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Alkali activated materials with recycled unplasticised polyvinyl chloride aggregates for sand replacement

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ABSTRACT

Incorporating recycled Unplasticised Polyvinyl Chloride (UPVC) aggregates into Alkali Activated Materials (AAMs) presents a promising approach to alleviate the environmental drawbacks associated with conventional recycling methods for UPVC. The distinctive characteristics of UPVC aggregates, as compared to natural sand, pose a challenge in the pursuit of enhancing the mechanical properties of composites. This research aims to achieve net-zero goals and promote circular economy principles by replacing traditional Portland cement (OPC) with low-carbon AAMs and natural aggregates with recycled unplasticised polyvinyl chloride (UPVC) which, accounts for 12% of global plastic production. Coarse and fine UPVC aggregates, measuring 4–6 mm and 0–2 mm, respectively, were incorporated into AAMs. An extensive array of tests was performed to assess their environmental benefits and overall performance enhancements. The results unveiled notable advantages in terms of thermal resistivity and resistance to chloride penetration in the UPVC-infused AAMs. Notably, mixtures containing 100% fine UPVC aggregates exhibited a remarkable 70% reduction in thermal conductivity (0.465 W/mk) when compared to the control. In mechanical assessments, composites containing fine UPVC aggregates surpassed those with coarse UPVC aggregates, showcasing promise for load-bearing applications. Substituting 30% of both fine and coarse UPVC aggregates with sand yielded impressive 7-day compressive strengths of 41 MPa and 35 MPa, respectively. Moreover, the utilisation of energy-dispersive X-ray spectroscopy confirmed the absence of chloride leaching after three months. The incorporation of UPVC waste aggregates led to a significant reduction in the carbon footprint of the tested AAMs. In conclusion, these composites offer an appealing and sustainable solution for both load-bearing and non-load-bearing structures.

1. Introduction

The cement sector is the second-largest emitter of greenhouse gases after the power plant industries. It generates around 4.1 billion metric tonnes of cement per year, accounting for 8–10% of worldwide human-caused CO_2 emissions. The industry is expected to increase CO_2 emissions in the future, necessitating a reduction of cement clinker by 60% by 2050 and the implementation of CO_2 capture and storage measures to mitigate its environmental impact, according to a Chatham House study [1]. Glukhovsky's research on "soil cements" utilising industrial waste materials as OPC replacements launched the development of Alkali-Activated Materials (AAMs) in the 1940 s and 1950 s. This laid the groundwork for further research on sustainable binding agents based on waste-based cementitious materials and activators. AAMs can reduce environmental impact while also encouraging cost-effective building practises [2]. Joseph Davidovits coined the term 'geopolymer' in 1978 to refer to an amorphous alkali aluminosilicate or alkali-activated cement. 'Geo' refers to geological or industrial materials such as fly ash, blast furnace slag, silica fume, etc., whereas 'polymer' refers to a chain of molecules derived from the same unit [3]. Geopolymer cement

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production emits only 0.18 kg of CO_2 per 1 kg, approximately one-fifth of OPC production, while geopolymer concrete reduces CO_2 emissions by 26–45% compared to conventional concrete [4,5]. A generic reaction mechanism was proposed for alkali-activated materials (AAM), including silica and alumina. Geopolymers are often thought of as a subgroup of AAM with the highest amount of Al and the lowest amount of Ca. They also have a binding phase that is mostly made up of aluminosilicate. The related reactions that make up the mechanism model are destruction, coagulation, condensation, and crystallisation. The first step is to break the bindings Si-O-Si and Al-O-Si that form when the pH of the alkaline solution is raised, so that these bonds may be transformed to a colloid phase. As a consequence, the fragmented products unite and react with one another to produce a coagulated structure, which results in the formation of a condensed and crystallised structure in a third phase [6].

Polyvinyl chloride (PVC), a chlorinated hydrocarbon polymer, was first manufactured in 1930 by the United States and Germany. It gained popularity due to its low cost, elasticity, light weight, and corrosion resistance, making it a widely used synthetic plastic polymer worldwide. Its chemical formula is (C_2H_3Cl) n [7]. PVC is a widely used thermoplastic polymer with diverse applications in domestic and industrial settings. Its versatility allows for the production of short-life items like food packaging and medical equipment, as well as long-life products like plumbing pipelines, doors, windows, and roofing sheeting [8]. About 3.6 million tonnes of waste polyvinylchloride were produced in the European Union in 2000 [9]. As the availability of the material increases, the quantity of waste PVC continues to grow daily. PVC usage accounts for approximately 12% of the world's plastic consumption, which was approximately 38.5 million tonnes in 2013 [10]. The entire worldwide PVC manufacturing volume in 2018 was 44.3 million tonnes. By 2025, the worldwide PVC market is estimated to reach over 60 million tonnes [11]. Unplasticised polyvinyl chloride (UPVC) exhibits reduced flammability due to the presence of chlorine, which produces hydrogen chloride (HCl) species at high temperatures [12]. On the other hand, natural sand which, used in concrete is chloride-free, preventing steel corrosion in reinforced concrete. While sand is abundant globally, extraction for construction is limited. Arid sand particulates are too fine for concrete use, while marine sand requires desalination to reduce chloride levels [13]. Quantitative data on aggregate extraction may be unreliable, but conservative estimates suggest global sand extraction exceeds 40 Gt, making it the most extracted material worldwide. The growing demand for sand has expanded sand frontiers, causing ecological degradation and environmental pollution due to significant geomorphological changes in sand regions [14]. In comparison to conventional concrete, geopolymer has a higher mechanical resistance and greater resistance to acid attacks, sulphates, and the freeze-thaw cycle. In contrast to OPC-based hydration products, geopolymer-based binders are resistant to exposure to high temperatures due to their chemical stability and fire resistance [15]. According to a study conducted by Kunthawatwong et. al (2023) [16], PVC residue from bottle labels was used as fine aggregates in geopolymer mortar at various replacement ratios with sand (5%, 10%, 15%, and 20%). The inclusion of PVC aggregates resulted in reduced mechanical strength due to a weakened interface with the paste compared to sand. However, it also lowered the composites' densities and thermal conductivities. For practical applications, a 10% substitution of PVC aggregates was recommended. In a study by El Seidy et al. (2022) [17], electric wire coating PVC waste was substituted for sand as fine aggregates in alkali-activated material composites with various PVC replacement ratios (up to 70%). The study found that adding PVC aggregates to the composites decreased their mechanical strength due to the differences between PVC and sand. However, the composites with PVC aggregates showed lower water absorption and thermal conductivity compared to those with sand. The most significant finding was that using PVC aggregates reduced CO_2 emissions by approximately 50–136% for various replacement ratios compared to using 100% sand, making it a promising approach for reducing environmental impact [17]. Numerous studies have explored the effects of incorporating PVC aggregates, granules, and wire insulation fragments in OPC-based concrete. Superplasticizer was utilised to maintain workability in lightweight concrete with PVC aggregate. Replacing sand with PVC aggregate significantly reduces concrete density, allowing for lightweight concrete production [18]. Concrete with shredded insulating wire e-waste showed marginal strength improvement. Mechanical properties, including compressive strength, follow similar trends. PVC aggregate decreases rigidity and fracture energy while increasing characteristic length, as per concrete fracture mechanics. Furthermore, PVC aggregate usage in concrete reduces chloride ion migration, potentially preventing steel reinforcing rod corrosion within the concrete [19–23].

This study, presents a comprehensive analysis of a wide range of tests performed on AAM composites incorporating UPVC aggregates. The replacement rate reaches up to 100%, involving two aggregate sizes (0–2 mm and 4–6 mm). The primary objective is to conduct an in-depth assessment of UPVC-AAM composites, aiming to provide evaluations of their strengths and weaknesses. Additionally, the study sets the stage for future research efforts focused on improving the mechanical, physical, and durability properties of these composites. While most existing research focuses on substituting sand in OPC-based cementitious composites, limited studies have been conducted on low-carbon AAM using waste aggregates. Furthermore, to the best of the authors' knowledge, there have been no comprehensive investigations on incorporating recycled, unmodified UPVC in alkali-activated materials. This research aims to fill this gap and shed light on the potential benefits of using UPVC as a feasible and more importantly sustainable alternative aggregate in AAM. Table 1.

2. Experimental structure

Fig. 1 illustrates the experimental framework and characterisation techniques used in this study to investigate the performance of low-carbon cementitious composites with waste plastic aggregate replacements.

2.1. Materials

The AAMs used in this research consists of the following components: (1) fly ash (Cemex, UK) that is in the normal fineness (N) Category of British standard BS EN 450–1:2012 [30]; (2) ground-granulated blast furnace slag (Hanson Heidelberg Cement, UK) that is in compliance with EN15167–1 [31]; (3) micro-silica (J. Stoddard & Sons Ltd), the detailed characterisations of the binders used in this work were presented in the authors' previous study [32]; (4) BS EN 410–1:2000 [33] compliant graded sand with particle sizes ranging from 0 to 2 mm; (5) Solution of sodium silicate (Na2SiO3) with a mass ratio of SiO2/Na2O of 3.23 (Solvay SA, Portugal); solution of sodium hydroxide (NaOH) with a concentration of 10 mol/l (Fisher Scientific, Germany), and (7) attapulgite nano-clay (provided by Attagel 350, Lawrence Industries Ltd., UK). UPVC aggregates provided by Rubber and Plastic Collection Services Ltd. (Berkshire, The UK), were used as sand substitution. At room temperature, the scrap from water pipes was mechanically crushed into UPVC aggregates. Afterwards, a sieve was used to generate a nominal size gradation of 4–6 mm, (named coarse, C) and 0–2 mm (named fine, F), respectively. The experimental density for both aggregate sizes was determined to be 1.6 g/cm3 for coarse UPVC and 1.5 g/cm3 for fine UPVC. According to a microstructure analysis of recycled aggregates, UPVC coarse aggregates (Fig. 2a and c) showed rounded edges and smooth surface while UPVC fine aggregates (Fig. 2b and d) showed jagged edges and rough surface.

2.2. Mix formulation and materials preparation

A total of nine AAM mixtures (see Table 2) were developed. The

Table 1
Summary of different PVC aggregates incorporating in cementitious composites.

