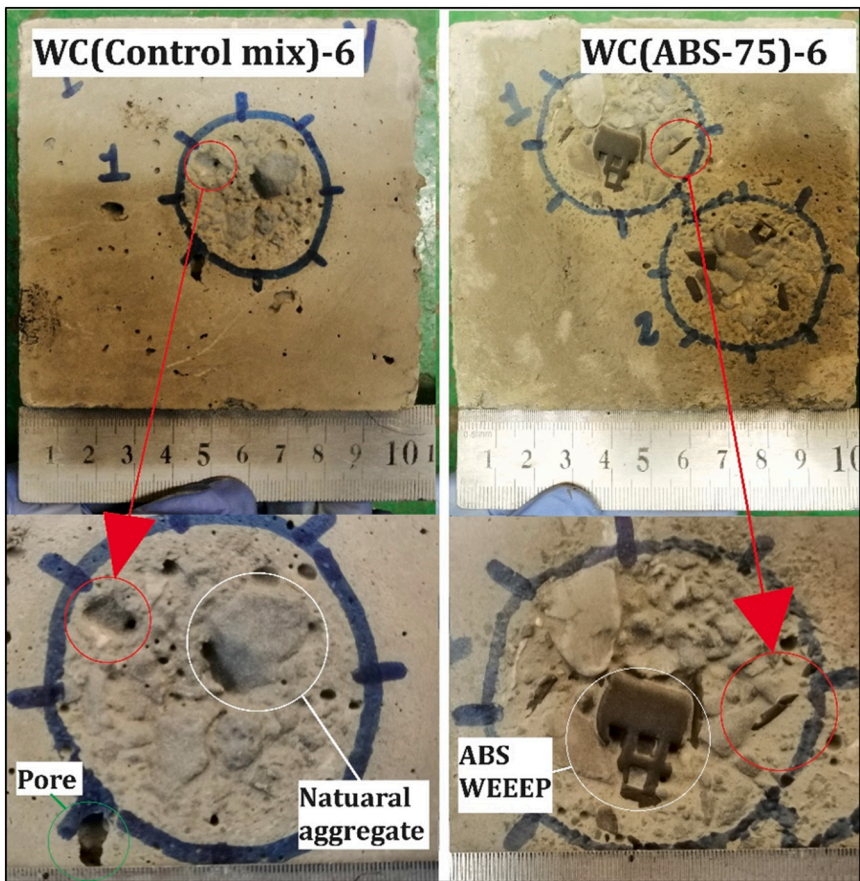


Fig. 25. Graphical comparison of craters made by sandblasting mixes containing 0 % and 75 % replacements at 28-days.

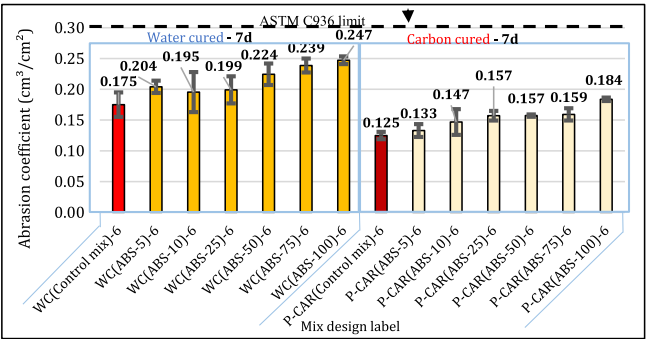


Fig. 26. A_c of water vs carbon-cured concrete at 7-days.

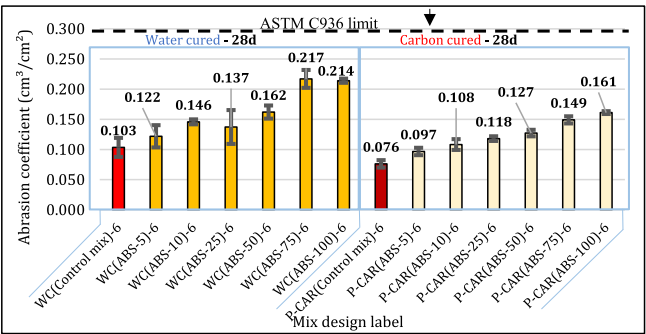


Fig. 27. A_c of water vs carbon-cured concrete at 28-days.

