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Comparison of locally manufactured composite tile adhesive using waste material with imported tile adhesive

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HIGHLIGHTS

- Tile adhesive was prepared by mixing cement, sand, polymer additives, and autoclaved aerated concrete waste powder.
- Compositions produced from the waste materials were comparable to or better than the standard adhesive.
- Using waste materials significantly reduced cost compared to pure cement adhesive.

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ABSTRACT

One of the most important construction activities worldwide is the construction using autoclaved aerated concrete units at the global level is increasing significantly and the use of these units leads to the consumption of large amounts of resources and causes large residues waste, which leads to great damage to the environment and significant economic losses for companies and people. In recent periods, a noticeable increase has been observed in the manufacture of building units in Iraq. Iraqi factories have been affected by the waste resulting from manufacturing processes. The main objective of the study is to utilize tons of waste caused by the process of manufacturing AAC block in many Iraqi factories and turn it into a high-quality, environmentally friendly, and economical cement-based polymer-modified adhesive. The experimental part was carried out by preparing the product first and then studying properties according to international standards, SEM, EDS, mapping, and other techniques have been used to characterize the prepared samples. The adhesive properties were strongly affected by autoclaved aerated waste powder. Excellent bond strength exceeded the standard by 30%. Building units had 50% higher adhesion and 30% higher tensile strength than standard. Compared to market adhesive, the study adhesive has better properties. As for the economic factor, using waste in adhesive manufacturing reduced the price of 1 m3 by 15% compared to the reference mixture, but the study's adhesive was at least 40% cheaper than imported adhesives.

1. Introduction

The construction industry is accountable for using natural resources and generating waste during the manufacturing process of materials and building construction. Building sustainability is currently among the most crucial objectives on a global level due to the abundance and diversity of resources utilized throughout all stages of construction [1]. Dry adhesive cement-based mortars are frequently used in contemporary and traditional building projects, making them a ubiquitous, high-impact composite material for masonry and plastering applications. Additionally, the creation of these mortars necessitates the use of resources and energy in the production of binders and aggregates, which results in the management of a significant amount of waste [2].

In recent years, multiple individuals in various fields have researched the sustainable potential of recycled aggregates. These aggregates stem from construction and demolition waste and the production of building materials. Some inquiries have concluded that using recycled conglomerates yields the same results as utilizing natural ones. Furthermore, incorporating waste or by-products in the construction process has demonstrated improved ecological [3]. Low-strength cement-based construction and demolition wastes are commonly found as autoclaved aerated concrete waste (AACW) [4]. AACW is usually obtained from the demolition of heat-conservation wall material. Autoclaved aerated concrete block, on the other hand, is a well-known lightweight building material with a porous texture and weak constitution. The raw materials for these buildings usually comprise cement, lime, and silicate materials (such as fly ash and sand) [5].

Clay bricks are increasingly being substituted by concrete blocks because of the high energy-saving requirements of modern green buildings. In Iraq, the demand for concrete blocks has risen significantly. Last year in Iraq, an estimated 2.5 million cubic

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meters of autoclaved aerated concrete blocks were manufactured. The raw materials used in production contained as much as 70% sand. Generating approximately 3-5% of scrap and waste, a considerable amount of AAC residues would be produced due to the creation and disassembly of these blocks. It results in a massive accumulation of autoclaved aerated concrete blocks [6]. Limited published articles focused on AACW as a supplementary cementitious material.The Swedish architects Dr. Johan Axel Eriksson and Professor Henrik Kreüger worked to develop the autoclaved aerated concrete (AAC) in 1924 [6]. It is an environmentally friendly structural material from contemporary trash and non-toxic, non-poisonous materials. The development process may be around 20% quicker using AAC. The use of AAC block can reduce the cost of construction for facilities such as schools and hospitals by roughly 5 percent and reduce operating costs for accommodation and places of commerce by 30 to 40 percent over time. According to one study, AAC currently accounts for over 40% of all construction in the United Kingdom and more than 60% of development in Germany [7]. The production process of Autoclaved Cellular Concrete creates a distinctive building material that sets it apart from other kinds of concrete. Made up of countless small cells that develop during manufacturing, it is unlike standard lightweight aggregate or other types of concrete. This concrete also stands out because it is cured using steam in a high-pressure autoclave instead of air- or moisture-cured.

As a result of this unique process, a chemical reaction occurs within the concrete.

$$2\mathrm{Al} + 3\mathrm{Ca(OH)_2} + 6\mathrm{H_2O} \dashrightarrow 3\mathrm{CaO.AI_2O_3.6H_2O} + 3\mathrm{H_2} \qquad (1)$$

During the manufacturing of AAC block, a lot of damage occurs and causes large losses, and the rates of damage range between 3-5% of the total production quantity [8,9]. Generating from demolishing the heat insulation walls, autoclaved aerated concrete waste (AACW) is a prevalent but weak cement-based residue [10]. Typically comprised of porous autoclaved aerated concrete block, this low-strength building material is produced using calcium and silicate materials like cement, lime, fly ash, and sand. As green building regulations demand energy-saving solutions, Chinese consumption of this concrete alternative to clay bricks has rapidly risen [11] producing around 110 million cubic meters of autoclaved aerated concrete

blocks in 2015, with fly ash making up to 7% of its raw materials. As a result, the AAC block production generated scraps and wastes of approximately 3-5%, leading to large amounts of AAC residues. Furthermore, huge numbers of waste AAC blocks were created during construction and demolition. In response to the construction industry's growing demands, Autoclaved Aerated Concrete (AAC) has become increasingly prevalent. Suwan and Wattanachai [12] have reported on this development. One of the promising ways to repurpose AAC waste is as a lightweight aggregate in concrete, which was thoroughly researched. The study confirmed that manufacturing errors can make up 3 to 5 percent of AAC production. Interestingly, the increase in volume and coarse size of AAC-LWA concrete led to a decrease in its compressive strength.

Renman and Agnieszka [13] introduced a unique method of using AAC to aid in environmental improvement efforts. The study tested crushed AAC (2-4 mm), also known as CAAC, for its ability to remove phosphorus (P) by filtering PO_4-P from a solution or pure wastewater in both bench-scale and field pilot-scale experiments. While the phosphate removal kinetics of CAAC were found to be slow, the removal efficiency was remarkable at 93-99%. Mineralogical analyses using ICP-OES showed that the solid CAAC contained concentrations of 39.6 g per Kg after contact with flowing wastewater. X-ray powder diffraction (XRPD) was then implemented to identify the minerals present in AAC, which confirmed that tobermorite ($Ca_5Si_6O_{16}(OH)_2{\cdot}4H_2O$) was the dominant mineral. Upon dissolution of tobermorite's crystalline structure, the material generated was porous and rich in tobermorite, thus capable of removing P and organic matter from domestic wastewater. Prior to its application in various technical solutions, crushing and sieving are the only necessary steps to obtain the appropriate particle size distribution.on., Jesus et al. [14] collaborated on a study regarding the conduct of cementitious renderings containing exceptionally fine recycled aggregates that originated from two different types of CDW. So, this study utilized recycled concrete aggregate (RCA) and mixed recycled aggregate (MRA), whose particle sizes were below 0.149 mm, as fillers. The proportions of incorporation employed were only 0%, 10%, 15%, and 20% of natural aggregates' volume. Diverse experimentations were conducted to appraise the mortars regarding mechanical strength, water vapor permeability, water absorption, dimensional instability, and workability.