Properties Studied	Types of (U)PVC	Type of Waste	(U)PVC Content %	Reference
Slump, fresh density, dry density, water absorption, compressive strength, abrasion resistance	Graded 2–4 mm granules and 0–0.25 mm powder	Not available	10%, 20%, 30%	Bolat and Erkus [24]
Compressive strength, splitting tensile strength	3 cm, 4 cm, and 5 cm fibres	E-waste (shredded wire)	0.4%, 0.6%, 0.8%, 1%	Gull et al.[25]
Compressive strength, splitting tensile strength, flexural tensile strength, elastic modulus, fracture mechanics	150 μm average size	Pulverized PVC	5%, 10%, 15%, 20%, 25%	Gesoglu et al. [26]
Slump, absorption, compressive strength, splitting tensile strength, elastic modulus	5 mm max. size	Scrapped PVC pipes	20%, 30%, 40%, 50%	Haghighatnejad et al.[22]
Thermal conductivity, acoustic insulation, slump, fresh density, dry density, compressive strength, flexural strength, splitting tensile strength	Graded 0.15–4.75 mm	PVC doors and windows	2.5%, 5%, 7.5%, 10%, 12.5%, 15%	Hussein et al. [27]
Slump, density, compressive strength, splitting tensile strength, elastic modulus, Poisson's ratio, drying shrinkage, and chloride ion penetration	95% passing a 5 mm sieve	Scrapped PVC pipes	5%, 15%, 30%, 45%	Kou et al.[19]
Slump, dry density, compressive strength	4 mm max. size	Ground plastic pipes	2%, 5%, 10%, 15%, 20%, 25%	Najjar et al.[28]
Slump, density, compressive strength, ultrasonic wave velocity, resistance to chloride ion penetration	Graded 0–3 mm and 3–8 mm	Scrapped PVC pipes	30%, 50%, 70%	Senhadji et al. [29]
Density, compressive and flexural strength, water absorption, chloride leach, sulphuric acid attack test, chloride ion penetration, thermal conductivity, sound insulation, freeze thaw test, thermal stability, life cycle assessment LCA, Carbon footprint	0–2 mm and 4–6 mm aggregates	Scrapped UPVC pipes	0%, 30%, 50%, 70%, 100%	Our current study

authors chose the control AAM mix formulation based on prior research in which the mechanical performance, workability, and durability of the control mix were enhanced [32]. The AAM mixes were produced in three steps. First, the dry components materials (FA, GGBS, SF, attapulgite (AT) nano-clay additive, were mixed together with aggregates (graded sand and UPVC) for aggregates (graded sand and UPVC) were mixed for 5 min at 250 rpm in the dry condition using a Kenwood planetary mixer (Germany). Sand aggregates were substituted with recycled aggregates (i.e., C and F) in fractions of 30 vol.- %, 50 vol.- %, 70 vol.- %, and 100 vol.-%. Based on the authors' earlier research, the dosage of attapulgite nano-clay addition was consistent and fixed at 1% by weight of binder to enhance the mechanical properties [32]. Second, using a magnetic stirrer, the alkali activator solutions (i.e., a combination of NaOH and Na_2SiO_3) with a constant mass ratio of 1:2, and w/b ratio of 2.5 were mixed for 5 min. Finally, already mixed alkali solutions were progressively added to the dry mixture and stirred for 10 min at 450 rpm to produce a homogenous AAM mixture. Following the mixing process, AAM fresh mixtures were cast in prismatic moulds with dimensions of 160×40×40 mm^3 and metal cubic moulds of 50 cm^3 (three samples of each mix) and kept for 24 h at 60 °C (heat curing phase), followed by 6 days at ambient temperature (air curing phase). All samples have been examined after 7 days of curing since this is typically when AAM reach the optimal alkalisation stage. For instance, 30 C, when we replace natural sand with UPVC by volume, the experimental density of UPVC in the (0–2 mm) range is measured at 1.5 g/cm^3 , while for (4–6 mm), it is 1.6 g/cm^3 . In contrast, the experimental density of natural sand is 2.35 g/cm^3 . The initial total amount of natural sand used is 1281 g for the control.

For the case of a composite with a 30% volume fraction of UPVC and a 70% volume fraction of sand (denoted as 30 C), the calculation proceeds as follows:

1. The initial volume of natural sand is calculated as 1281 g / 2.35 g/cm^3 = 545 cm^3 .
2. For the 70% volume fraction composed of sand: 545 cm^3 x 70/100 = 381.5 cm^3 .
3. The corresponding weight of 70% sand by volume: 381.5 cm^3 x 2.35 g/cm^3 = 896.5 g.
4. For the 30% volume fraction consisting of coarse UPVC: 545 cm^3 x 30/100 = 163.5 cm^3 .
5. The corresponding weight of 30% coarse UPVC by volume: 163.5 cm^3 x 1.6 g/cm^3 = 261.6 g.

Therefore, in this composition (30 C), the weights of sand and coarse UPVC can be determined as 896.5 g and 261.6 g, respectively.

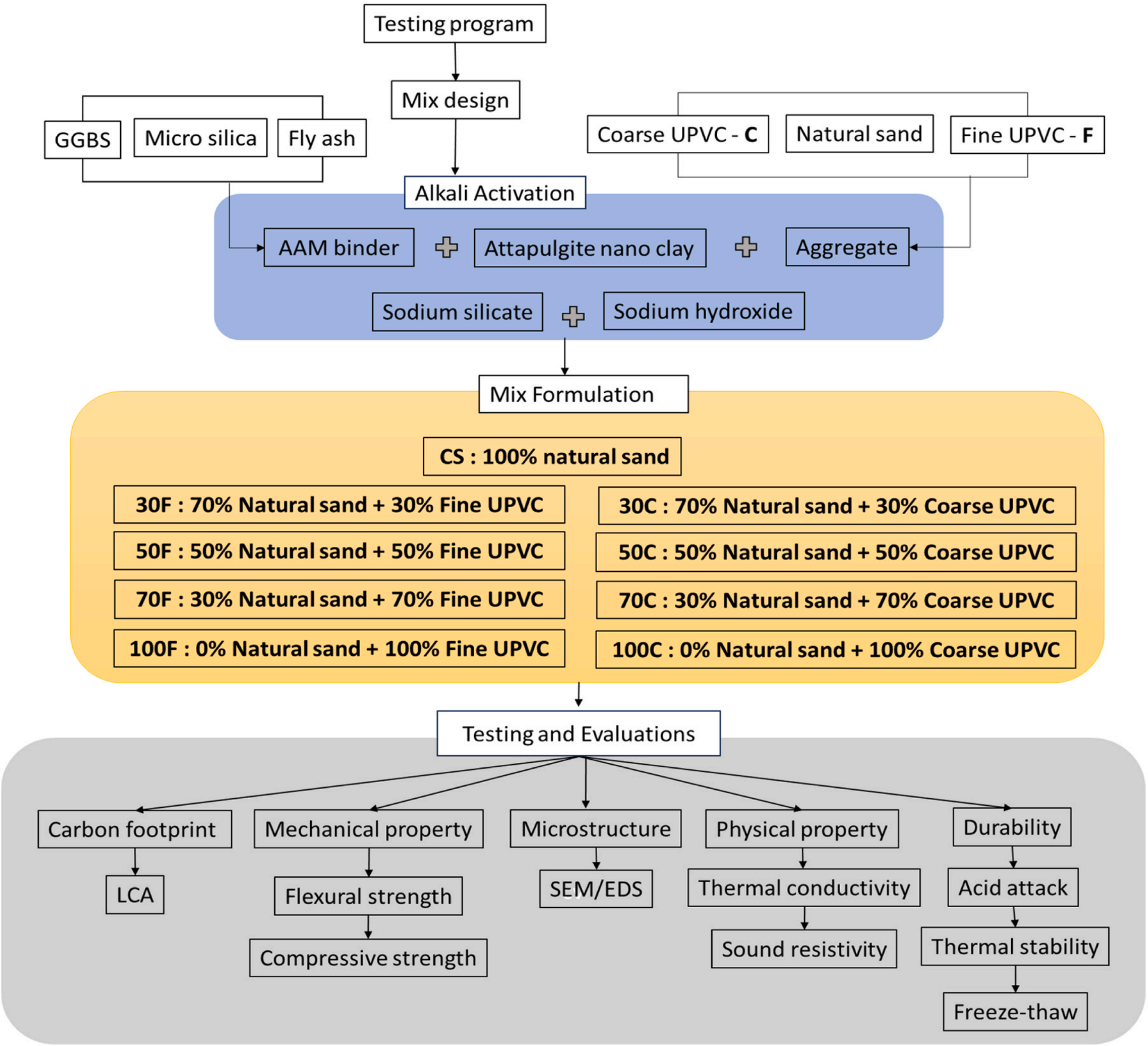

Fig. 1. The framework for experimental program and analysis.

2.3. *Experimental tests*

2.3.1. *Mechanical properties*

After seven days of curing, the mechanical performance of AAM composites (i.e., flexural, and compressive strengths) was examined using an Instron 5960 Series Universal Testing System in accordance with the standards of BS EN 196–1:2016 [34].

2.3.2. *Microstructure examination*

SEM (Supra 35VP, Carl Zeiss, Germany) was used to investigate the microstructure of AAM composites. Control samples, as well as AAM samples containing UPVC particles, were evaluated using SEM. Before inserting the samples in the SEM, they were chopped into 8 mm^3 pieces and gold-coated with an Edwards S150B sputter coater to increase their electrical conductivity. For each type of composites, an average of five samples were examined SEM coupled with energy dispersive spectroscopy (EDAX, USA) was used to analyse chlorine leaching inside AAMs containing UPVC aggregates [35]. The purpose of assessing chloride leaching was to identify traces of chloride in AAM and ensure the safe usage of recycled PVC aggregates.

2.3.3. *Water absorption*

The water absorption test was performed in accordance with a modified ASTM C1585–13 [36] protocol. To suit the purpose of this test, three cubic samples with dimensions of 50×50×50 mm^3 were cast for each mixture composition. After seven days of curing, the samples were tested. After 5 min, 10 min, 15 min, 30 min, 1 h, 2, 3, 4, 6, 12, 24, 48, and 72 h of immersion, samples were weighed. The water absorption rate of samples was calculated using the following formula:

$$Water \quad absorption \quad (\%) = \frac{M_t - M_0}{M_0} \times 100 \tag{1}$$

Where M_0 (g) refers to the oven-dried mass and M_t (g) refers to the saturated surface-dry mass.