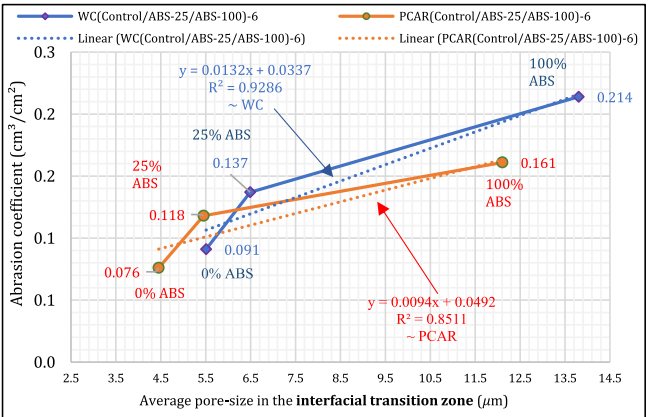


Fig. 28. Correlation between the abrasion-wear resistance vs average pore size in the bulk HCP.

pore size in the bulk HCP.

4.6. Abrasion resistance of concrete

4.6.1. Results of the abrasion resistance of concrete

Table 8 presents the average abrasion coefficient (A_c) for mixes made using ABS WEEEP at different replacement intervals at 7 and 28-day curing. The A_c was determined by taking the average of eight readings. Fig. 25 presents photographs of WC mixes containing 0 % and 75 % ABS WEEEP replacements for visual aid. Comparing the mix containing ABS WEEEP to the Control indicates deeper craters for ABS-containing

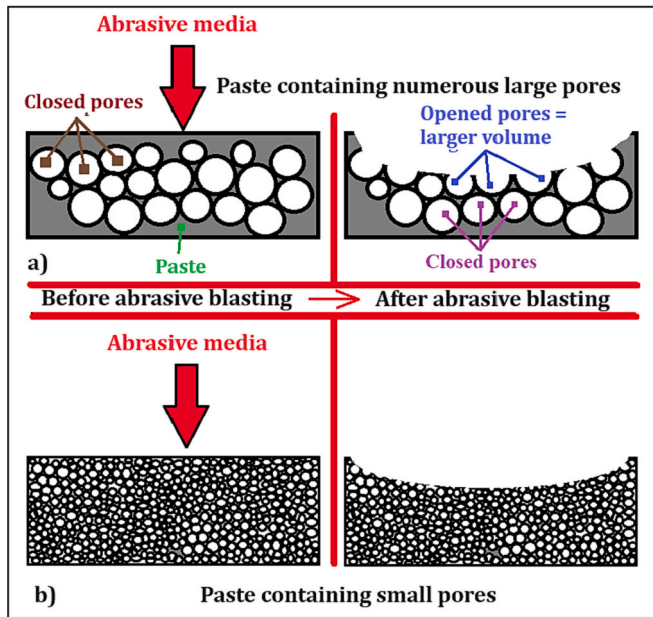


Fig. 29. Comparison of the abraded area of concrete containing large pores (a) vs. concrete containing small pores (b).

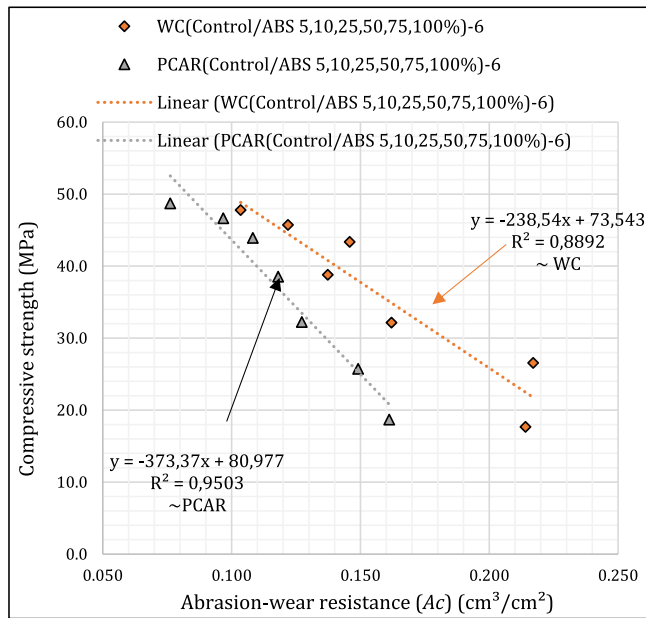


Fig. 30. Correlation between the compressive strength and abrasion-wear resistance of concrete using ABS WEEEP.

concrete (indicating reduced abrasion-wear resistance). In addition, the ABS WEEEP in WC(ABS-75)-6 seem to be protruding more than the natural aggregate in WC(Control mix)-6.