The test outcomes divulged that the mortars that had undergone modification provided better behavior than those devoid of CDW. The experimental program, carried out in a series of three phases, involved a thorough examination of the features of the top-performing mortars. It was revealed that mortars consisting of 20% RCA and 15% MRA showed the best performance overall.In this study, cementitious adhesives will be investigated, and waste materials from autoclaved aerated concrete (AAC) will be added as patrial alternative materials for cement. AAC waste was used as a partial cement alternative to manufacture high-performance and high-quality tile adhesives. All properties and specifications were studied according to international standards EN12004 and ASTM, which determine the quality of adhesives, the cost of manufacturing waste powder, and the project's economic feasibility. None of these uses were addressed by anyone before this study. In Iraq, many manufacturers of AAC blocks and AAC waste have an issue within the factory during manufacturing and end-user use.

2. Experimental works

In this study, polymer-modified cement adhesive mortar production is carried out in stages. The first stage is preparing sand by sieving it until it reaches a size below 600 µm. Then, the second stage is balancing the raw materials, cement, sand, and polymeric addities in the desired weight. The third stage is mixing all materials together with water and testing the final mixture.

2.1 Materials

Common Portland cement from the (Falcon brand) located in Iraq – Basra of generally available materials was used in this experiment. It was kept in a dry atmosphere to protect it from external elements like humidity. As a result, the cement's chemical and physical characteristics, as given in Table 1, show that it complied with Iraq's requirements (I.Q.S.) No. 5/1984 [15]. Natural sand from the Safwan area, with a maximum particle size of 0.6 mm, was used as a fine aggregate. The grade and physical characteristics of the sand utilized in this experiment are shown in Table 2, according to Iraqi Standard No. 45/1984, it is graded [16]. Table 3 shows the chemical analysis of the sand used.

Table 1: Chemical and Physical properties of cement

	I.R	L.O.I	F.CaO	SO_3	MgO	CaO	Al_2O_3	Fe_2O_3	SiO_2
Test results	1	2	1	1.6	2.5	63.5	4.3	5	20.4
SD	±0.2	±0.3	±0.2	±0.2	±0.3	±0.3	±0.2	±0.2	±0.2

	Blain cm^2/gr	Initial Setting time (min)	Final Setting time (min)	Strength Mpa	
				2 day	28 days
Test result	≥ 3400	190	280	23.6	44.8

Table 2: Sand sieving analysis

Sieve No.	Sieve opening (mm)	Mass retained (g)	Percent of mass retained Rn	Cumulative percent retained ∑Rn	Percent finer (100-∑Rn)
10	2	0	0	0	100
20	1.85	5.76	1.152	1.152	99.76
30	0.6	10.28	2.05	3.202	96.79
40	0.426	186	37.2	40.402	59.598
50	0.3	214	42.8	83.202	16.798
200	0.075	77.8	15.56	98.762	1.238
Pan	-------	5.2	1.04	100	0
Total		499.04			

$$\text{Massoss during sesieving} = \frac{w\_w1}{w} * 100 \qquad (1)$$

Mass loss= 0.192%.

Table 3: Sand chemical analysis

Chemical analysis % by weight	Sand
L.O.I	2.76
SiO_2	87.96
Al_2O_3	-
MgO	-
SO_3	0.78
Fe_2O_3	-
CaO	-
Silt	1.2
TSS	1.9
CL	0.08

Two advantages of using a finely ground calcium carbonate (90 µm) are decreased porosity and enhanced early-age strength. [17,18] Table 4 shows the chemical analysis of calcium carbonate supplied by the Iraqi southern cement company, Karbala Lime Factory.

Table 4: Calcium carbonate chemical analysis

Element	$CaCO_3$ %	SiO_2 %	SO_3 %	L.O.I	SiO_2 %	$CaCO_3$ %
Test results	81.3	11.2	1.75	31.7	11.2	81.3

In the following, introduce two additives studied in the present study. They include HPMC and PVA powder. The HPMC improves the tile adhesive's anti-slip property while strengthening its bonding strength. Increase the tile adhesive's capacity to retain water and facilitate a satisfactory water-hardening process. Good opening time and operable time, which is convenient for workers to adjust the error of tile placement. HPMC makes dry powder ingredients easy to mix without causing agglomeration, saving working time. It also makes construction more efficient, improves work performance, and reduces costs. HPMC makes tile adhesives have better plasticity and flexibility [19]. Due to its superior mechanical and chemical qualities, polyvinyl alcohol (PVA), a water-soluble polymer, is often employed in many different sectors. Polyvinyl alcohol is often used in construction as an adhesive, modifier, and pretreatment agent for aggregate surfaces, fiber reinforcement, etc. Many studies have demonstrated that adding a small quantity of polyvinyl alcohol to cement-based products during fresh mixing can increase workability and water retention [20].

Prewetting was suggested by Kim et al. [21] or manufacturing polyvinyl alcohol-modified cement-based materials. They found that this approach could reduce the porosity of modified cement-based materials to 6%. Less than 2% of PVA is used in new mortar and concrete to enhance the air void content and viewed fluidity while decreasing bleeding. The slump of the modified concrete increases as fluidity increases [21]. Over the last few years, the construction industry has been making great efforts to decrease the negative environmental impacts it produces by adopting sustainable construction practices. This involves the utilization of by-products, recycled materials, and industrial waste in construction.

2.2 Production of AAC waste

The powder for this study was prepared using a two-stage process. First, the AAC block waste was crushed with a jaw crusher machine to lessen its size and subsequently sifted to pass through a 4.75 mm sieve size. Second, the planetary was utilized to complete the milling process. The process of ultra-fine grinding brittle materials can be achieved using a ball mill. This apparatus features a hollow cylindrical container lined with manganese steel capable of rotating on its axis. The ball mill contains balls of various sizes, made from steel or stainless steel, which serve as the grinding media. The diameter of these balls must be much greater than the largest pieces of material to be ground. The materials and inner wall of the milling bowl are impacted by stainless steel balls, ranging in diameter from 12 mm to 32 mm, that rotate within the center line of the container.