2.3.4. *Thermal conductivity analysis*

The thermal conductivity of the AAM specimens was measured using a C-Therm TCi thermal analyzer (ASTM D7984 [37]-compliant) from C-Therm Technologies in New Brunswick, Canada. The measurement process involved applying a current to an alumina sensor’s heating element, which generated a controlled amount of heat. This heat caused a slight temperature to increase of 1–3 degrees Celsius at the sensor-composite contact. As the temperature at the contact point rose, the sensor element’s voltage drops varied accordingly. By analysing the rate of rise in sensor voltage, the thermal conductivity of the composite materials was determined. The measurements were conducted on 160×40×20 mm^3 samples, with three samples tested for each combination, and two testing points were used at room temperature. To minimise heat resistance, a contact agent (bidi distilled water) was introduced between the sensor and the sample during the

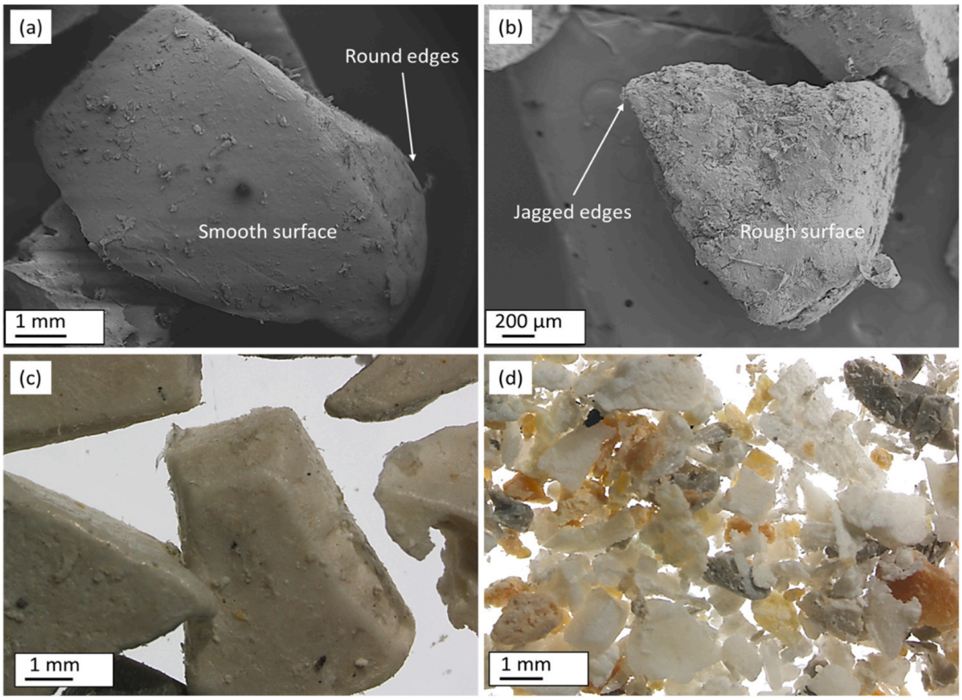

Fig. 2. SEM and optical images of UPVC (a, c) coarse, and (b, d) fine aggregates.

Table 2
Mix formulation for AAM mixtures with fine (F) and coarse (C) UPVC at different replacement ratios kg/tonne.

Sample ID	Binder (kg)			Aggregate (kg)			Activator (kg)	
	FA	GGBS	Micro silica	Recycled aggregate		Natural sand	Sodium Silicate	Sodium Hydroxide
				UPVC (4–6 mm)	UPVC (0–2 mm)			
CS	226.54	94.39	56.63	0	0	471.40	100.68	50.34
30 C	237.18	98.82	59.29	100.94	0	345.61	105.41	52.70
50 C	244.98	102.07	61.24	173.51	0	254.85	108.88	54.44
70 C	253.22	105.51	63.30	251.09	0	158.04	112.54	56.27
100 C	266.67	111.11	66.66	377.75	0	0	118.52	59.26
30 F	238.71	99.464	59.67	0	95.16	347.83	106.09	53.04
50 F	247.64	103.18	61.91	0	164.5	257.62	110.06	55.03
70 F	257.22	107.17	64.30	0	239.2	160.53	114.32	57.16
100 F	273.06	113.77	68.26	0	362.84	0	121.36	60.68

measurements. The final thermal conductivity value was calculated by averaging the measurement results from each sample, providing an accurate representation of the AAM composite's thermal conductivity.

2.3.5. *Freeze- thaw test*

For each composite, three 50×50×50 mm^3 cubes were frozen and thawed in computer-controlled freeze-thaw chamber using the ASTM C666/C666M standard [38]. The freezing and thawing temperatures (F-T) were − 20 °C and 20 ± 2 °C, respectively and 95% RH. The freezing and thawing times were both set to 12 h, implying a single F-T cycle. Furthermore, the number of F-T cycles is 70. The deterioration of the AAM's structure owing to F-T cycles was then investigated in terms of weight and compressive strength loss.

2.3.6. *Chloride attack test*

As per ASTM D114198 [39], samples of composites were immersed in a 5% NaCl solution for this test. For six weeks, samples measuring 50×50×50 mm^3 were submerged. Following that, all samples were dried, and then the degradation of composite mechanical characteristics caused by chloride penetration was investigated in terms of compressive strength loss.

2.3.7. *Acid attack test*

Cementitious samples measuring 50×50×50 mm^3 were tested for acid resistance by immersing them in an 5% sulphuric acid solution for 28 days in accordance with ASTM C189820 [40]. The damage to the composite's mechanical properties due to acid attack was then investigated in terms of weight loss and compressive strength loss.

2.3.8. *Thermal stability analysis*

According to Ali et al. (2021) [41], the highest overall geopolymer mass loss when exposed to heat occurs at three levels: a) free and chemically bound water dehydration (up to 200 °C); b) de-hydroxylation in the presence of Si-OH, Al-OH, and even Ca-OH groups (300–650 °C); and c) carbonate-class breakdown mechanisms (over 750 °C). In this study, the AAM composites are made with UPVC aggregates, which melts at temperatures ranging from 115 °C to 245 °C [42]. Eventually, the AAM composites of this study measuring 40×40×40 mm^3 were exposed to elevated temperatures increasing by 5 °C per minute from room temperature to 250 °C for an hour. The degradation of the samples was inspected in terms of weight loss, visual appearance, and compressive strength loss.

2.3.9. *Sound insulation assessment (Eq. (2))*

Sound insertion loss (SIL) is an acoustic parameter used to assess the noise barrier characteristics of various construction materials. SIL is precisely defined as the decrease of noise level at a specific location caused by the installation of a noise control device (noise barrier) in the sound channel between the sound source and that position [43]. In this study, SIL serves as an indicator to assess the impact of UPVC aggregates on the noise attenuation performance of AAM composites. The experimental characterisation was carried out using a resistance tube system and the ISO 7235 standard [44] technique on a batch of three prismatic samples measuring 80×40×40 mm^3. The SIL-index was experimentally evaluated by measuring the sound pressure level decrease when the test material was inserted in the tube between two ¼” microphonic transducers. After positioning and calibrating the microphones, a loudspeaker (power of 30 W) placed at one end of the tube emitted a sine wave signal of specific frequency. The microphone upstream of the sample records the sound pressure level of the incident acoustic wave. The transducer placed after the sample records the transmitted signal. The difference in sound pressure level between the incident and transmitted levels was examined over two frequency ranges: low-medium (100 Hz, 250 Hz, 500 Hz) and high-frequency (1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz). By averaging the SIL values in each frequency band, the sound reduction index (SRI) may be calculated, which is a performance indicator that gives a more thorough and exact assessment of the acoustic reduction behaviour. SRI is a single measurement (in decibels) that quantifies the decrease in sound intensity as it travels through a barrier, indicating the material’s efficacy as an acoustic insulator. SRI is measured in two frequency ranges in accordance with the equations below.

$$SRI_{low-middle \quad frequency \quad range} = \frac{SIL_{(63Hz)} + SIL_{(125Hz)} + SIL_{(250Hz)} + SIL_{(500Hz)}}{4} \tag{2}$$

$$SRI_{high \quad frequency \quad range} = \frac{SIL_{(1000Hz)} + SIL_{(2000Hz)} + SIL_{(3000Hz)} + SIL_{(4000Hz)}}{4} \tag{3}$$

2.3.10. *Carbon footprint analysis*

The impact of replacing sand with recycled coarse and fine UPVC aggregates was evaluated through a carbon footprint assessment. A carbon footprint calculation method was used to figure out the embedded CO2 (ECO2) of AAM composites. The carbon emission coefficients (EC) of the raw materials, as previously determined in another study by the authors, were employed [45,46]. A life cycle assessment (LCA) was conducted using SIMAPRO software, following ISO 14040 standards [47], to analyse the environmental impact associated with the processing of recycled aggregates [48]. The recycling models considered the energy input from the European medium-voltage power supply for grinding operations and accounted for the quantity of recycled material recovered as an avoided product. It was assumed that all waste entering the system was treated and made recyclable, and the proportions of the avoided product were aligned with the functional unit. Additionally, the environmental contribution of the avoided product was expressed as a negative value, indicating a net environmental benefit in terms of carbon footprint. The Intergovernmental Panel on Climate Change (IPCC 2021)[49] impact assessment approach was used to assess the environmental consequences, providing CO_2-equivalent values for each kilogramme of recycled material generated. The recovery operations relied on secondary data from the Ecoinvent 9.3 database, recognised as a comprehensive and reliable life cycle inventory (LCI) database [17]. The functional unit is defined as 1 m^3 of the mixture. Consequently, the environmental impacts of the individual components are assessed from cradle-to-gate, considering the geographical allocation of processes within Europe. The evaluation of recycling processes adopts a "cut-off" approach, assigning environmental costs and benefits to the material’s second life cycle. This allows for the aggregation of environmental impacts related to the different mix formulations. The total Global Warming Potential (GWP) of each mixture was computed as the algebraic sum of the ECs of each component composing the mix.