Figs. 26 and 27 present bar graphs comparing the abrasion coefficient of mixes made subjected to WC and PCAR curing regimes, respectively at 7 and 28-days. The error bars indicate a confidence interval of 95 % and thus provide the range around the mean where 95 % of the results are likely to occur should the test be repeated multiple times. Results showed that all mixes attained good abrasion-wear resistance. It was noted that mixes subjected to the PCAR curing regime had lower abrasion coefficients and, therefore, higher abrasion wear resistance compared to WC-cured counterparts at 7-day curing.

Fig. 26 showed that all mixes attained adequate abrasion-wear

resistance. The graph further shows that mixes subjected to the PCAR curing regime containing 0 % and 5 % replacements had an improved abrasion wear resistance of $0.027 \text{ cm}^3/\text{cm}^2$ and $0.025 \text{ cm}^3/\text{cm}^2$, while 10 % and 50 % replacements improved by $0.035 \text{ cm}^3/\text{cm}^2$ and $0.038 \text{ cm}^3/\text{cm}^2$ when compared to the WC curing regime. The highest difference, and therefore, the most improved abrasion-wear resistance, occurred at 75 % ABS replacements ($0.068 \text{ cm}^3/\text{cm}^2$).

Fig. 28 shows a very strong linear correlation between the average pore size and abrasion-wear resistance of concrete at the HCP. This indicates that some correlation exists between the increase in A_c and an increase in pore size as the replacement level of ABS WEEEP increased.

For concrete made using ABS WEEEP, it was observed that the increased WEEEP replacement resulted in higher A_c (lower wear resistance). One possible explanation could be the porous nature of the bulk HCP with increased WEEEP replacements. The porous nature of the HCP may have provided less impact resistance, which exposed the pores and increased the volume of the abraded specimen, as shown in Fig. 29. Furthermore since the ITZ was more porous around the ABS WEEEP, it had a higher likelihood to abrade than the bulk HCP, which could then easily dislodge an ABS WEEEP aggregate, increasing the volume of the exposed region.

Fig. 30 shows a linear relationship between the average compressive strength and abrasion-wear resistance for WC and PCAR mixes, which is similar to observations made by Huovinen [92], Galvão [118] and Lv et al. [119].

It was noted that PCAR mixes had a very strong negative correlation while WC mixes were moderately lower. The data shows that as the strength decreased, the abrasion coefficient increased. This suggests that some of the mechanisms responsible for concrete failure in compression (weak ITZ and numerous pores in bulk HCP) relate to removing material and weak boundaries to open closed pores and dislodge ABS WEEEP from the concrete.

4.6.2. Applications of results for the abrasion resistance of concrete

Most codes or standards only provide abrasion-wear resistance indexes as a measure of surface quality rather than the expected life of a structure. As a result, abrasion-wear resistance is assumed adequate based on the compressive strength alone due to their respective linear relationship [34–37]. Although this is true to some extent, abrasion-wear resistance is a surface attribute. Attention should be given to different surface finishes, toppings and surface treatments [33,34,37,38]. ASTM C418 provides methods to obtain abrasion-wear resistance indexing values, which could be used to compare the abrasion-wear resistance of different mixes in concrete hydraulic structures, floors and roads [34,93]. However, many abrasion tests, including ASTM C418, do not predict the service life of a structure but are rather an indication of the surface quality. Even so, these tests often serve as good comparisons between experimental results.

Concrete floors do not often experience high abrasion-wear from pedestrian traffic due to soft rubber shoes. Abrasion in these circumstances is often derived from scraping, attrition, and local stress exerted during service life. Similarly, mechanical abrasion by light vehicular traffic is minimal due to soft rubber tyres, which have a polishing effect. On the other hand, heavy vehicular trucking and chains around tyres have been shown to exert extensive mechanical abrasion due to heavy impacts or scraping effects [34].

Results suggest that most abrasion tests generally show a poor relationship between laboratory test results and results measured in practice (ibid) as they do not simulate the actual abrasion conditions and thus have limitations to their application [120]. By contrast, Papafus [38] developed limiting criteria for abrasion wear to traffic based on strong correlations between laboratory and field results.

Papafus subjected concrete pavers to light traffic abrasion derived mainly from pedestrians and heavy traffic abrasion from busses at Westgate (Gauteng) over six years. Based on the results, it was suggested that four degrees of abrasion and two transition zones exist until failure

Table 7

Compressive strength at 3, 7, 28 and 90 days of curing.