2.3 Mix proportion

Various trial mixes were conducted to determine the appropriate mixture ratio for cementation tile adhesive mortar to comply with recommendations for fresh properties. Dry mixing was the technique utilized.

Here is the production's mixing process:

1) Until a consistent distribution is achieved, mix cement with additives like HPMC and PVA powder by hand.
2) While the mixer operates at a low speed for 1 min, include the fine sand and AACW (measuring 0.6 mm).
3) The mixer operates at low speed for a minute, including the fine Calcium Carbonate and AAC waste with particles smaller than 100µm.
4) Using the Brookfield viscometer, the standard viscosity range of (450 to 550 mPa·s) can be used to calculate each sample's water volume.

After that, the tile adhesive mortar was used to evaluate the properties according to EN12004. Details of the mix proportion for tile adhesive mortar are given in Table 5 [22].

Table 5: Mix proportion

	For 1000g without additives				
MIX ID	**Cement**	**Sand**	**Calcium carbonate**	**AAC wast**	**Additives**
MIX M	-	-	-		
MIX R	340	540	45	60	15

3. Fresh and hardened mixtures testing methods

According to physical requirements, mortar cements are classified into Type M, N, and S. Test Method C109/C109M demands that molds, base plates, dry materials, mixing bowl, and the air in the mixing slab's vicinity meet specific requirements for temperature and relative humidity. There are many methods used for checking the adhesive properties during application time. These tests are very important and will be discussed in this study.

The first is the consistency test, which includes the dry mortar mixed with water before being applied to support. A sufficient amount of water leads to the desired application consistency. A higher or lower amount of water causes unexpected properties of the mortar. A mortar sample is first placed in a conical mold, and then the mold is removed before a mechanical drop is applied to the whole table. The frequency of the table shocks is often taken 15 times in 15 seconds.The open-time test is designed to study the behavior of the adhesive when, once applied to the substrate, it remains exposed to the air for a long time: this happens when the operator tiles a large surface and thus spends more time applying all the tiles.

Open application time test Procedure

- The first contact layer of the adhesive to be tested is applied to the concrete slab. Immediately afterward, a second layer is applied, combing it with 6x6 mm (cementitious adhesives).
- Ceramic tiles of type P1 lay in wait for 30, 10, 5, and 20 minutes before installation. These tiles experienced pressure amounting to (20±0.05) N during a 30-second duration.

This specification applies to thin-bed mortar for autoclaved aerated concrete (AAC) masonry [23]. White or ordinary Portland cement adhesive, polymer-modified, is what this specification applies to, particularly in its usage for interior and exterior wall construction of Autoclaved Aerated Concrete (AAC) masonry. The pull-off test is one of the most important tests to check the adhesive bonding strength. this test is according to ASTM D7234 – 12 and C1583/C1583M – 13. There are different instruments used that comply with this test method. The specific instrument used should be identified when reporting results. This test is destructive, and spot repairs may be necessary [24]. Using the smooth edge of the notched trowel, the surface of the concrete slab is covered with a thin layer of adhesive. Next, the 6x6 mm notched trowel is held at 60º to comb a second adhesive layer. During this step, the adhesive beads will align with the edges of the concrete slab.

4. Results and discussion

4.1 Characterization of AAC waste powder

X-ray diffraction results for AAC waste powder were demonstrated in Figure 1. It showed that the material contained quartz, etteringite, and quantities of Tobermorite. Tobermorite is a calcium silicate hydrate mineral with chemical formula $Ca_5Si_6O16(OH)_2{\cdot}4H_2O$ or $Ca_5Si_6(O, OH)_{18}{\cdot}5H_2O$, the principal crystal hydration product in AACW is tobermorite. The quartz might be a component of the fine aggregate (sand). Calcite should be produced by the carbonation of calcium hydroxide (lime). This is shown by heat treatment's dehydroxylation of the water molecules that exist in the AACW structure. The major peak present in the AAC was at $2\Theta = 26.63^{\circ}$, attributed to residual quartz in the material.

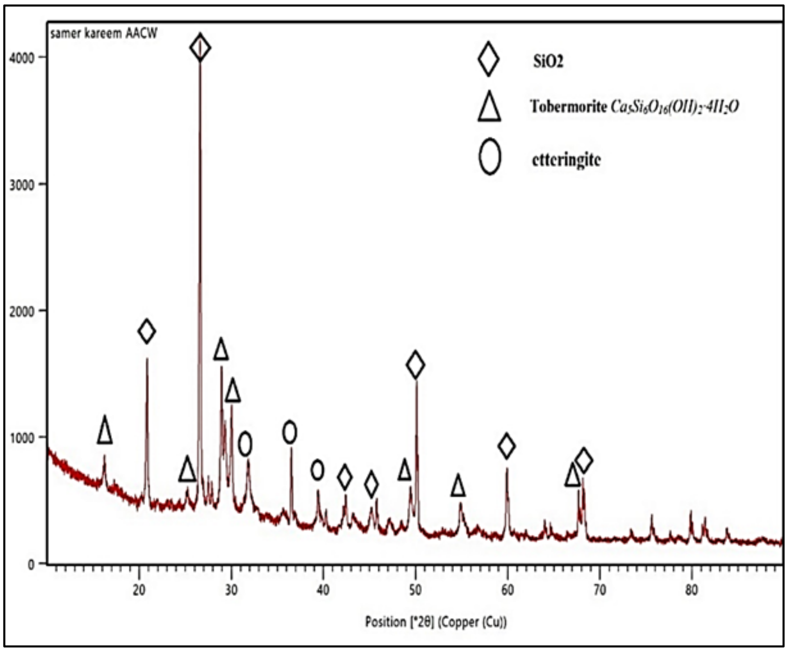
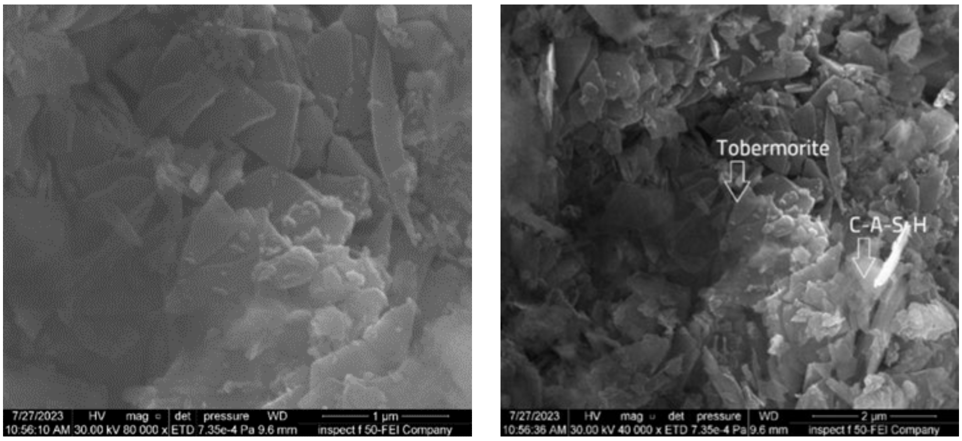