3. Results and discussions

3.1. *Mechanical properties*

The size, characteristics, and replacement ratios of aggregates determine the mechanical properties of AAM composites[17]. The flexural and compressive strengths of specimen incorporating UPVC aggregates are illustrated in Fig. 3. Evidently, increasing the volume percentages of UPVC aggregates resulted in a gradual decrease in compressive and flexural strengths. This might be because of the hydrophobic nature of UPVC used in this study, and its low specific gravity of aggregates (e.g., 1.55 g/cm^3) as compared to natural sand aggregates (2.35 g/cm^3), resulting in a lower density and, therefore poor adhesion between the aggregates and the matrix, eventually, inferior mechanical performance [17,46,50]. When natural sand was substituted with UPVC fine aggregates (0–2 mm), composites displayed higher flexural and compressive strength values than their UVC counterparts with coarser aggregates (4–6 mm). The compressive strengths of 30 F and 30 C were reduced by around 20% and 30%, respectively, while 100 F and 100 C revealed compressive strength reductions of roughly 33% and 42%, respectively, compared to the control. The composites’ flexural strength followed a similar trend. 30 F and 30 C and 100 F and 100 C exhibited flexural strength decreases of 20% and 33% and 44% and 66%, respectively, compared to the control. The reported findings might be attributed to the increased plastic hydrophobic surface area of the UPVC, which results in a weak interaction between aggregate and matrix [51] (see Fig. 4 a-b). The mechanical properties of the composites developed during this work are influenced by two key parameters: (1) the UPVC aggregate sizes, with fine (0–2 mm) aggregates being more compatible with the AAM matrix than coarse (4–6 mm) aggregates, and (2) the aggregate replacement ratio. The augmentation in plastic aggregate size had an adverse effect on the mechanical properties, primarily due to the larger smooth surface of plastic, which weakens the interfacial bond between the aggregate and the cementitious matrix. Additionally, the shape of the plastic aggregate also played a crucial role, as lamellar aggregates exhibited a more pronounced detrimental impact than spherical ones [51], (see Fig. 2.).

Moreover, the deterioration in mechanical properties is due to the difference in characteristics between natural aggregate and polymeric substitutes. The substitute’s mechanical properties are inferior, causing polymer to behave like voids or porosities, weakening the structure and causing a decline in mechanical properties with the increase in the polymer replacement ratio [9]. Several studies align with the observations of our research, the lamellar shape increased the surface area and water demand, consequently leading to a further weakening of the interlock zone between the aggregate and the matrix Eventually, the plastic coarse aggregates with a larger surface area become less entangled with the matrix than the fine plastic aggregate, resulting in a reduction in the composite’s overall mechanical strength. Lamellar aggregates exhibited a more negative influence on plastic aggregate shape than spherical aggregates. The lamellar form of plastic aggregate may increase surface area and hinder paste-aggregate interlock [52–55]. It is important to note that the SEM was solely used to analyse the aggregate-matrix interfacial bond. Because of the comparable big dimensions of both UPVC aggregate sizes, there are no differences in matrix morphology. Even though all developed composites displayed compressive strengths of more than 30 MPa, additional research is needed.

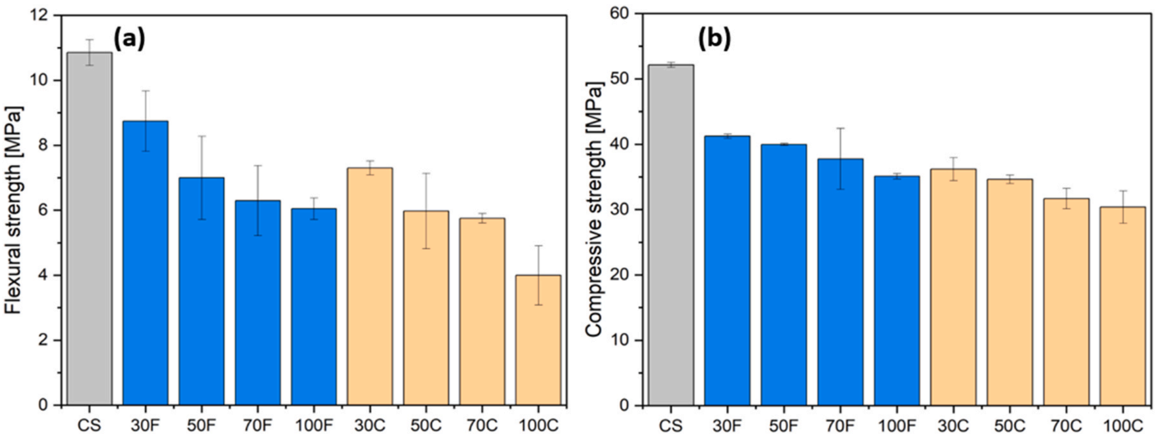

Fig. 3. a) Flexural and b) compressive strengths at 7 days for AAM composites with UPVC aggregate replacements at different ratios and sizes.

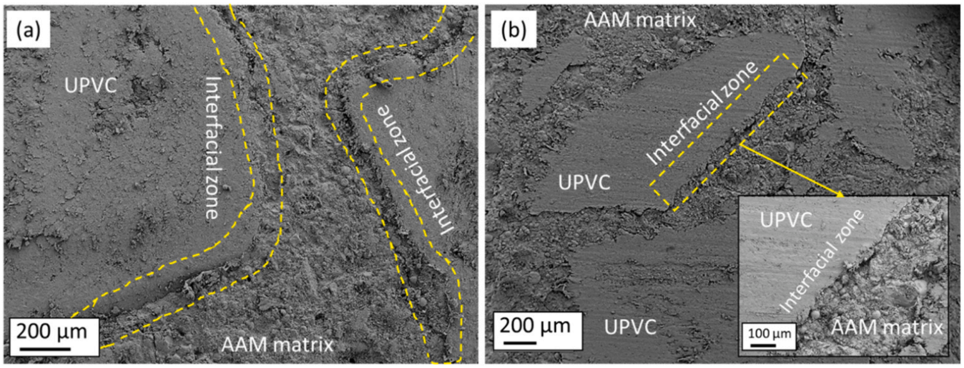

Fig. 4. SEM Images of AAM composites with coarse (a) and fine (b) UPVC aggregates.

3.2. *Physical properties*

3.2.1. *Water absorption*

All the composites displayed a similar increasing trend in water absorption over time (see Fig. 5 a and b). The control specimen had the lowest water absorption rate, while 100 F and 100 C had the highest (see Fig. 5 a and b). After 72 h, the control had around 2.7% water absorption, whereas 100 F and 100 C had about 3.5%, leading to a 29% increase in water absorption compared to the control. The water absorption of composites containing coarse UPVC aggregates increased depending on the integrated amount of polymer aggregates. 30 C had the second lowest water absorption of 2.8%, with a 4% increase compared to control. Moreover, the water absorption of, 50 C and 70 C increased by 18% and 25%, respectively. Composites containing fine polymer aggregates, on the other hand, showed an unproportioned tendency towards increasing their water absorption rate as the amount of integrated polymer aggregates increases. Water absorption increased by around 18%, 11%, and 4% for 30 F, 50 F, and 70 F, respectively,

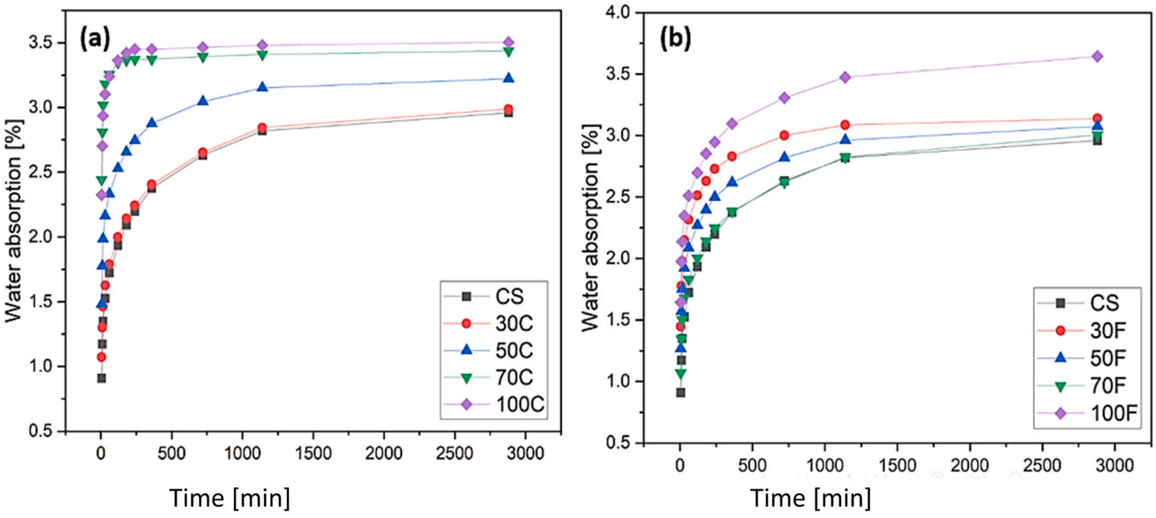

Fig. 5. Water absorption of composites with a) coarse aggregates and b) fine aggregates of UPVC at different replacement ratios.

when compared to the control (see Fig. 5 b). The disproportionate water absorption tendency observed in composites containing fine UPVC particles could be attributed to the lower density of the fine aggregates (1.5 g/cm^3) compared to the density of the coarse aggregates (1.6 g/cm^3), resulting in a higher proportion of coarse aggregates at equivalent replacement ratios. The lightweight and small size of the fine particles contributed to an uneven distribution of aggregates within the matrix, consequently impacting the water absorption behaviours. The results of this study align with previous researches [56–59], indicating that the inclusion of plastic aggregates in cementitious composites results in elevated water absorption. This increase in water absorption, observed with higher plastic content, can be attributed to inadequate mixing and the introduction of heterogeneities caused by the plastic aggregates into an initially homogeneous cement matrix. Consequently, these factors contribute to an increased porosity of the developed composites. Moreover, it was stated by L. Gu et al. (2016) [60] that the replacement quantities, type, size, and shape of the utilised plastic aggregate may all alter the morphology of concrete or mortar containing plastic aggregate. Záleská et al. (2018) [61] proposed that the hydric performance of developing building materials be evaluated on a case-by-case basis. In general, the water absorption increase in our investigation was obviously minimal; the maximum water absorption value was about 3.5%, demonstrating the capabilities of the composites' included with UPVC aggregates to preserve water absorption at a tolerable level.