Concrete mix label	3 Day			7 Day			28 Day			90 Day		
	fcu (MPa)	StD (%)	CoV (%)	fcu (MPa)	StD	CoV (%)	fcu (MPa)	StD (%)	CoV (%)	fcu (MPa)	StD (%)	CoV (%)
WC(Control mix)-6	33.2	1.71	5.16	39.8	1.26	3.16	47.8	0.87	1.83	52.1	0.23	0.44
WC(ABS-5)-6	32.2	0.76	2.37	38.8	0.18	0.47	45.7	0.32	0.70	49.5	0.80	1.61
WC(ABS-10)-6	30.2	2.52	8.34	35.5	0.41	1.15	43.4	0.83	1.92	46.1	0.57	1.24
WC(ABS-25)-6	25.1	0.18	0.71	28.6	0.85	2.98	38.8	0.29	0.75	40.8	0.40	0.98
WC(ABS-50)-6	20.5	0.47	2.29	26.9	1.53	5.68	32.2	1.67	5.19	33.9	1.94	5.73
WC(ABS-75)-6	17.2	0.27	1.59	21.3	0.28	1.30	26.6	1.36	5.13	28.5	0.25	0.88
WC(ABS-100)-6	17.4	0.91	5.25	16.4	0.65	3.94	17.7	1.18	6.68	27.7	0.84	3.02
PCAR(Control mix)-6	37.1	1.97	5.31	43.2	1.89	4.36	48.7	0.88	1.81	52.6	1.27	2.41
PCAR(ABS-5)-6	36.1	0.62	1.73	42.4	1.01	2.39	46.6	1.03	2.20	49.1	1.30	2.64
PCAR(ABS-10)-6	33.4	0.34	1.00	38.4	0.37	0.97	43.9	1.29	2.94	45.7	0.96	2.09
PCAR(ABS-25)-6	28.8	3.29	11.41	32.5	0.18	0.55	38.5	0.63	1.62	40.1	4.11	10.27
PCAR(ABS-50)-6	24.2	0.93	3.84	28.5	1.33	4.67	32.2	0.53	1.65	32.6	0.26	0.79
PCAR(ABS-75)-6	20.9	0.32	1.52	23.6	0.34	1.45	25.7	0.40	1.57	29.5	0.70	2.36
PCAR(ABS-100)-6	20.7	1.12	5.44	18.7	0.57	3.04	18.7	0.23	1.20	28.7	0.85	2.98

Table 8

Abrasion-wear resistance of concrete at 7 and 28-days of curing.

Concrete mix label	Abrasion coefficient at 7 days			Abrasion coefficient at 28 days		
	Mean* (cm ³ /cm ²)	StD (%)	CoV (%)	Mean* (cm ³ /cm ²)	StD (%)	CoV (%)
WC(Control mix)-6	0.156	0.05	30.45	0.091	0.04	41.70
WC(ABS-5)-6	0.204	0.02	11.73	0.107	0.04	41.38
WC(ABS-10)-6	0.195	0.08	39.83	0.146	0.01	6.74
WC(ABS-25)-6	0.199	0.05	26.46	0.137	0.07	48.89
WC(ABS-50)-6	0.224	0.04	18.63	0.162	0.03	16.06
WC(ABS-75)-6	0.239	0.03	11.38	0.217	0.04	16.35
WC(ABS-100)-6	0.247	0.02	6.08	0.214	0.01	3.88
PCAR(Control mix)-6	0.125	0.01	11.47	0.076	0.01	19.32
PCAR(ABS-5)-6	0.133	0.03	18.78	0.097	0.01	15.13
PCAR(ABS-10)-6	0.147	0.05	34.08	0.108	0.02	19.79
PCAR(ABS-25)-6	0.157	0.02	11.93	0.118	0.01	7.85
PCAR(ABS-50)-6	0.157	0.01	2.91	0.127	0.01	10.19
PCAR(ABS-75)-6	0.159	0.02	14.96	0.149	0.01	9.50
PCAR(ABS-100)-6	0.184	0.01	3.66	0.161	0.01	3.47

Table 9

28-Day limiting criteria for three abrasion tests [23].