Figure 1: XRD pattern for AAC waste powder used in this study

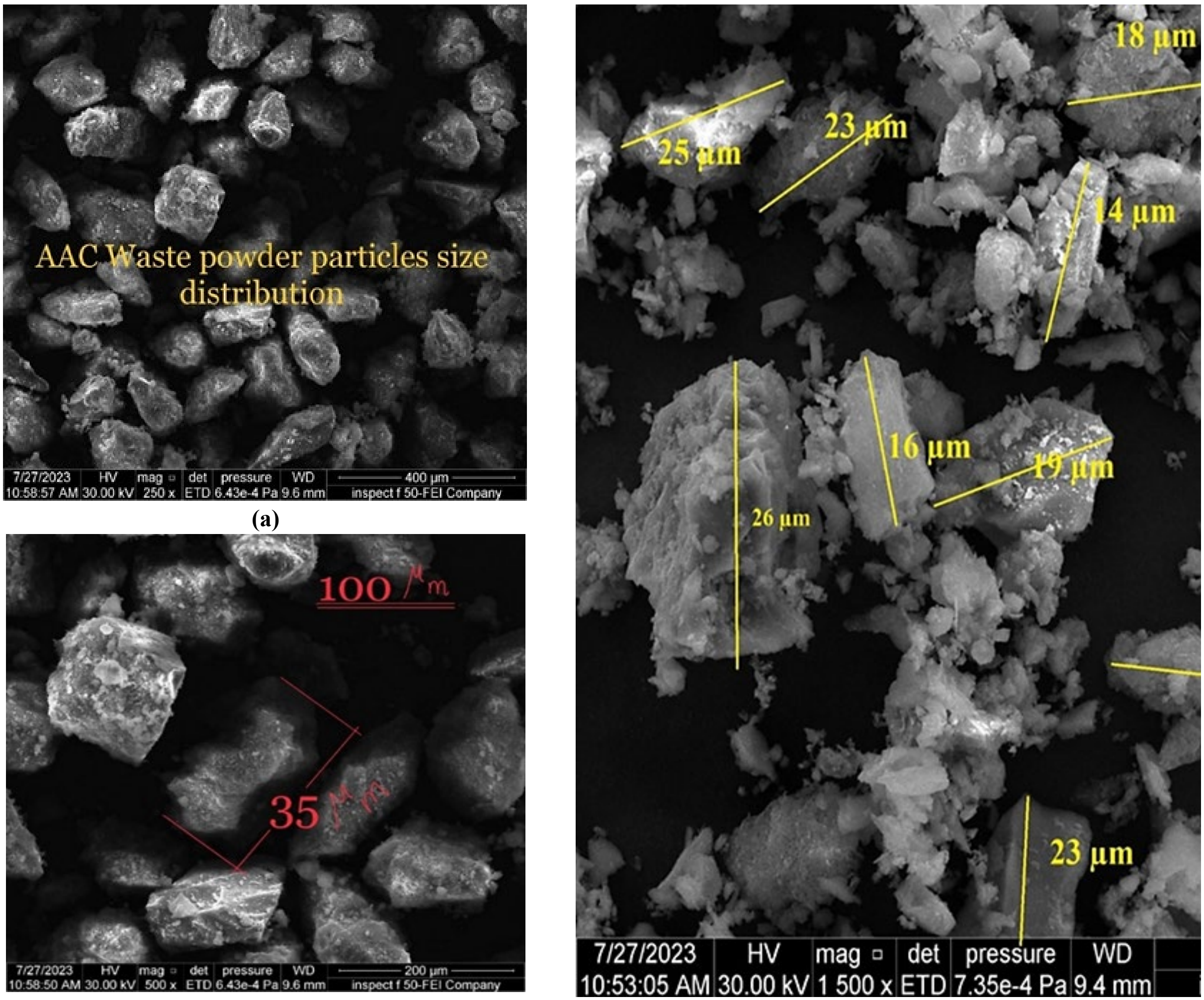
4.2 SEM for AAC Waste Powder

The SEM image in Figure (2a) clearly shows the complex structure of the hydration reaction, showing the ettringite phase [25]. SEM micrographs of tobermorite produced by hydration of autoclaved aerated concrete curried for 12h under 12 bar with 200℃are shown in Figure (2b). Figure 3 shows the morphological pictures of AACW acquired by SEM; the crushed raw AACW is porous, according to the initial observation. This physical texture lets it absorb water, resulting in internal effective potential [26]. Figure 3 shows SEM images of AAC waste particles (a) AAC waste powder particles distribution (b) average particles size of AAC powder (c) agglomerates in fine particles the porous structure of AAC waste powder, which means high water absorption.



(a) (b)

Figure 2: SEM image of the complex structure of the hydration reaction shows Tobermorite



(a) **(b)** **(c)**

Figure 3: SEM image of AAC waste particles (a) AAC waste powder particles distribution (b) average particles size of AAC powder (c) agglomerates in fine particles

4.3 EDS for AACW

Figure 4 illustrates the EDS analysis for AAC waste powder. Table 6 shows the results of the EDS test element atomic weight and percentage from a total element in the interfacial area. Figure 4 and Table 6, we can see that C, O, Ca, Si, and Al were shown in tobermorite in AAC waste powder, the contents of Ca (14.5%), Si (19.4%), C (13.9%) and O (48%). The Al contents (1.4%) are due to the aluminum powder used as a foaming agent. The percentage of Al shown in Table 6 shows that the quantity used in the AAC production process is low, which is a fact.