3.2.2. *Thermal conductivity analysis*

UPVC is a form of plastic that has low heat conductivity [46]. When UPVC aggregates replace sand in mortar, its overall composition changes, decreasing heat conductivity. The plastic particles operate as insulators inside the concrete matrix, creating air pockets or spaces that prevent heat transmission, air thermal conductivity is about 0.024 W/mK [62]. Notably, the decrease in heat conductivity depends on several parameters, including the quantity of plastic particles, their size and shape, and the overall composition of the mortar mixture. As shown in Fig. 6**.** samples containing fine UPVC particles (100 F) had the lowest thermal conductivity, measured at 0.465 W/mk, which is about 70% lower than the control. At the same time 100 C achieved the second lowest thermal conductivity of 0.638 W/mk, which is about 60% lower than the control. The thermal conductivity of composites showed a clear trend: as the UPVC aggregate content increased, the thermal conductivity of the composites dropped. Furthermore, composites with fine particles displayed better thermal resistivity for all replacement ratios, than their counterparts with coarse aggregates. Thermal conductivity decreased by around 27%, 40%, and 57%, respectively, when 30 F, 50 F, and 70 F mixtures compared to control. 30 C, 50 C, and 70 C composites on the other hand, showed thermal conductivity decreases of roughly 20%, 25%, and 44%, respectively, when compared to the control (see Fig. 6). This may be because fine UPVC aggregates improve insulation. Because fine UPVC particles have a greater packing density inside the matrix, they provide superior insulation. The tightly packed, fine UPVC particles produce extra heat conduction barriers, lowering thermal conductivity. It is crucial to note that the exact influence of UPVC aggregate size on thermal conductivity is also dependent on other parameters like the composites' particular composition, dispersion, and overall microstructural properties. Our findings were supported by Basha et al. (2020) [63], who stated that the thermal conductivity of samples of OPC-based concrete developed with different types and quantities of recycled plastic aggregate (RPA). The thermal conductivity of the control concrete was 1.7 W/mK, whereas the thermal conductivity of the RPA-incorporated samples varied between 1.1 and 0.6 W/mK. Because of plastics' low thermal conductivity, the thermal conductivity of concrete tends to decrease as the quantity of RPA increases. The thermal conductivity of concrete developed using different types of RPA changed just a little. Furthermore, the results of [29,64,65] are comparable to our findings and consistent with our observations. The decrease in heat conductivity observed in the AAM composites is attributed to the inherent properties of UPVC aggregates. Compared to conventional sand aggregates, UPVC, being a plastic material, exhibits lower heat conductivity. Consequently, incorporating UPVC aggregates introduces voids or air pockets that hinder heat transfer, leading to a lower thermal conductivity rating. These findings suggest the potential of using UPVC aggregates to enhance the thermal insulation properties of cementitious composites, which could have significant implications for the energy efficiency and thermal performance of buildings constructed with such materials.

3.2.3. *Freeze -thaw test*

The ability of a material to withstand cyclic freezing and melting is known as freeze and thaw resistance. It is one of the most essential phenomena that describes a material's durability. The irregular and nonhomogeneous pores of the matrix may compensate for these hydraulic forces to some degree, but when these pores are filled, the matrix may suffer from internal pressures caused by the freezing of water, which expands by roughly 9% by volume during the frozen state. When the pressure level exceeds the matrix's stress, micro-cracks may form, and the propagation of these micro-cracks and their connection to one another may result in degradation [66]. Fig. 7. illustrates compressive strength and weight loss of the composites with UPVC aggregates after

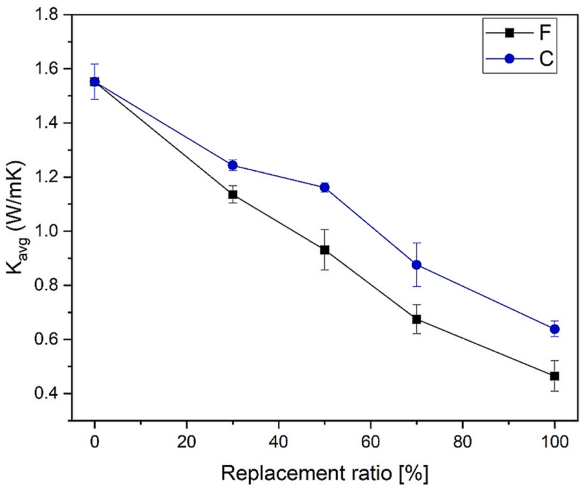

Fig. 6. Thermal conductivity of AAM with fine and coarse UPVC at different replacement ratios.

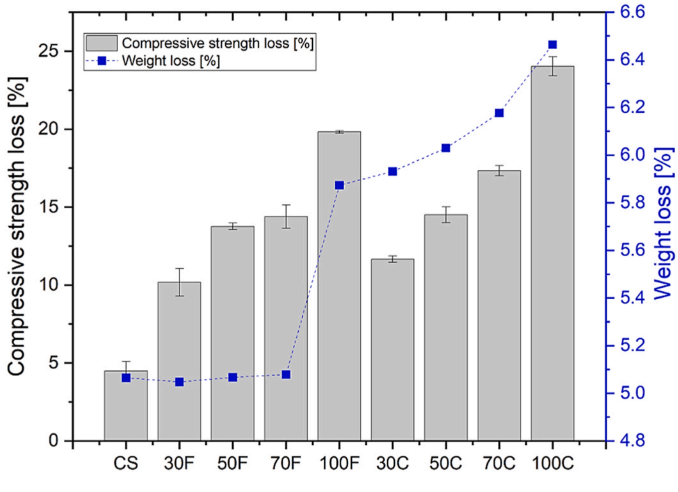

Fig. 7. Variation of the compressive strength and weight loss of the AAM composites with fine and coarse UPVC at different replacement ratios after F-T cycles.

70 freezing and thawing (F-T) cycles. There was a definite pattern of compressive and weight losses, which increased with the proportion of UPVC in the composites. Moreover, the composites with fine UPVC particles showed less relative deterioration compared to their counterparts with coarse UPVC particles. This may be due the superior mechanical properties of the composites with fine aggregates, which is due to an intimate interlock between aggregates and matrix (see Fig. 4 a). The control specimen recorded the lowest compressive strength and weight loss of about 5% after 70 F-T cycles. On the other hand, 100 C recorded the highest loss of about 23% and 6.5% for compressive strength and weight, respectively. The other composites exhibited a similar pattern of proportionate loss of compressive strength and weight as the quantity of UPVC particles increased. The loss in mechanical capabilities and weight following the freeze and thaw cycles was caused by the materials' repeated thermal contraction and expansion, which caused cracks and voids to develop in the composite. The Thermal Expansion Coefficient (CTE) is a measure that indicates how a material reacts to changes in temperature. It describes the extent to which a structure expands or contracts when subjected to variations in heating and cooling. CTE is crucial in understanding how construction may undergo dimensional changes due to temperature fluctuations. CTE values in cementitious composites are significantly affected by the variety of aggregate used in its production [67]. Even though the CTE of is based on the combined CTE of the cement paste and aggregate, the aggregate is still the most important factor in determining the CTE of concrete (mortar) because it makes up most of the structure. The CTE varies depending on the aggregate type [68,69]. The thermal coefficient of expansion (contraction) of polymers is substantially larger than that of inorganic materials [70]. Eventually, incorporating UPVC aggregates in the inorganic AAM matrix promoted the composites deterioration after F-T cycles. The weight loss of the composites was consistently similar, ranging from 5.1% to 6.5%. This similarity in weight loss can be attributed to the comparable mechanical properties of the composites, which ranged from 40 MPa to 30 MPa. The findings of our study align with those of Mahmood et al. (2020) [71], who stated that the compressive strength and relative dynamic modulus of elasticity of concrete made with modified waste expanded polystyrene (MEPS) aggregates declined considerably after 300 freezing and thawing cycles. Furthermore, fine lightweight aggregates were shown to be less vulnerable to freezing and thawing cycles than coarse lightweight MEPS aggregates.

3.2.4. *Chloride attack test*

Chloride-induced corrosion is a widespread durability concern that continues to trouble reinforced concrete buildings across the globe Each year, about 3.4% of worldwide GDP ($2.5 Trillion) is spent on preventing, mitigating, and repairing civil infrastructure damage caused by chloride-induced corrosion [72]. Chloride transport in porous cementitious materials is influenced by hydrostatic pressure, capillary absorption, and diffusion. Under pressure gradients, chloride ions enter the cement matrix, while capillary absorption allows for ionic liquid absorption in small pores. Chloride ions also diffuse across the material following concentration gradients. When the concrete is sufficiently saturated, a considerable amount of chloride ions permeate into the bulk through interconnected pores with lower initial chloride concentrations [73,74]. Fig. 8. illustrates the observed variation in the compressive strength of the composite during the chloride attack test. Except for 100 F and 100 C which had a decline of about − 7%, all composites showed enhancements in compressive strength. However, as the content of UPVC aggregates increased, the magnitude of compressive strength improvement exhibited a clear declining trend. Among all the composites, 30 C and 30 F demonstrated the highest improvements in compressive strength, approximately 20% and 13%, respectively. On the other hand, CS and 70 C exhibited the lowest improvements in compressive strength, approximately 3% and 2%, respectively. This study's findings are consistent with a previous investigation. According to Almeshal et al. (2020), [75] the increased resistance to chloride penetration is due to impermeable PVC particles that obstruct the passage of the chloride ion. In a study conducted by Xiaoyan Li et al. [76] (2022), it was observed that the addition of fly ash (FA) and ground granulated blast furnace slag (GGBS) to ordinary Portland cement (OPC)-based composites resulted in enhanced compressive strength following chloride ion attack. At 28, 100, and 180 days, the compressive strength improvements were measured at 3%, 14%, and 8%, respectively. This improvement may be attributed to the chemical reaction between chloride ions and GGBS in the hydration process, leading to the formation of Friedel's salt. The presence of Friedel's salt helps seal off some micro fractures, thereby contributing to the overall enhancement in compressive strength. Friedel's salt formation has been reported in another study carried out by T. Zhang et al. (2023) [77] on AAM-based composites using GGBS as a binder. Furthermore, in a research study conducted by S.C. Kou et al. (2009) [19], PVC plastic waste granules were introduced into an OPC-based composite at different volume percentages, ranging from 0% to 45%. The investigation focused on assessing the impact of these granules on chloride ion penetration after 28 and 91 days. The outcomes of the study indicated that with the increase in the volume of PVC granules, the penetration of chloride ions decreased. The observed increase in compressive strength in our study's control specimen can be attributed to the enhanced mechanical strength resulting from the hydration of GGBS. However, in the case of composites containing up to 70% UPVC aggregates, both as fine and coarse aggregates, the improvement in mechanical properties can be attributed to the combined effects of GGBS hydration and the blockage of ions by UPVC aggregates. Beyond the 70% replacement of UPVC aggregates, the observed mechanical improvement diminishes. This decline can be attributed to the fact that, at this point, the original mechanical properties of the composites have reached their lowest levels. Consequently, neither the hydration process nor the ion blockage provided by UPVC aggregates are sufficient to maintain the strength of the composites. Instead, they contribute to the deterioration of the overall mechanical performance of the composites.