Test	2nd Stage wear-abrasion		3rd Stage wear-abrasion	
	Severe traffic (bus lane)	Normal traffic (pedestrian sidewalk)	Severe traffic (bus lane)	Normal traffic (pedestrian sidewalk)
ASTM C418 (cm ³ /cm ²)	0.250	0.305	0.360	0.475
Mean visible depth (mm)	0.50	0.50	1.00	1.00

occurs. There are no signs of wear in the zero-degree stage, while the first stage shows some degree of wear as the top mortar layer (0.1 to 0.5 mm) is removed. In the second stage (crater depth – ASTM C418 < 0.50 mm), the aggregate protrudes slightly higher than the surrounding mortar. Similarly, the third stage (> 0.75 and <1.00 mm) is comparable to the second, except that the coarse aggregate protrudes proudly from the rest of the mortar. Lastly, at the fourth stage (> 1.25 mm), the mortar is abraded away to an extent where it cannot support the coarse

aggregate, which, in turn, breaks out of the matrix under an applied load. The first transition zone occurs between the second and third stages, while the second transition zone occurs between the third and fourth stages.

Table 9 shows the 28-day limiting criteria for the second and third stages of wear. The results have a strong (> 0.93) correlation with a mean visible depth measured after six years of service.

Although the above tests were conducted on concrete pavers with strengths >25 MPa, it is interesting to observe how the abrasion-wear resistance relates to the depth created by different types of traffic (mean visible depth). The results presented in this paper showed that the highest abrasion index value of 0.247 cm³/cm² was measured using 100 % ABS WEEEP. These results indicate that all WEEEP mixes may provide sufficient abrasion-wear resistance under severe traffic conditions for stage two wear-abrasion.

4.6.3. Potential environmental risk associated with abrading concrete made using ABS WEEEP

ABS WEEEP may either be dislodged from the concrete matrix, as presented in Section 4.6.1, or abraded over time when subjected to abrasion-wear. These two processes have the potential to add mesoplastics (plastic with a size ranging between 1 and 25 mm) or secondary microplastics (0.1 to 1000 µm) [121], which subsequently have the potential to accumulate in the environment. There is currently no known study on the potential particle size and concentration of ABS WEEEP micro-plastic derived from concrete subjected to abrasion, such as vehicular traffic, but a study by Morioka et al. [122] may aid in understanding the potential size of ABS micro-plastic found in street dust in Japan. Their study involved analysing the various particle sizes and concentrations of 12 types of microplastics such as polyethylene, polypropylene, polystyrene and ABS (derived presumably from internal automobile parts). Results indicate that most plastics, such as polystyrene, have higher concentrations with an increase in size fraction between 53 and 75 µm. In contrast, ABS showed higher concentration in size fractions between 1.1 and 2.1 µm (ibid) since ABS generally becomes brittle when exposed to UV light for extended periods [123]. This is of concern as ABS WEEEP often contains flame-retardant additives such as bromine and antimony [7], which could be harmful to humans when inhaled or digested. A study by Van den Eede et al. [124] found that flame retardants in household dust-derived from furniture, carpets and electrical and electronic equipment may cause adverse respiratory health outcomes, among others [125].

For the reasons mentioned above, it is suggested that concrete made using ABS WEEEP should preferably be used where it would be exposed to minimal abrasion, such as internal concrete members in structures such as beams, interior walls or retaining walls, similar to concrete made using polypropylene fibres in fibre reinforced concrete [126,127].

5. Conclusions

Based on the results presented in this paper, the following conclusions can be drawn:

- Concrete compressive strength decreased with increasing ABS WEEEP replacements at all ages, and curing regimes of all the mixes containing $\leq 75\%$ ABS WEEEP replacements in concrete achieved structural strength (> 25 MPa) at 28-days.

- All PCAR-cured mixes had higher compressive strengths than WC mixes at 3 and 7 days but comparable strengths at 28 and 90-days.

- The findings showed a strong negative linear correlation for WC ($R^2 = 0.9654$) and PCAR ($R^2 = 0.9522$) mixes between the increase in ABS WEEEP replacements, a decrease in compressive strength, and an increase in average pore size in the ITZ.

- The abrasion-wear resistance of concrete was reduced with an increase in ABS WEEEP substitution at 7 and 28-days for all curing regimes.

- PCAR curing increased the abrasion-wear resistance of all mixes compared to WC curing alone at 7 and 28-days.

- A positive linear correlation for WC ($R^2 = 0.9286$) and PCAR ($R^2 = 0.8511$) mixes exists between an increase in abrasion-wear resistance and the increase of pore size at the HCP and ITZ with the gradual replacement of ABS WEEEP for the natural aggregate.

- A strong negative linear correlation for WC ($R^2 = 0.8892$) and PCAR ($R^2 = 0.9503$) mixes between the abrasion-wear resistance and compressive strength was observed with the gradual replacement of the natural aggregate with ABS WEEEP.

CRediT authorship contribution statement

Lewis A. Parsons: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sunday O. Nwaubani:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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