Table 6: The results of the EDS test

Weight %	Atomic %	Element
13.9	21.7	C
48.0	56.1	O
0.5	0.4	Na
0.5	0.4	Mg
1.4	1.0	Al
19.4	12.9	Si
0.2	0.1	S
0.1	0.0	Cl
0.7	0.3	K
14.5	6.8	Ca
0.9	0.3	Fe

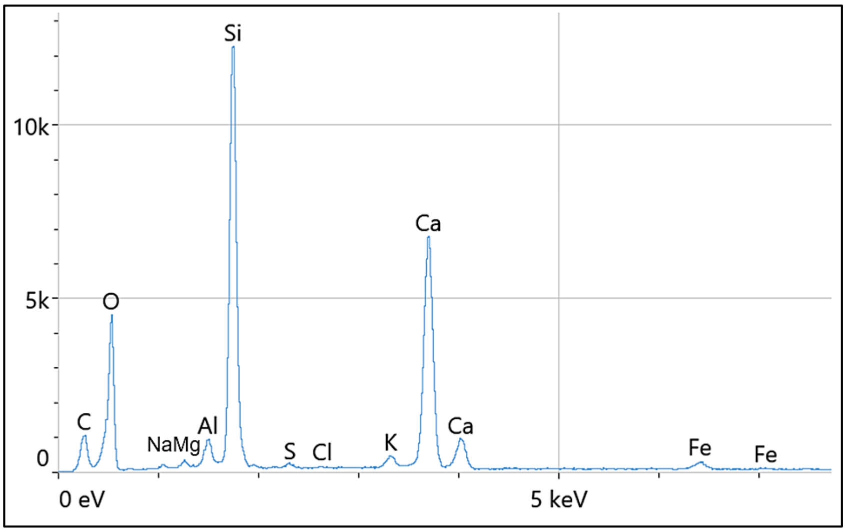
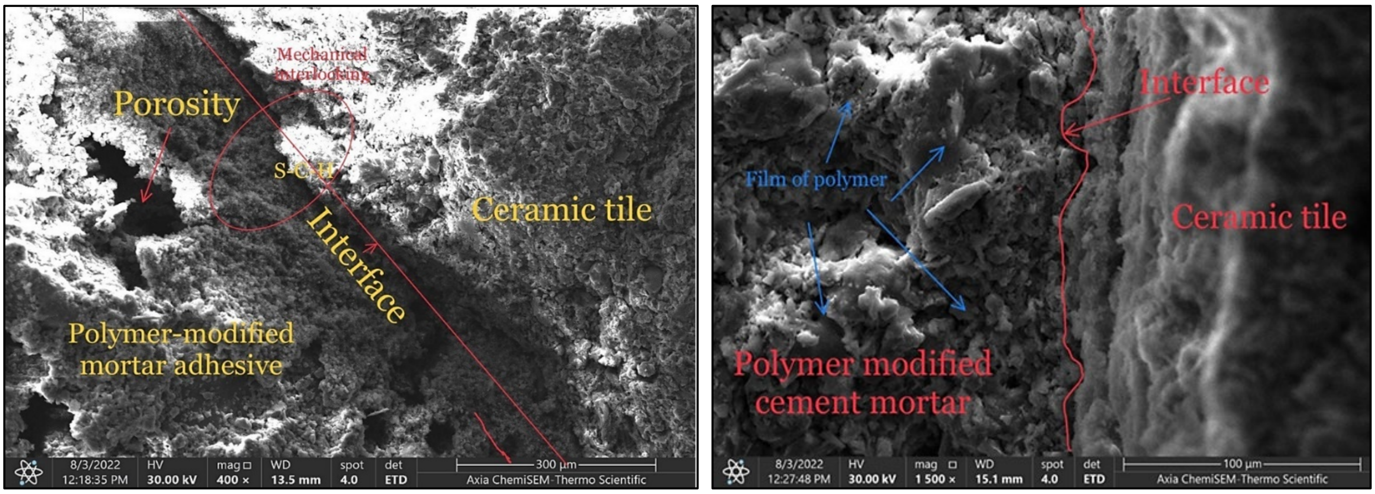


Figure 4: Show the EDS analysis for AAC waste powder

4.4 Microstructural analysis - sem for hardened mortar

SEM imaging is effective in identifying the microstructural properties of polymer-modified mortar. From observations, it was found that the microstructure of such mortar was uniformly distributed. A denser microstructure was formed due to an additional hydration product (C-S-H). This densification enhanced the interfacial transition zone between the polymer-modified cement paste and the tile interface surface. Incorporating particle additives into the cement mortar led to reduced pore size and increased microstructure density, making it less permeable than standard mortar. Powder particles play a dual role in enhancing the performance of the interfacial transition zone between polymer-modified cementitious materials and tile surfaces while improving the cement matrix's quality. In combination with water, the micro AAC waste powder and Portland cement undergo hydrating, forming calcium silicate hydrates—Figure (5a) SEM image at the bonding zone for optimum reference mix at 400 magnification.

Figure (5a) demonstrated that the distribution of microparticle powder allowed for identical and superior microstructures of hardened mortar. Observing the microstructural properties of polymer-modified cement through SEM images would provide clarity. A uniform microstructure had formed. The interfacial transition zone between the polymer-modified cement paste and tile interface surface underwent densification due to the creation of an additional hydration product (C-S-H), producing a denser microstructure. A comparison to the microstructure of reference mortar reveals that the addition of particles in polymer-modified cement mortars resulted in a more compact and less permeable microstructure with smaller pores. Micro-AAC waste powder and Portland cement hydrate mix with water to form calcium silicate hydrates, enhancing the cement matrix's quality and the interfacial transition zone between the tile surface and the polymer-modified cementitious components.



(a) **(b)**

Figure 5: (a) SEM image at the bonding zone for optimum reference (b) SEM image of the interface between a polymer-modified tile adhesive (left) and a ceramic tile (right). The polymer film is clearly visible at the interface

The microparticle powder would also react with excess calcium hydroxide to form a finely dispersed gel that fills the large pores and micro-cracks. As a result, the hardened cement paste contains fewer calcium hydroxide crystals and has fewer large capillary pores. Also, the distribution of microparticle powder allowed the creation of the same products with a better microstructure of hardened mortar, as observed in Figure (5b).

SEM images would clarify the microstructural properties of the polymer-modified cement. The microstructure was shown to be uniform. The production of a denser microstructure and densification of the interfacial transition zone between the polymer-modified cement paste and the tile interface surface can also be observed due to the formation of the additional hydration product (C-S-H). Compared to the reference mortar's microstructure, the polymer-modified cement mortars containing particle additions were found to be less permeable, with smaller pores and a densified microstructure. The powder particles serve as a filler or binder to improve the cement matrix's overall quality and the performance of the interfacial transition zone between the tile surface and the polymer-modified cementitious components. The presence of micro-AAC waste powder and Portland cement hydrate, together with water, forms calcium silicate hydrates.

The calcium silicate hydrate (C-S-H) and $Ca(OH)_2$ on the hexahedron may be seen connecting on SEM images of the aggregation of mortar-hydration products on the bonded interface between mortar and tile. Clearly, the C-S-H gel was linked by a network structure and formed a fine fibrous structure on the mortar's surface. The "root pile" effect of the C-S-H gel, formed by the cement-AAC waste's hydration reaction to the fine aggregate pores, enhanced the bonding capability. Figure 6 demonstrates how the strength was mainly responsible for the strength between the mortar and aggregate [27].