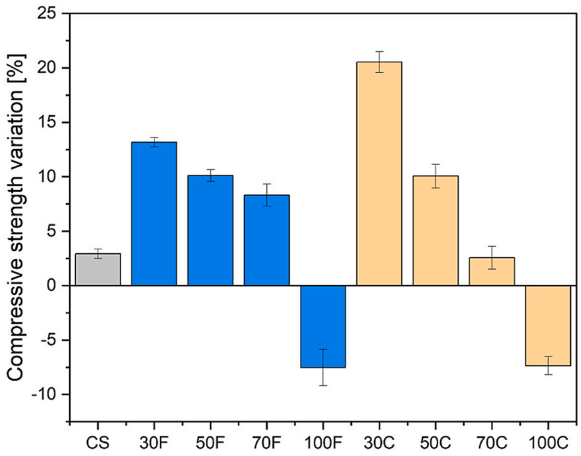

Fig. 8. Variation in the compressive strength of the AAM composites with fine and coarse UPVC at different replacement ratios after the Chloride attack test.

3.2.5. *Acid attack test*

The global economy's rapid growth has led to increased fossil fuel consumption and emissions like SO_2 and NO_x, causing acid rain in various regions. Acidic environments reduce building material lifespan, resulting in economic losses. OPC, is highly susceptible to acid attack [78]. Fig. 9. Illustrates composites after acid attack exposure, where all composites showed decreased compressive strength and weight loss. The control and specimen with fine UPVC particles performed better in terms of strength and weight loss compared to those with coarse UPVC particles. The control had the lowest compressive strength and weight loss at

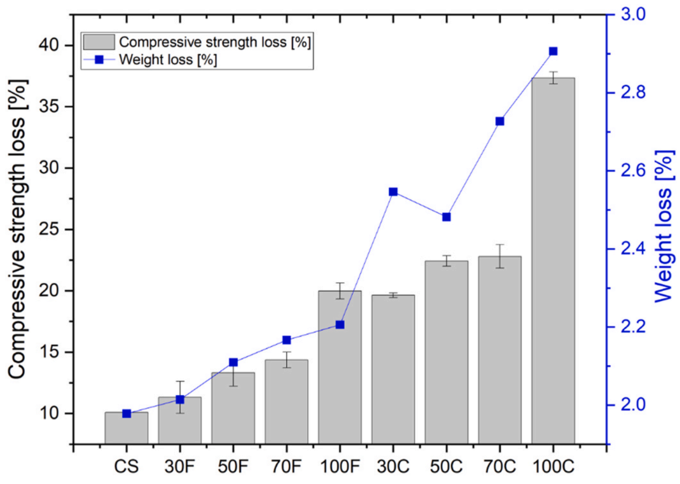

Fig. 9. Variation in the compressive strength and weight loss of the AAM with fine and coarse UPVC aggregates at different replacement ratios the after-acid attack.

approximately 10% and 2%, respectively. As the proportion of fine UPVC aggregates increased, the composites showed a clear pattern of decreasing strength and weight, with losses ranging from 12% to 17% for 30 F, 50 F, 70 F, and 100 F, respectively, which can be considered insignificant. However, composites with coarse UPVC particles showed a noticeable decline in compressive strength with increasing UPVC content. The 30 C composite had a reduction of approximately 20%, while the 100 C composite experienced a more significant decrease of around 36%. The 50 C and 70 C composites exhibited losses of approximately 22% and 23% in compressive strength, respectively. The weight loss of composites with coarse aggregates showed a minor trend, ranging from 2.5% to 2.9%. In Aan experiment by A. Nış, et al. (2019) [79] they examined the reaction of fly ash and GGBS-based geopolymer to acid attack and found similar results to this research. Cubic specimens ($150\times150\times150$ mm^3) showed more significant deterioration than cylinder specimens ($100\ \times200$ mm^3) after two months of sulphuric acid exposure, likely due to the larger surface area exposed to the acid. FA-based specimens exhibited the highest deterioration (49% loss), attributed to higher permeability and porosity in the less dense microstructure. GGBS-based specimens experienced a comparable compressive strength reduction (42% loss) attributed to the high CaO content in the sulphuric acid solution. In a study on OPC- based composites incorporated with PVC aggregates by Y. Senhadji et al. (2019) [80], they found that sulphuric acid reacts with cementitious materials to produce calcium sulphate (gypsum) and calcium sulfoaluminate (ettringite), leading to deterioration and damage in concrete. However, when PVC material was incorporated, it retained certain acid ions, reducing the abrasiveness of the acidic solution, and mitigating the detrimental effects on the OPC-based concrete. In this research, we utilised low-calcium fly ash (FA) and GGBS, both of which contain calcium. The observed damage in the composites was caused by the interaction between calcium and sulfuric acid. Notably, the fine UPVC aggregates showed excellent performance in preventing H_2SO_4 solution from penetrating the composite matrix, effectively minimising the harmful effects of acid degradation. This conclusion underscores the direct link between the mechanical properties of the composites and the degree of acid intrusion, highlighting the importance of acid resistance in determining the composites' performance.

3.2.6. *Thermal stability analysis*

The geopolymers have exceptional fire resistance due to their ceramic-like properties, and they are produced using alkali activation and alumino-silicate- based materials [81]. The degradation of this study's composites measured in terms of compressive strength and weight loss, was significantly influenced by two key parameters: the size and replacement ratios of UPVC aggregates. Notably, composites containing fine aggregates demonstrated superior mechanical properties compared to those with coarse aggregates. Furthermore, composites incorporating fine UPVC aggregates exhibited enhanced resistance to elevated temperatures, whereas composites with coarse aggregates experienced complete breakdown, making compressive strength testing unattainable. Composites with fine UPVC aggregates maintained some strength, while those with coarse aggregates completely lost their strength (Fig. 10 and Fig. 11**)**. Plastics often have low melting points temperatures ranging from 100 to 200 °C soften and deform polymers [82]. The composites thermal discrepancy may be due to the surface area and bonding characteristics of the UPVC aggregates with the matrix. Coarse UPVC aggregates possess a larger surface area and weaker bonding with the cementitious matrix compared to fine aggregates, which impacts their behaviours under thermal stress. As a result, when both composites were exposed to accelerated heat (i.e.,250 °C for an hour), the larger surface area of coarse aggregates led to more significant thermal deformation than fine aggregates. Consequently, the deformation of coarse UPVC aggregates within the (AAM) matrix induced stress on the matrix structure, causing the formation of cracks. The size of the aggregates played a crucial role, as larger aggregates resulted in more cracks and more significant damage to the composites. In contrast, the fine UPVC aggregates exhibited better compatibility and encapsulation with the matrix, mitigating the formation of cracks and preserving the overall structural integrity of the composites. For 30 F, 50 F, 70 F, and 100 F, compressive strength reductions were about 34%, 55%, 71%, and 83%, respectively. Weight reductions ranged from 4% to 16% for different composites which increased with the increase of replacement ratios. Moreover, the weight loss ratios were similar for composites of the same replacement ratios, regardless of aggregate size. Based on the findings of this study, fine UPVC aggregate replacement ratios of 30% or less is suggested to be used in AAMs to minimise matrix breakdown when a fire is anticipated.

3.2.7. *Assessment of chloride leaching*

In response to growing environmental concerns, proper PVC disposal has become crucial. PVC-based products contain additives like organotin stabilizers and plasticizers that can be released into the environment, leading to adverse health effects. Organotin catalysts and stabilizers have been linked to endocrine damage, while certain dioctyl phthalate plasticizers are listed as priority pollutants by USA Environmental Protection Agency (USEPA) and can adversely effect on reproductive health, especially in children and pregnant women. Developing effective and sustainable PVC disposal methods is essential to mitigate these risks [83–85]. The authors considered using recycled UPVC as aggregates in cementitious composites as a viable approach to preventing chlorine leakage into the environment, thus mitigating potential harm to the ecosystem. In this research, EDX line analysis was utilised to investigate the occurrence of chloride leaching at the interface between PVC and the cementitious matrix. The study selected random locations within the composite to verify this hypothesis. Fig. 12. illustrates two specific points along the UPVC/AAM interface, and a diagram showing the quantities of Cl between the two points. The x-axis refers to the distances between the two points, and the y-axis refers to Roi (Region of Interest), which refers to a specific area or region within a sample that is selected for a detailed examination of the leaching analysis. The two points are one on UPVC aggregate and the other on another UPVC aggregate across the AAM paste. The EDX results provide evidence that UPVC particles can be successfully incorporated into the AAM matrix with minimal chlorine leakage beyond the matrix structure. This incorporation mechanism effectively prevents the hazardous chlorine from permeating into the surrounding environment.

3.2.8. *Carbon footprint analysis*

Various materials were considered during the Life Cycle Inventory

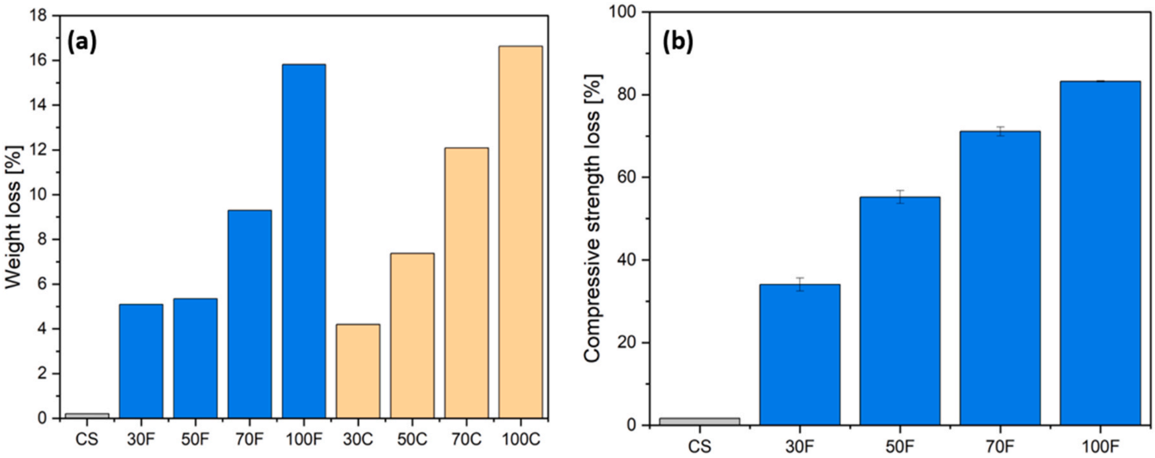

Fig. 10. (a) Weight loss and (b) compressive strength loss of the AAM composites with fine and coarse UPVC aggregates after exposure to 250 °C.

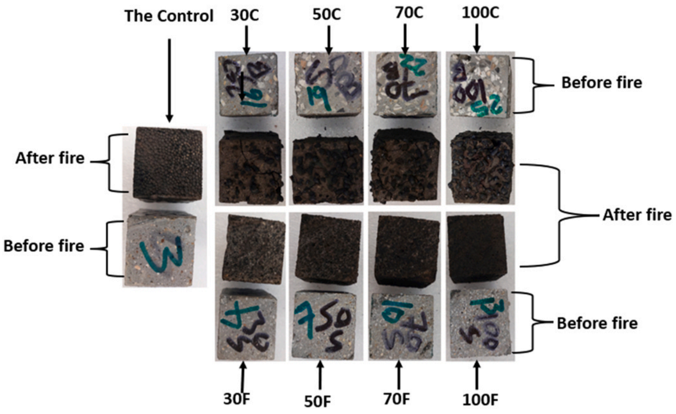

Fig. 11. Images of the AAM composites with fine and coarse UPVC aggregates after and before the 250 ∘C heat exposure.

(LCI) phase, such as fly ash, GGBS, micro silica, sand, sodium silicate, and sodium hydroxide. The process of obtaining granulated UPVC was modelled for two different size ranges. It was assumed that recycling 1 kg of granulated UPVC from 4 to 6 mm rigid PVC required the same energy consumption as finely grinding soft UPVC (i.e., 0.6 kWh). Existing literature data suggested that achieving a fine grind for thermoplastic materials demands up to six times more energy than coarse grinding, depending on the grinding technology [86]. Taking a conservative approach, the recycling process of fine granulation from rigid UPVC was associated with an electricity consumption of 3.6 kWh. The process networks related to UPVC, as provided by SimaPro, are depicted in Fig. 13**.**

Table 3. presents each component's calculated Environmental Coefficients (ECs). Notably, the results indicate positive effects for materials in their original life cycle. However, recycling of 1 kg of granulated PVC yields an environmental benefit represented by a negative value of − 1.89 kg CO2-eq. In line with life cycle thinking, the negative effects of recycling are understood as acquiring an object while avoiding its manufacturing and, consequently, all associated environmental issues. This negative value is algebraically added to the environmental impact of the grinding phase, which incurs electricity consumption of 1.38 kg CO2-eq for fine grinding and 0.23 kg CO2-eq for coarse grinding. Remarkably, both UPVC particle sizes exhibit negative impact values, demonstrating the environmental benefits of recycling. Specifically, recycling UPVC with particle sizes ranging from 4 to 6 mm results in more significant environmental benefit of − 1.66 kg CO2-eq/kg compared to recycling UPVC with grain sizes ranging from 0 to 2 mm, which yields a benefit of − 0.509 kg CO2-eq/kg. These findings underscore the advantages of recycling PVC and the importance of particle size in influencing the overall environmental benefits achieved through the recycling process.

The total Global Warming Potentials (GWPs) for the different combinations were calculated based on the various binders' proportions. The data depicted in Fig. 14. indicate that CS (Control Sample) exhibited a higher environmental impact of 0.338 kg CO2-eq compared to the other formulations. However, the environmental impact decreases as the quantity of granulated UPVC increases, i.e., substituting natural sand.

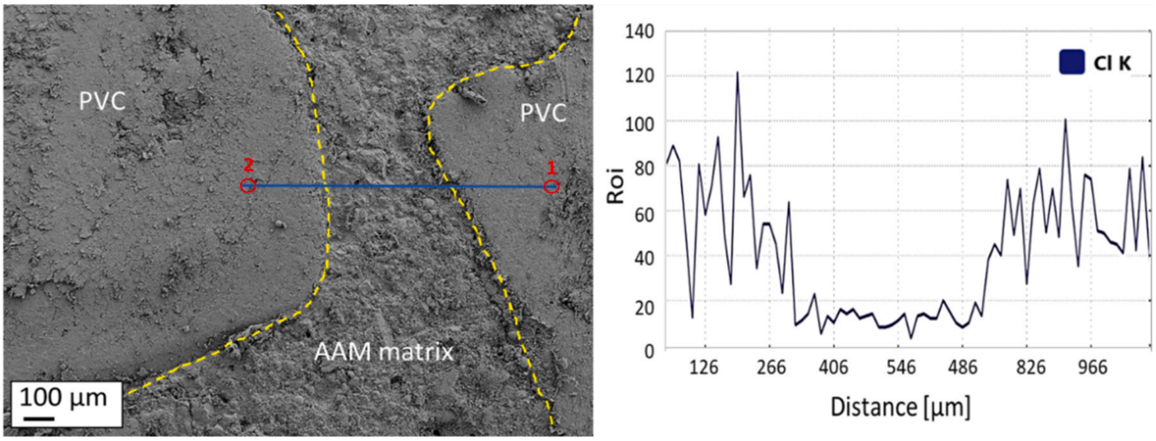

Fig. 12. Chloride (Cl) detection EDX images in the AAM composite**. Roi (Region of interest).**

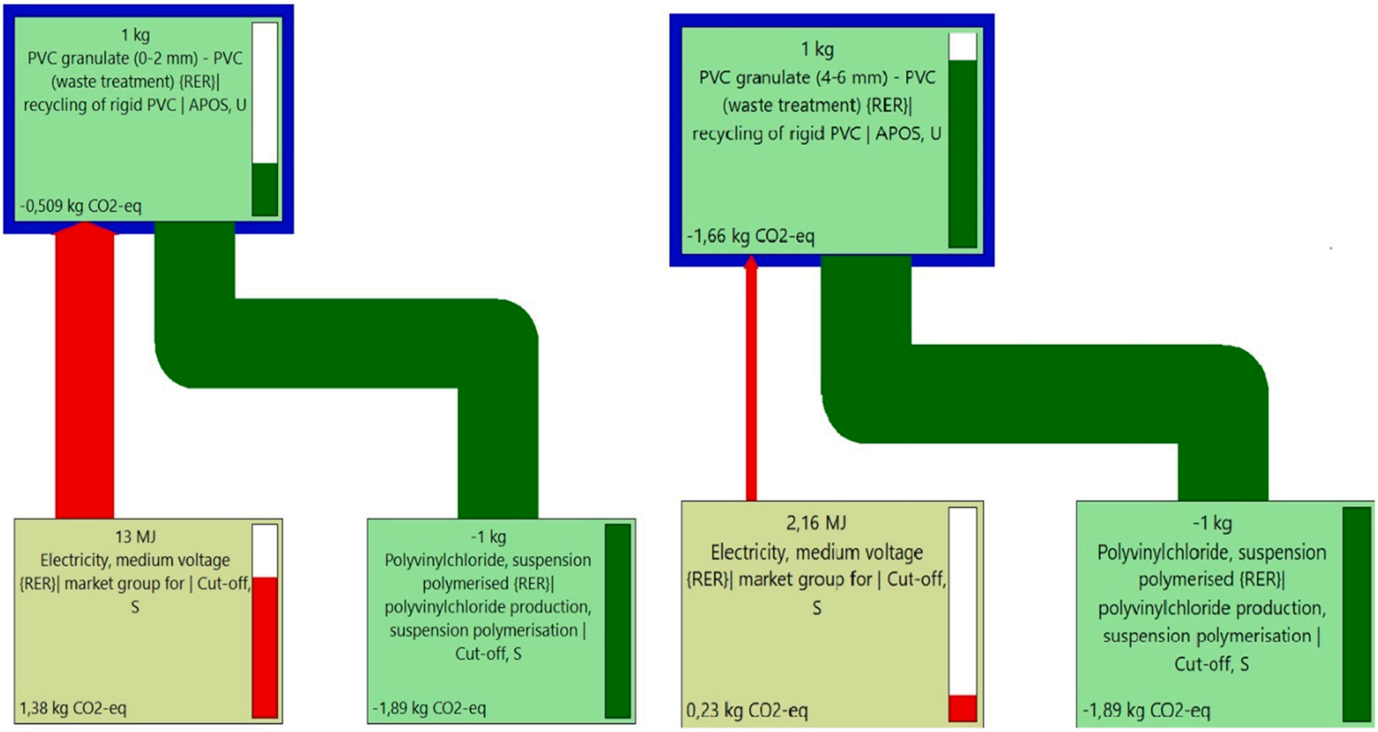

Fig. 13. SimaPro network of granulated UPVC production processes (a) fine and (b) coarse aggregates from recycled rigid UPVC.

Table 3
Environmental coefficients of the materials used for the mixtures [46,86].

Components	EC (kg CO2-eq/kg)
FA	0.0213
GGBS	0.0729
Micro silica	0.00313
UPVC 0–2 mm	-0.509
UPVC 4–6 mm	-1.66
Sand	0.00471
S.Silicate	0.705
S.Hydroxide	0.777

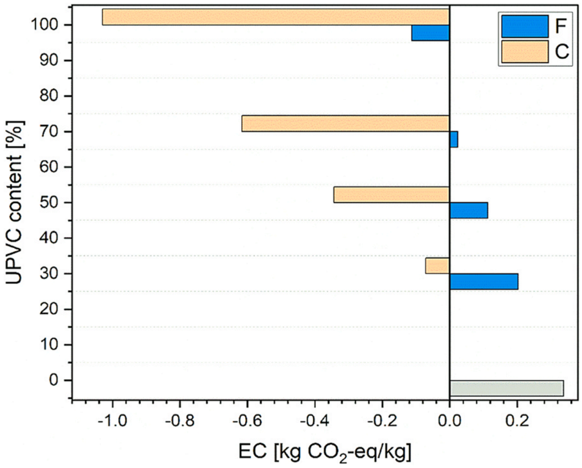

Fig. 14. GWP values of the control and composites with UPVC aggregates at different substitution percentages.