4.5 Eds for hardened mortar

Analysis conducted by EDS focused on the interface zone between the tile surface and the polymer-modified cement mortar. The optimal mixture batch was used for testing, as shown in Figure 6. The results revealed that free ions Ca^{2+} played a significant role in forming C-A-S-H gel at the interfacial zone. These ions were believed to be produced from calcium hydroxide ($Ca(OH)_2$) breakdown during the OPC concrete hydration process. Through SEM mapping, Figure 7 clearly demonstrates that strong bonding and mechanical strength were improved by forming a C-A-S-H gel with a predominant ratio at the interfacial zone. In contrast, potassium-activated GP yielded an inferior and feeble interface region, depicted in Figure 7. EDS mapping of the tile adhesive / ceramic tile interface of mix 3 a, b, c, d, e, f, g, h, i, j ,k, l, and m represent each element's concentration in the test area.

As seen in Table 7, Eds' analysis focused on the optimal mix batch and examined the interface zone where the polymer-modified cement mortar met the tile surface. The outcome of the analysis revealed the presence of the C-A-S-H gel, which was formed through the involvement of free ions Ca^{2+} in the interfacial zone.

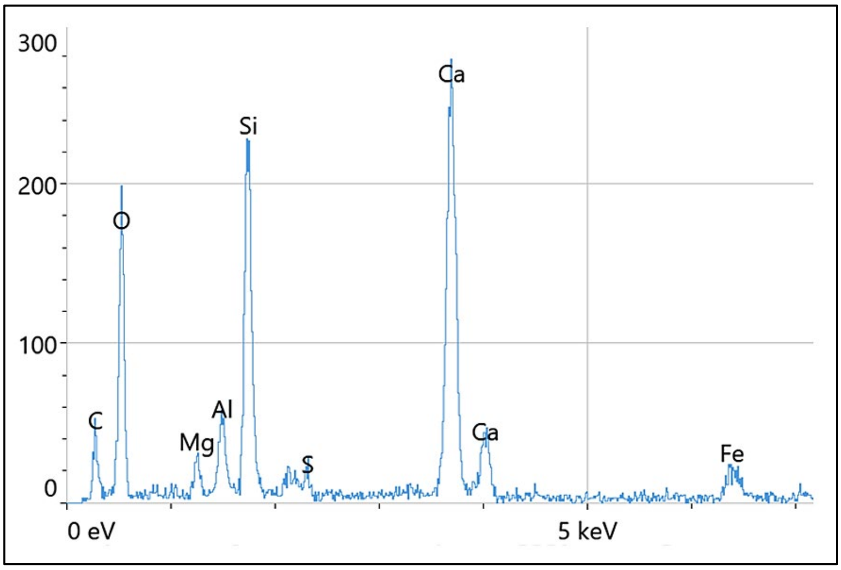
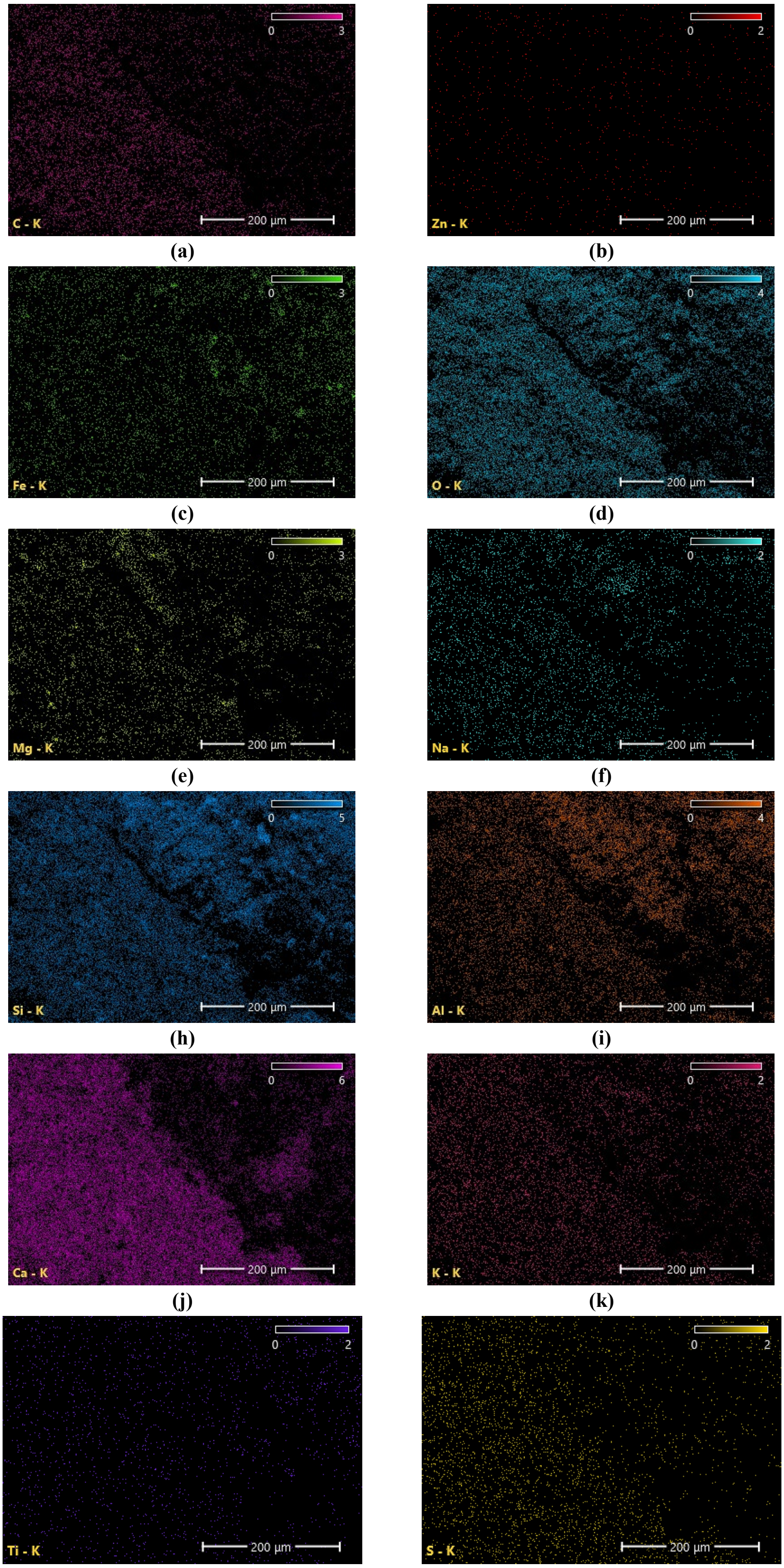


Figure 6: EDS analysis for ceramic tile and adhesive interface

Table 7: The weight percentage of each element at the interface zone

Element	Atomic%	Weight%
C	17.2	10.7
O	60.8	50.5
Mg	1.4	1.8
Al	2.1	3.0
Si	8.2	11.9
S	0.2	0.4
Ca	9.0	18.7
Fe	1.0	2.8

Figure 7 and Table 7 show that C, O, Ca, Si, and Al were shown in the interface region. The contents of Ca (18.7%), Si (11.9 %), C (10.7%), and O (50.5%), this quantity led to the effect of AAC waste powder reacting with other components and showing strong structure, causing the increase in strength. The Al contents (3%) are due to the aluminum powder used as a foaming agent. The percentage of Al shown in Table 7 shows that the quantity used in the AAC production process is low, which is a fact.



(a) **(b)**

(c) **(d)**

(e) **(f)**

(h) **(i)**

(j) **(k)**

(l) **(m)**

Figure 7: EDS mapping of the tile adhesive/ceramic tile interface of mix 3 a, b, c, d, e, f, g, h, i, j ,k, l, and m represent each element's concentration in the test area

4.6 Consistency test

The dry mortar is mixed with a certain amount of water before applying to support. Enough water leads to the desired application consistency. A higher or lower amount of water causes unexpected properties of the mortar. Therefore, controlling the mortar consistency plays an important role in the construction. For the mortar in the fresh state, the consistency is identified using a flow-table apparatus (ASTM C270), in which a mortar sample is first placed in a conical mold. Then, the mold is removed before a mechanical drop is applied to the whole table. The frequency of the table shocks is often taken 15 times in 15 seconds. The results presented in Table 8 show the results of the consistency test, which matched the standard limitation.

Table 8: Shows the results of the consistency test

Mix No.	Mixing water % of solid content	Consistency (mm)
Mix R	24	176
Market brand	25	180

The test was performed according to ASTM standard C270. According to the consistency of mortars with a bulk density over 1200 kg/m^3, it should be 175 mm ± 10 mm, and this was the criterion used to define the mixing water content.

4.7 Open application time

Figure 8 shows that the open application time of the reference mix is higher than that of the market mix because the content of the additive is higher than that of the market brand. The open time (in minutes) is when a tile adhesive will no longer have the required tensile strength. According to EN 12004, it has reached [18].

This finding held despite the porosity and fineness of the AACW powder. Free water within fresh cement paste can be categorized as filling or absorption water - the former resides in the space between particles. At the same time, the latter is absorbed by the surface or interior of particles. Consistency increases as absorption water content rises, given that the water-to-binder ratio remains constant. As depicted in Figure 8, it is evidenced that AACW possesses physical porosity. Autoclaved aerated concrete's pore size can span from a few millimeters to dozens of microns. As a result, the higher water requirement in the same consistency of reference mix is due to the water absorption of porous AACW.

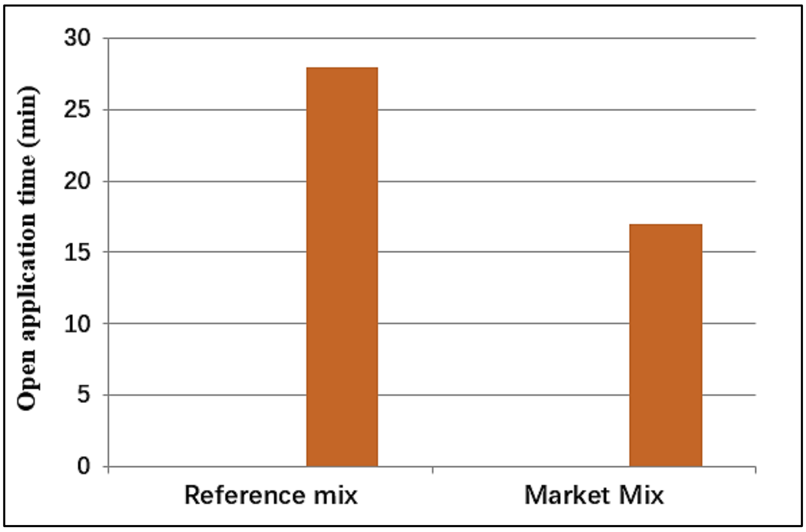


Figure 8: Open application time test for average results

4.8 Splitting tensile strength

Figure 9 shows that the splitting tensile strength of polymer-modified cementation mortar is higher than the mortar used from the market. The increase in splitting strength was due to the tobermorite deposited in the AACW powder, which is a very strong component compared to the C-S-H cement system. The inclusion of quartz produces tobermorite, meaning that the formation of tobermorite causes the strength to increase.

The results show that the splitting tensile strength of polymer-modified cementation mortar increased with the increase of microparticle size powders, and it was continuously developed then started to decrease after 15% of waste according to the water absorption ratio mentioned below the increasing of water content caused decreasing of strength compared to reference mortar. The result of the test compared with ASTM C1660 is acceptable. Figure 9 shows the splitting tensile strength test failure mode of the sample the test occurred according to ASTM C 1660.

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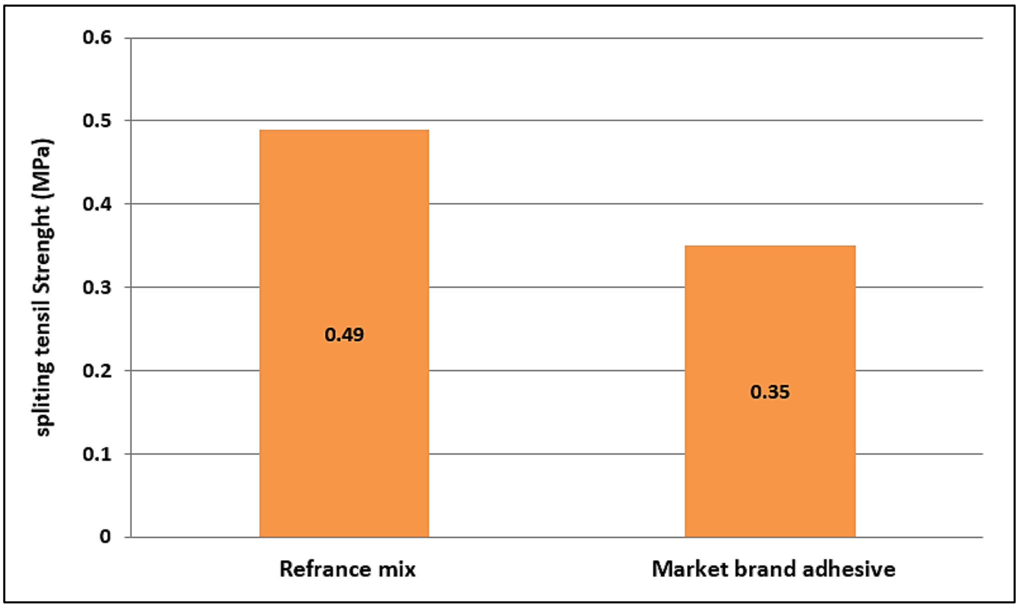

Figure 9: Splitting tensile strength test results

4.9 Pull-Off Test

The Pull-off samples, including 15 % of AACW, passed the EN 12004 type C1 requirement shown in Figure 10. The result shown in Figure 10 illustrates that the polymer-modified cementation composite adhesive is better than the adhesive supplied by the market in the pull-off test, and both of them passed the quality limit mentioned in the EN 12004 standard.