When incorporating fine UPVC granulate, the effects diminish from 0.203 kg CO2-eq for the 30 F combination to 0.113 kg CO2-eq for 50 F, further reducing to 0.024 kg CO2-eq for 70 F. Notably, the overall substitution of fine granulated UPVC may lead to a net environmental benefit of − 0.113 kg CO2-eq, showing a reduction in carbon emissions. Conversely, the coarse UPVC mix formulations demonstrated negative GWP values, implying even more significant environmental benefits. The GWP values for these combinations are − 0.071 kg CO2-eq for 30 C, − 0.343 kg CO2-eq for 50 C, − 0.616 kg CO2-eq for 70 C, and − 1.03 kg CO2-eq for 100 C. These findings highlight the positive impact of incorporating UPVC aggregates into the cementitious composites, indicating the potential to reduce carbon emissions.

SimaPro network representative of the production of the CS mixture showed that the CS aggregate is not the major contributor to the highest GWP (Global Warming Potential). However, it is crucial to recognize that the GWP indicator primarily focuses on greenhouse gas emissions. The extraction of natural sand poses significant environmental impacts, predominantly associated with the depletion of natural resources, and land use which should also be considered. Given the limitations of relying solely on the GWP indicator, the results obtained may underestimate the overall environmental impact, leading to a conservative analysis. This emphasises the need to consider broader environmental factors when evaluating the sustainability of construction materials. In this context, the environmental benefits derived from recycling UPVC justify the rationale behind designing cementitious mixtures without using natural sand as an aggregate. By opting for mixtures that incorporate recycled UPVC aggregates instead of natural sand, we not only address the reduction of carbon emissions but also contribute to mitigating environmental issues related to natural resource depletion and ecosystem disturbance. This sustainable approach aligns with the principles of circular economy and responsible resource management, promoting environmentally justifiable choices in the construction industry. SimaPro network representative of the production of the 50 F and 100 F mixtures was also investigated to study the influence of replacing natural sand with 50% UPVC and 100% UPVC particles, on the Global Warming Potential (GWP). The investigation focused on the variable parameter of aggregate replacement, which provided insights into the environmental impact of utilising UPVC aggregates. For the 50 F mixture, the GWP was measured at 0.113 kg CO2-eq, indicating a certain level of carbon emissions associated with this composition. Remarkably, the 100 F mixture exhibited a GWP of − 0.113 kg CO2-eq, signifying a reduction of approximately 200% in terms of CO2-eq (see Fig. 14.). This result implies that the complete replacement of natural sand with soft UPVC particles resulted in a net environmental benefit, considerably mitigating carbon emissions, particularly in the 100 F composition, emphasizes the potential of UPVC aggregates as a viable and sustainable alternative to natural sand, thereby contributing to environmentally responsible construction materials. On the other hand, the GWP of the 50 C mixture was measured at − 0.343 kg CO2-eq, while the 100 C mixture recorded a remarkably reduced GWP of − 1.03 kg CO2-eq. This represents a decrease of approximately 200% in terms of CO2-eq (see Fig. 14.), highlighting the substantial environmental benefits of complete replacement with coarse UPVC aggregates. At the same level of sand-PVC substitution, the extent of the carbon footprint reduction is strictly related to the type of polymeric fraction used. As expected, obtaining a finer fraction requires higher energy requirements and therefore greater carbon emissions. This relationship between energy input for grinding and carbon footprint is clearly highlighted [87]. It is equally evident that the "negative" environmental coefficient established by the recycled polymer aggregates progressively reduces the carbon footprint as the level of sand-PVC substitution increases. Although, reductions of more than 200% in carbon emissions are strongly positive in environmental terms, it is necessary to consider the significant decrease in some engineering performance of the material (specifically mechanical strength) when high substitution rates occur. For this reason, the carbon footprint analysis must be interpreted through rigorous sustainability indices combining environmental characteristics, technological performance, and final application of the material [88].

3.2.9. Sound insulation assessment

Colossal materials provide an effective sound barrier because of their great density and mechanical rigidity, making them an excellent acoustic solution in terms of insulation efficacy. As a result, the control mix is projected to have much better noise-dampening performance than the composite mixes, which include lightweight polymeric aggregates [17]. Sound reduction index (SRI) findings in (Fig. 15a and b) reveal an entirely different pattern, exhibiting comparable and greater SRI values for the developed mixes than the control for certain levels of UPVC percent replacement in various sizes. Polymer aggregates create an extra acoustic dissipation mechanism because of their viscoelastic nature and dissipative capabilities against vibro-acoustic phenomena [89]. Different auditory responses were identified in the two frequency ranges under consideration. The values of insulating ability were seen in the low-middle frequency band (<500 Hz), and the acoustic response of the studied samples was comparable, ranging from 5.50 dB in the 70 C to 8.50 dB in the 30 F. The highest SRI values were recorded for 30 F and 30 C, with increases of about 27% and 17%, respectively, compared to the control. Lightweight materials have a bad flaw due to the mass law: their low-frequency sound insulation ability is poor. To minimise low-frequency noise, a thicker material is required to provide low-frequency sound reflection without breaking the mass [90]. The impact of polymer percentage or size on the acoustic resistivity of AAM composites at high frequencies was not significant and showed an unclear pattern. As for the influence of UPVC aggregates, there was only a slight acoustic insulation effect observed at two polymer replacement levels. Specifically, the most substantial increase in SRI (+7%) was observed for the 70 F composite, and a more minor increase (+3%) was seen for the 30 C composite compared to the control. The poor sound insulation capabilities and ambiguous trend of composites using UPVC aggregates can be attributed to the lower density of UPVC compared to natural sand. Additionally, the inhomogeneous distribution of polymeric aggregates within the matrix might have contributed to these outcomes.

4. Conclusion

Utilising recycled fine and coarse UPVC aggregates sourced from discarded pipes within AAM composites represents an eco-conscious approach aligned with the sustainable objectives of the construction industry. This study was conducted to validate the potential utility of UPVC waste as aggregate materials in environmentally responsible, low-carbon cementitious composites. A thorough analysis was performed to assess the microstructure, mechanical strength, physical attributes, and durability properties of these waste aggregates, leading to the following key findings:

- Composites with fine UPVC particles showed higher mechanical performance (compressive strength: 41 MPa, flexural strength: 9 MPa) than coarse UPVC at all replacement ratios.
- Both fine and coarse UPVC aggregates reduced thermal conductivity, with the lowest values observed in 100 fine (0.465 W/mK) and 100 coarse aggregates (0.650 W/mK) specimens.
- 30% fine UPVC replaced aggregates had the lowest compressive strength and weight loss after 70 freeze-thaw cycles (i.e., 10% and 5%, respectively).

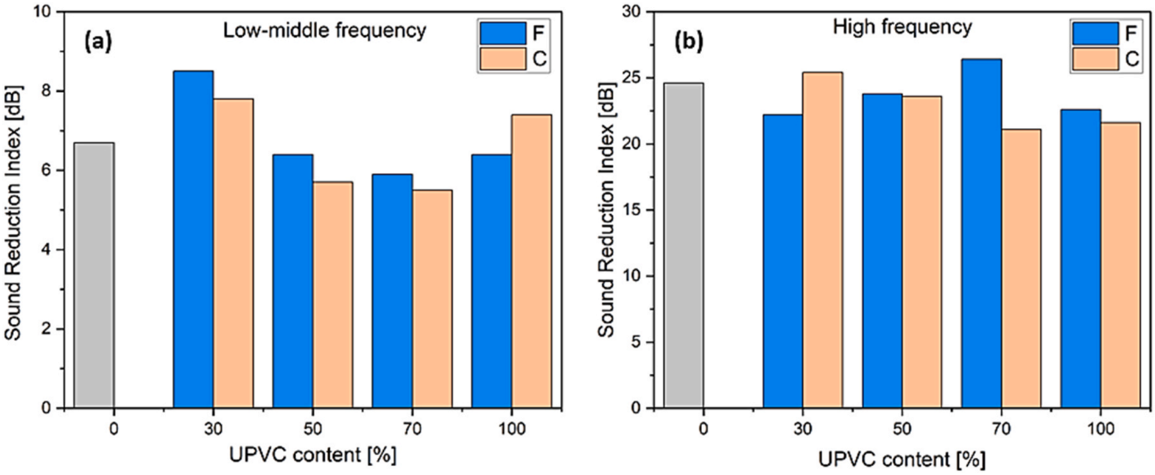

Fig. 15. Sound reduction index at different UPVC replacement ratios (a) low-middle frequency and (b) high frequency.

- After chloride penetration, 30% coarse UPVC replaced aggregates specimen exhibited a 20% increase in compressive strength.
- 30% fine UPVC replaced aggregates specimen displayed the lowest compressive strength and weight loss after exposure to 250 °C for 1 h (34% and 5%, respectively).
- The EDX findings offer evidence supporting the successful incorporation of UPVC particles into the AAM matrix, with minimal chloride leakage occurring beyond the matrix structure.
- The Sound reduction index improved by 27% (30 F) to 17% (30 C) compared to the control sample, enhancing sound insulation due to the dissipative impact of polymer aggregates.
- Using one kg of coarse UPVC as aggregates results in the avoidance of approximately 1.66 kg of CO2-eq emissions, while one kg of fine UPVC as aggregates prevents about 0.509 kg of CO2-eq emissions.
- Composites made completely of coarse UPVC aggregates have a GWP of around − 1.03 kg CO2-eq, whereas composites made entirely of fine UPVC aggregates have a GWP of about − 0.113 kg CO2-eq. This demonstrates the significance of grinding energy consumption.

The research has shown that recycled, unaltered UPVC aggregates can be effectively employed in low-carbon cementitious composites, resulting in enhanced durability, improved thermal resistance, and superior sound insulation. This presents an environmentally sound substitute for conventional natural aggregates. Further investigations are warranted to explore the feasibility of blending various aggregate sizes within composite mixes. Such an approach has the potential to enhance mechanical characteristics and expand the scope of applications for these materials. Additionally, the application of surface treatments to UPVC aggregates could offer further improvements in the overall mechanical and physical attributes of the composites.

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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