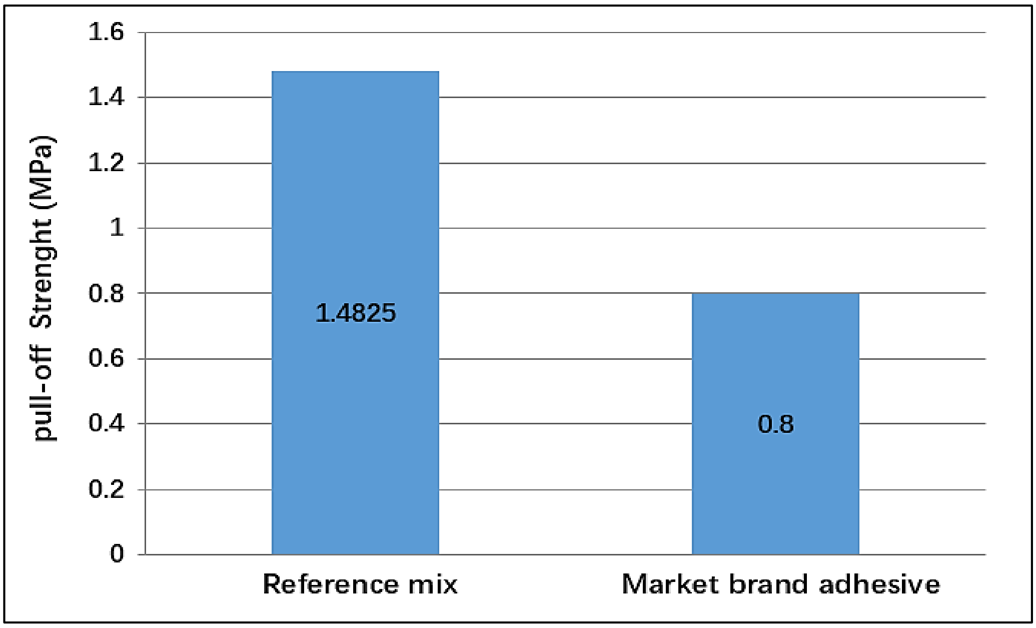

Figure 10: pull-off test results

The Pull-off samples, including 15% AACW, met the EN 12004 type C1 requirement.

The average results for the adhesive strength of tile adhesive were significantly greater than the reference value of 0.5 MPa. In many cases, they were even higher than 1.0 MPa. This finding can be observed. There were discernible differences in the standard deviations for both materials put through the test. The high values that were found, particularly for samples that contained 15 percent of AAC waste powder, were because of the high water retention and the fact that AAC waste contains high-strength components such as tobermorite and ettringite; all of these phases were shown in the SEM test unlike most solid waste additions which were studied by Bentz and Ferraris, [28]. Grounded waste concrete powder showed a similar trend to the increase in setting time caused by solid waste. This was especially true for samples that contained 15 percent of AAC waste powder. The observed level of variability in these examinations was often quite high, which was reflected by variation coefficients that ranged from forty to one hundred percent. According to international standards, the level of adhesion strength can be evaluated for various systems and components. Nevertheless, laboratory testing is the primary focus of these standards.

Compared to the lowest limit of the standard EN12004, the findings of market adhesive are lower than those of reference mortar, but they are still acceptable.

5. Economic and environmental benefits

In Iraq, the economic evaluation considers local factors such as regulations and market attributes to ensure a practical outcome. AAC manufacturers may consider implementing a new commercial line by recycling off-cuts from their main production process to capitalize on two benefits. This approach aligns with a common trend in the building industry that promotes the reuse of materials, thereby cutting down on economic expenses and reducing the environmental impact of natural resources. Additionally, this approach is advantageous for AAC due to its higher production cost. The Iraqi market values waste containing cement and lime, with the cost of disposal being 80 USD/Ton for cement and 100 USD/Ton for lime. Contrastingly, AAC waste powder is only worth 15 USD/Ton. This makes cement five times more valuable than AAC waste. Additionally, each 1-ton sack of Tile adhesive premixed mortar comes with 300 kg of these valuable ingredients.

The cost of cement used for producing one toe of tile adhesive = 0.250 tons of cement*80 USD= 20 USD of binder cost in tile adhesive, the used of AAC Waste with 15% of cement weight the new cost of 1 ton as bellow. The cost of tile adhesive = 0.25 ton of cement *0.85*80 USD+ 0.25 ton of AACW *0.15*15 USD = 17.56 USD of binder cost in tile adhesive made by using AAC Waste powder. The cost was saved by 13%.

6. Conclusions

The present study investigated the feasibility of producing sustainable, high-quality, and performance cement-based adhesives using autoclaved aerated concrete waste (AACW).

Based on the results obtained in this study, the following conclusions are attained:

1) The bonding strength obtained (1.48 N/mm^2), shear strength (1.4 N/mm^2), and splitting tensile strength (0.64 N/mm^2) are all greater than the EN12004 requirement—furthermore, the application time and slipping test match EN 1348 standard.
2) Environmental and financial benefits resulted from the use of AACW in the manufacturing of construction materials.
3) Compared to normal cement paste, the bonding strength of cement-based tile adhesive mortar substituted cement pastes is greater, within a 15% replacement level. Additionally, the fine, dry-milling AACW significantly improved the structure.
4) Including AAC waste below 100 µm particle size for a percentage (15)% of cement weight increased bonding strength and splitting tensile strength. Furthermore, it caused a reduction in dry density.

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Author contributions

Conceptualization, S. Turki. and S. Ibrahim; methodology, M. Al Maamori.; software, S. Turki.; validation, M. Al Maamori and S. Ibrahim; formal analysis, S. Turki. and S. Ibrahim; investigation, M. Al Maamori; resources S. Turki. and S. Ibrahim; data curation, S. Turki. and S. Ibrahim; writing—original draft preparation, S. Turki.; writing—review and editing S. Turki.; visualization, S. Turki ; supervision, S. Ibrahim, M. Al Maamori; project administration, S. Turki. and S. brahim. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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